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Systematic Review

Decision Support Frameworks in Solid Waste Management: A Systematic Review of Multi-Criteria Decision-Making with Sustainability and Social Indicators

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Abstract: Waste management is a critical sector that needs to co-ordinate its activities with outcomes that impact society. Multi-criteria decision-making methods for waste management have been widely considered using environmental and economic criteria. With the development of new social regulations and concerns, sustainable waste management needs to additionally target socially acceptable practices. Despite the need to aid solid waste management decision-makers in contemplating the three pillars of sustainability, a limited inclusion of social impact has been found in the multi-objective decision-making literature. This study presents a systematic literature review of multi-criteria decision-making methods in solid waste management. The purpose of this study is threefold. (1) Emphasize the application of multi-objective decision-making methods, summarizing the models that have been used and their applications; (2) provide insights into the quantification of social aspects and their inclusion in decision-making methods, providing a list of social indicators collected from the reviewed studies; (3) offer an analysis of stakeholders' involvement in waste management. From the articles investigated, one can observe the importance of understanding the local context in which the waste management system is located and the necessity of community consultation to recognize the potential challenges and improvements to solid waste management systems. Consequently, the involvement of stakeholders is crucial during the quantification process of social indicators. In alignment with the findings and needs raised by this review, a methodological approach is suggested for integrating optimization, social aspects, and stakeholders under a waste management context.

Keywords: multi-criteria decision-making; multi-objective optimization; sustainability criteria; social indicators; literature review

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1. Introduction

Waste management (WM) is one of society's critical sectors, although it was relatively unregulated until 50 years ago [1]. With the advent of environmental laws and the greater public awareness of the impacts of poorly managed waste, as well as technologies, there is a greater need to provide more advanced decision support. Inappropriate waste management can cause severe consequences for the planet (e.g., air pollution, climate change, biodiversity loss, etc.) and its inhabitants [2,3]. WM operations are increasingly included in city, county, or state climate action or other pro-environmental efforts, e.g., waste diversion from landfills to recycling or reuse. In the past few years, there have been examples across the United States of staffing shortages in WM [4,5], necessitating that managers improve working conditions in terms of safety and or compensation. Accordingly, more attention is being given to the inclusion of social aspects (e.g., labor, public health, social acceptance, and visual pollution) in addition to commonly used economic and environmental criteria to complete the three pillars of sustainability.

It is increasingly difficult for managers to identify and achieve sustainable WM, targeting the protection of human health, the environment, workers, and citizens while keeping costs affordable [3,6,7]. Decision support methods can help waste managers consider the interactions of the three pillars of sustainability as they plan for near and long-term operations and infrastructure investments. One common challenge when considering the three pillars is that they often conflict with each other [8]. As exemplified by Goulart Coelho et al. [9], for a firm, the preferred solution would be the one involving the least cost, whereas, for public authorities, the pertinent solution would be the one with the least risk to the public and/or environment. Multi-objective decision-making (MODM) methods can capture these trade-offs and facilitate decision-makers' understanding of a set of alternative solutions instead of a unique solution. MODM comprises a continuous space in which alternatives are not predetermined, providing breadth when considering WM strategies. In this way, the decision maker has more freedom to make an informed selection of an alternative that satisfies the needs of the systems based on the importance given to each objective under consideration. The aim of this review is to summarize the state-of-the-art in the use of decision support methods, with a focus on MODM, for WM, as well as identify the gaps in their application, particularly with respect to quantifying and assessing social aspects as a criterion to be introduced into a decision framework.

A stakeholder is a group or individual that can affect or is affected by the achievement of a solid waste management (SWM) system's objectives [10]. Social impacts are the downstream effect of a stakeholder's decisions, and they can represent positive or negative pressures on social endpoints (i.e., the well-being of stakeholders) [11]. Stakeholders' perspectives are vital for guaranteeing the legitimacy and utility of model results [12], particularly for social considerations. In particular, if the target of decision-making is to change stakeholder behaviors, the requested changes must make sense to stakeholders if the changes are to be adopted [13]. Therefore, the objectives of this literature review are to present MODM applications in WM, provide insights on social aspects and the metrics used to represent them and their inclusion in MODM, offer an analysis of stakeholder involvement in waste management, recommend a conceptual framework that considers these elements based on the lessons learned from this review, and suggest future research directions for decision-making areas in WM.

1.1. Decision Support Framework Classification

There are several methods used in decision support frameworks in the WM context. Figure 1 displays the classification considered in this review paper based on Goulart Coelho et al. [9], who identified the most widely used decision support frameworks in the field of WM as life cycle assessment (LCA), cost-benefit analysis (CBA), and multi-criteria decision-making (MCDM). LCA most commonly focuses on environmental aspects and has guidance on the development of social indicators [11] but does not routinely include social indicators, whereas the maximization of economic efficiency is the major goal of cost-benefit analysis. Neither have the capacity that MCDM approaches have for assessing alternatives by simultaneously employing multiple conflicting criteria.

MCDM approaches can be further categorized into multi-attribute decision-making (MADM) and multi-objective decision-making (MODM). The first one refers to the selection or ranking of problems that function in a discrete decision space with a predetermined and limited number of alternatives evaluated against a set of attributes or criteria. Whereas MODM implies the optimization of problems, including a continuous space in which alternatives are not predetermined; instead, a set of objective functions, subject to constraints, is maximized or minimized to find a set of optimal alternatives. This set of optimal alternatives represents the advantage of MODM since the decision-makers can clearly examine the trade-offs of selecting one solution over another, whereas MADM captures stakeholders' preferences at the beginning and presents a solution based on those initial choices. As stakeholders are usually involved during the execution of MADM approaches, these have more commonly included all three pillars, and it has been more challenging to include all three pillars in MODM approaches. Within the three pillars, social impacts are interpreted as the consequence of social interactions resulting from the execution of an activity or the outcomes obtained from it by considering the actions taken by stakeholders [11]. In this context, we refer to the effect on social endpoints caused by waste management activities influenced by stakeholders' decisions to operate WM systems.

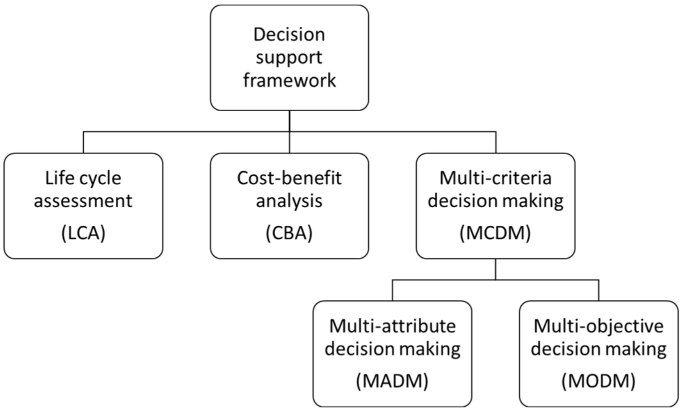

Figure 1. Decision support framework classification in WM.

1.2. Previous Studies

Previous reviews related to decision support frameworks in WM have been completed. Table 1 shows a summary of the key aspects considered in these reviews, including the number of articles reviewed (when available), the decision support framework covered, Figure 1, and whether or not the authors considered the three pillars of sustainability. Although most of these articles reviewed papers that addressed the three pillars of sustainability, only one of them did so in combination with MODM: Goulart Coelho et al. [9] reviewed the applications of MCDM in WM and found that only 19% of the articles referred to MODM, highlighting the under-utilization of these methods in WM applications.

Table 1. Previous review articles related to decision support frameworks in WM.

Review Article	Number of Articles Analyzed	Decision Support Framework	Three Pillars of Sustainability
Pires et al. (2011) [14]	N/S	CBA, LCA, MCDM, and others	Yes
Achillas et al. (2013) [15]	79	MADM	Yes
Allesch and Brunner (2014) [6]	151	LCA, MADM	Yes
Goulart Coelho et al. (2017) [9]	260	MCDM	Yes
Singh (2019) [16]	N/S	MCDM	No
Garcia-Garcia (2022) [17]	43	MADM	Yes

Numerous MCDM approaches have been integrated into methods to assess or make decisions within WM, including system engineering models and system assessment tools, as presented in the review by Pires et al. [14]. System engineering models include cost-benefit analysis, optimization, and simulation models, whereas system assessment tools comprise scenario development, material flow analysis, LCA, and other environmental, strategic, socioeconomic, or sustainable assessments. Although Achillas et al. [15], Allesch and Brunner [6], and, more recently, Garcia-Garcia [17] stated that they had considered MCDM approaches, the reviewed articles presented only MADM, restricting such reviews from MODM applications. Moreover, the majority of the studies presented by Allesch and Brunner [6] referred to LCA, and only one-tenth mentioned MADM methods.

Regarding the three pillars of sustainability, Pires et al. [14] found that system assessment tools were successful for environmental aspects and have the potential to incorporate social impacts. However, few of the system engineering models included social impacts. The authors discussed that the contribution of these models with social impacts is limited since the necessary assumptions may not be realistic. Consequently, the mathematical outputs could be contradictory. Singh [16] focused on environmental aspects, whereas Achillas et al. [15] and Allesch and Brunner [6] emphasized costs and environmental impact, but here the social criteria were rarely included. On the other hand, most of the papers reviewed by Garcia-Garcia [17] included all three pillars; however, the author focused more on the methods and applications, and it was not specified how the social metrics were defined or measured.

Thus, despite the existence of previous review articles, these reviews have primarily focused on MADM methods. Although the environmental, economic, and social criteria have been considered in some of them, little to no evidence on social metrics has been introduced in terms of MODM methods.

1.3. Research Objectives

This literature review collected information related to three areas: (1) multi-objective decision-making methods in SWM, including economic, environmental, and social criteria; (2) quantitative methodologies and indicators to assess social dimensions; (3) engaging stakeholders in waste management.

2. Methodology

Our literature review protocol followed the guidelines provided by Kitchenman and Charters [18], and it is in accordance with the preferred reporting items for systematic reviews and meta–analyses (PRISMA) [19] (see Supplementary Materials for the checklist according to PRISMA methodology). The protocol consists of six steps, as presented in Figure 2. The first two steps are presented in Section 1; this section elaborates on the search, selection, and extraction strategies, and the synthesis of the extracted data is presented in Section 3.

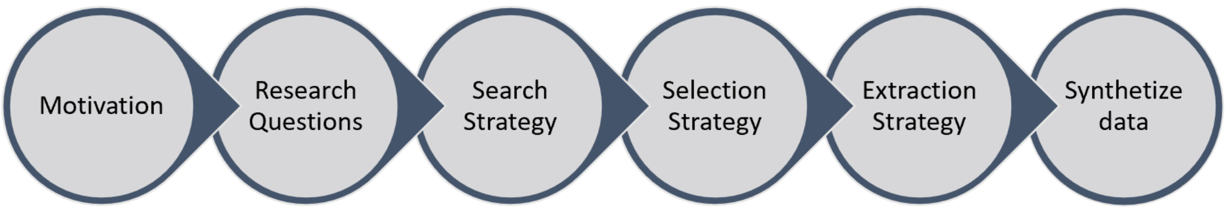

Figure 2. Literature Review Protocol.

2.1. Search Strategy

The PRISMA method provides guidelines for the search, selection, and extraction strategies, which are specified from item #5 to item #15, according to the PRISMA checklist [19]. The first step in the methodology (item #5) is to specify the inclusion and exclusion criteria for the review and grouping for synthesis. The search terms were defined based on keywords and synonyms intended to capture the work completed on multi-objective decision-making for waste management and with a focus on the inclusion and development of a social indicator, Table 2. The stakeholder keyword was added in a search of the literature that expressly included stakeholder input in the development of the indicator.

Spelling variants were also considered (e.g., decisionmaking or decision-making), but since no difference was found, they were excluded from the search queries.

Table 2. Keywords and their synonyms.

	Keyword	Synonyms and Variants	Source
1	Multi-objective decision-making	Multi-objective optimization Multi-objective stochastic optimization	[9]
2	Solid waste management	Municipal waste management	[15]
3	Sustainability criteria	Economic, environmental, social	[20]
4	Quantitative methods	Measurable methods	[21]
5	Social dimension	Social aspects Social measure	[22]
6	Stakeholders' opinion	-	-

The second step in the PRISMA method (item #6) involves specifying the databases and other reference lists and dates of the searches, with the third (item #7) presentingthe search strategy. Four database sources were selected: Web of Science, Science Direct, Engineering Village, and Academic Search Premier. The combination of all keywords in one query returned no results; thus, the keywords were combined in different queries, with one query per research question, as shown in Table 3. Table 3 summarizes the keyword queries in relation to the research question, databases queried, and the date of the search. The articles included in the search belong to one of these categories: journal articles, review articles, research articles, or other articles. The only language included was English, and the timespan covered ranged from January 2011 to January 2022. The search began with 2011 because of the significant increase in publications on MCDM methods applied in SWM after 2010, which was found by Goulart Coelho et al. [9].

Table 3. Queries per database source.

	Research Question	Database Queried	Keywords Searched
Query 1	What multi-objective decision-making methods have been utilized in solid waste management that consider the three pillars of sustainability?	Engineering Village	((((((multi objective optimization OR multi objective decision making OR multi objective stochastic optimization) AND (solid waste management OR municipal waste management) AND (sustainable criteria OR (economic AND environmental AND social)))) WN ALL)) AND ({ja} WN DT)) AND ({english} WN LA))
		Science Direct	(multi objective optimization OR multi objective decision making OR multi objective stochastic optimization) AND (solid waste management OR municipal waste management) AND (sustainable criteria OR (economic AND environmental AND social)
Query 2	How have the authors quantified and assessed the social dimension in solid waste management?	Web of Science	TS = ((social dimension OR social aspects OR social measure) AND (solid waste management OR municipal waste management))
Query 3	How have the authors introduced stakeholders' perspectives in solid waste management?	Web of Science	'TS = ((stakeholder opinion) AND (solid waste management OR municipal waste management))
		Engineering Village	((stakeholder opinion) AND (solid waste management OR municipal waste management))
		Academic Search Premier	((stakeholder opinion) AND (solid waste management OR municipal waste management))
		Science Direct	((stakeholder opinion) AND (solid waste management OR municipal waste management))

On 9 February 2022, we searched for Query 1 in Science Direct. On 10 February 2022, Queries 2 and 3 were searched for in each database, according to Table 3. On 15 February

2022, we conducted a search for Query 1 in Engineering Village. Finally, we updated the database search on 4 August 2023 for all queries. We used the same search queries, except that we narrowed the search timelines from February 2022 to July 2023.

2.2. Selection and Extraction Strategies

We used the PRISMA flow diagram [19] to report the selection of relevant papers (Figure 3). A total of 637 papers were initially identified. The selection process (item #8) to assess whether a study met the inclusion criteria for this review was first conducted according to the article title to eliminate articles outside of our study focus. Specifically, our study bounded the WM system from collection to disposal; hence, the studies solely dedicated to collection were discarded. Household practices, e.g., waste separation, were removed as this research does not target any improvement in user practice. Consequently, we filtered unrelated topics, such as sustainable infrastructure, urban planning, smart cities, utility consumption, environmental sanitation, anti-littering behavior, recycling behavior, consumer behavior, environmental ethics, laws, and taxes. The out-of-scope topics that consider other waste streams that are not municipal solid waste, recycling and technology-specific research, waste generation prediction, waste classification, waste separation, waste collection, and packing waste were also excluded.

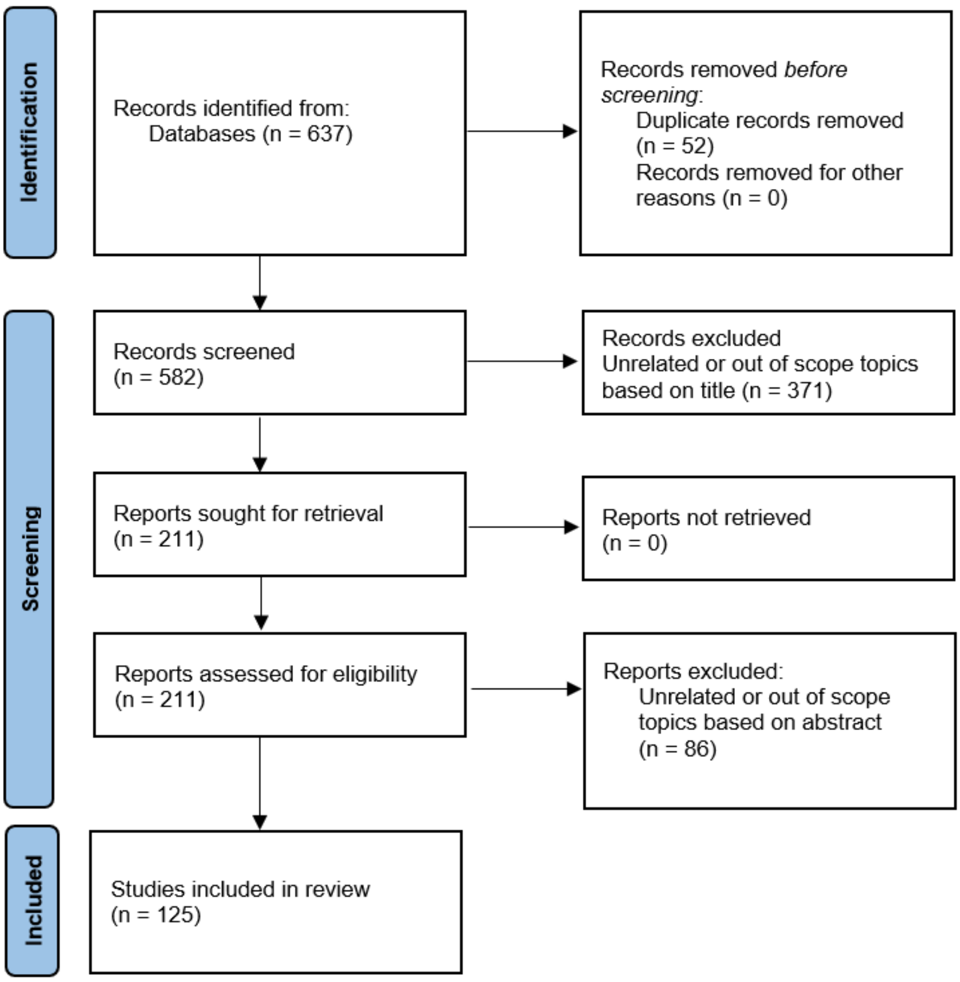

Figure 3. PRISMA flow diagram.

Then, the abstracts of the remaining papers were analyzed against the same inclusion criteria topics to eliminate the papers that were irrelevant to this study (Figure 3). The final list consisted of 125 unique papers. In order to account for the study risk of bias assessment (item #11), the filtering of the articles was performed by one researcher and reviewed by a second researcher. Any disagreements on article selection were thoroughly discussed until a consensus among the researchers was reached.

Each of the 125 articles was reviewed to search for information related to the research questions, as presented in Table 4 (item #9). The presence of relevant data was noted, and a qualitative description of these was recorded in Microsoft Excel. The sought data items (items #10a and #10b) refer to decision-making methods, social metrics or indicators, data collection, stakeholders, and WM applications according to each of the research questions defined (Table 4). Another feature considered was uncertainty since there are parameters or variables that can shift decisions significantly based on the value adopted. The methods were classified based on the inclusion of uncertainty as either deterministic or probabilistic methods. In addition, any special remarks or comments from the articles were recorded at the researcher's discretion. This review does not target quantitative results (i.e., statistics) from the articles selected; hence, the effect measures (item #12) used to present the results refer to the answers to our research questions. The synthesis methods (item #13) that we followed simply tabulated the information collected, according to Table 4. The tabulation of the articles was useful for computing the descriptive statistics of the review (e.g., the percentage of articles reviewed that included the three pillars of sustainability).

Table 4. Data items to extract from articles.

Research Question Topic	Data Items
Q1: Multi-objective decision-making method	Decision-making method
	Deterministic or probabilistic classification
	Three pillars of sustainability
	Application
	Uncertainty
Q2: Social dimension	Method
	Metrics or indicators used
	Data collection
	Application
Q3: Stakeholders' involvement	Method
	Stakeholder list
	Data collection
	Application

3. Results and Discussion

3.1. Overview

The 125 papers reviewed demonstrated the challenge of developing social indicators and the apparent disconnection of this with MODM methods. Direct engagement with stakeholders can guide this task; however, only 12 papers included all three of the research question topics. The distribution of the papers among the areas of interest is presented in the Venn diagram in Figure 4. Decision-making articles were found (shaded area in Figure 4), and their corresponding sustainability indicators are discussed further in Figure 5. It was found that social indicators were more commonly included when using approaches such as questionnaires and surveys, fuzzy theory, and game theory. The quantitative social aspects (e.g., the number of jobs created) were usually included with MODM methods, whereas qualitative social metrics (e.g., social acceptance) were first processed by MADM methods before their consideration in MODM, as MADM more readily receives stakeholder input and facilitates the quantification process of subjective metrics. Geographical representation was not evenly distributed (Figure 6); notably, there were no studies found in the US, and decision-making research is strongly represented in Iran. Social dimension research is more uniformly distributed, but the leading countries are Brazil, India, Italy, and Thailand. Stakeholder involvement research is limited, with prominent studies from India and the United Kingdom.

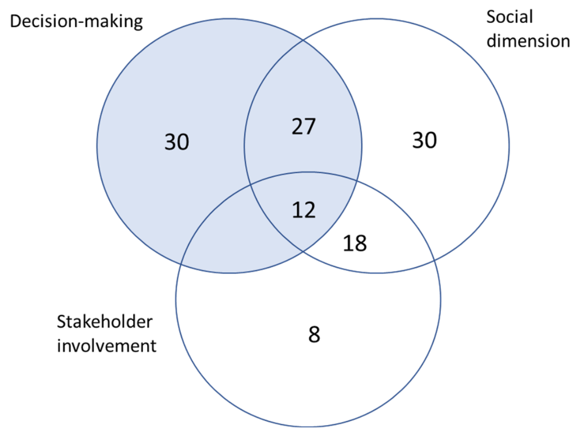

Figure 4. Venn diagram of the three areas considered in the literature review.

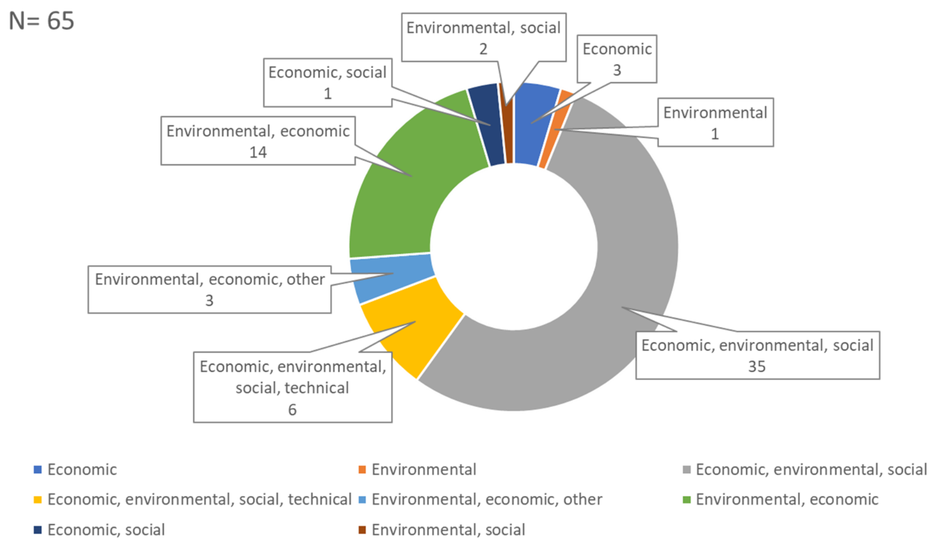

Figure 5. Distribution of sustainability indicators in SWM.

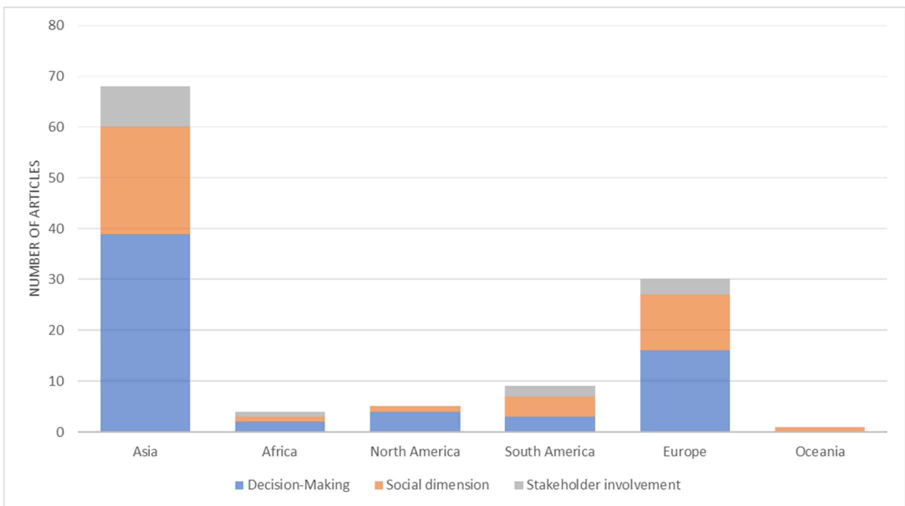

Figure 6. Geographical location of articles (by area) considered in the review.

The decision-making methods were well-represented, with 69 papers, as can be seen in the shaded area in Figure 4. We omitted the literature reviews to end up with a total of 65 papers. From this total, 35 papers included all of the three pillars, and 17 papers examined environmental and economic criteria, with three of these papers also including resource recovery and energy consumption as criteria (Figure 5). Six papers expanded upon the three pillars to include criteria referred to as technical. Two papers included economic and social information, one paper considered environmental and social information, and the remainder discussed only economic or environmental information.

3.2. *Multi-Objective Decision-Making*

This section reports the findings of reviewing the articles based on the data items in Table 4.

3.2.1. Multi-Objective Decision-Making with Deterministic Models

A total of 14 papers reviewed in the literature considered a multi-objective single-period model, and of these, nine applied mixed-integer linear programming, whereas the other five utilized continuous linear or nonlinear optimization. Another three papers considered a multi-objective in combination with a multi-period formulation using either linear or mixed-integer linear programming (Figure 7). Of all those, eight included a social indicator (Table 5).

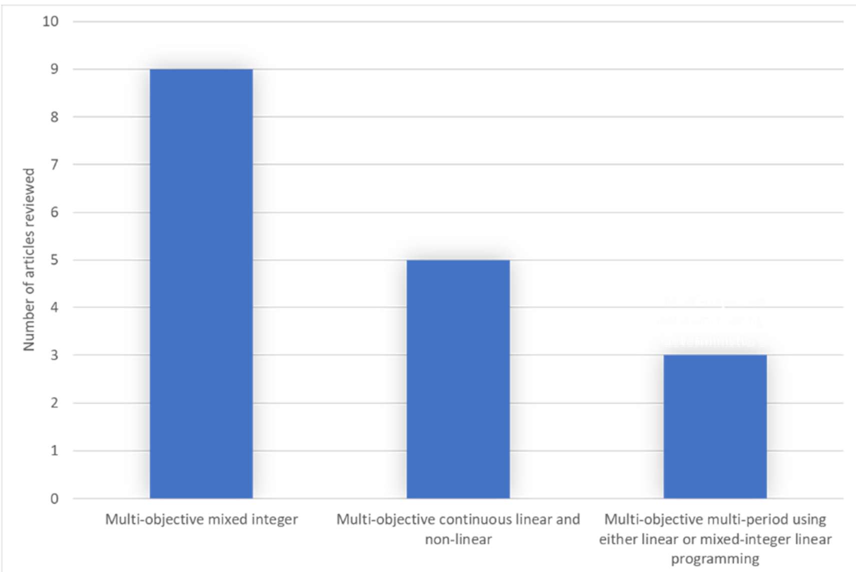

Figure 7. Deterministic multi-objective decision-making distribution.

A common characteristic in the papers that address social criteria was the inclusion of social aspects in the model's objective function. Santibañez-Aguilar et al. [23] defined the social aspect as recycled waste, implying a decrease in waste sent to the landfill simultaneously reduced land and water pollution. Further, the reuse processes are assumed to generate jobs, which improves quality of life. Later, Santibañez-Aguilar et al. [24] expanded their model to include a safety objective function to capture the exposure of a population to toxicity due to leaching and burning dumps. Olapiriyakul [25] included a social objective function to account for people living within 1 km of disposal and treatment sites. Comparably, by using distance, Yousefloo and Babazadeh [26] developed a risk function to reflect the population affected by the facilities by assuming an inverse relationship between the distance of the facilities from residential areas. Mostafayi Darmian et al. [27] measured social dissatisfaction by collecting data through questionnaires completed by WM experts. This dimension encapsulated information regarding the annual impact of waste turnover on traffic jams, job creation, social acceptance, and customer satisfaction.

The strategy used to include social aspects in an optimization model by Cucchiella et al. [28] was carried out by using an externality cost in the objective function as "wealth public benefit" (net externality of EUR 9 per ton per incinerator). Similarly, Mavrotas et al. [29] incorporated social aspects into external costs or benefits as an additional term in an objective cost function. Mirdar Harijani, Mansour, and Karimi et al. [30] applied a social life-cycle assessment (S-LCA). The social criteria discussed by the authors was the most sensitive, indicating that when the social score improved, environmental and economic cost worsened significantly.

Table 5. Papers reviewed that applied deterministic multi-objective decision-making.

Author	Criteria	Application
Multi-objective mixed-integer		
Santibañez-Aguilar et al. [23]	Environmental and social	Supply chain optimization
Santibañez-Aguilar et al. [24]		Supply chain optimization
Olapiriyakul [25]	Economic, environmental, and social	Sustainable network design
Yousefloo and Babazadeh [26]		Sustainable network design
Mostafayi Darmian et al. [27]		Sustainable location-districting
Šomplák et al. [31]	Economic and environmental	Network design
Mohsenizadeh et al. [32]		Facility location
Pluskal et al. [33]		Facility location
Ooi et al. [34]		Waste allocation
Multi-objective linear and nonlinear		
Cucchiella et al. [28]	Economic, environmental, and social	Improve performance of sustainable SWM strategies
Sornil [35]	Economic and environmental	Waste distribution
Ayvaz-Cavdaroglu et al. [36]		Selection of a mixture of SWM technologies based on a given waste composition
Pourreza Movahed et al. [37]		Optimize energy consumption of treatment technologies
Boffardi et al. [38]		Selection of treatment plants to be built
Multi-objective multi-period using either linear or mixed-integer linear programming		
Mavrotas et al. [29]	Economic, environmental, and social	Structural, design, and operational optimization of the MSW system
Mirdar Harijani, Mansour, Karimi, et al. [30]		Integrated recycling and disposal network for SWM
Mavrotas et al. [39]	Economic and environmental	Structural, design, and operational optimization of the MSW system

3.2.2. Multi-Objective Decision-Making with Probabilistic Models

A total of 13 papers applied a probabilistic method, and of those, two included only the economic aspects, four included the economic and environmental aspects, and seven included the economic, environmental, and social aspects. The specific methods implemented and applications are shown in Table 6. The social aspects were incorporated as an objective function in the optimization models in six of the papers and as a constraint in one paper. Some of the techniques used to extract information from stakeholders were surveys [40], fuzzy theory [41], and cross-impact analysis (CIA) [42]. Moreover, a project-specific approach accounting for multiple stakeholder perspectives was implemented with the objective of maximizing the benefit to all; however, this benefit was defined in economic terms rather than in social aspect terms [43].

Table 6. Papers reviewed that applied probabilistic multi-objective decision-making.

Author	Criteria	Specific Method	Social Indicator	Application
Habibi et al. [40]	Economic, environmental, and social	Multi-objective robust optimization	Visual pollution, determined through stakeholder survey	Site selection and capacity allocation of recycling and disposal facilities
Edalatpour et al. [44]		Multi-tiered reverse logistics	Economic impact, social cost of carbon (1)	Sustainable network design
Mamashli and Javadian [45]		Multi-objective mixed integer linear programming (LP)	Worker safety, population-based location risk, and job opportunities	Sustainable network design
Xu et al. [46]		Multi-objective mixed-integer dynamic model	Job opportunities	Selection of treatment technologies
Abdollahi et al. [47]		Two-stage stochastic programming	Job opportunities	Sustainable network design
Mirdar Harijani and Mansour [41]		Multi-period two-stage stochastic model	Damage to workers, social acceptance, job opportunities, quality of products, and annual turnover	Sustainable network design
Yousefloo et al. [42]		Multi-objective scenario-based robust stochastic optimization model	Social score using seven indicators	Sustainable network design
Zhang et al. [48]	Economic and environmental	Inexact reverse logistics model	NA	Supply chain optimization
Yin et al. [49]		Inexact two-stage multi-objective planning (ITMOP) model	NA	Waste allocation and facility capacity expansion decisions
Liang et al. [50]		Multi-objective programming using interval-valued fuzzy numbers	NA	Waste treatment facility planning and waste stream allocation strategies
Li et al. [51]		Crisp and fuzzy optimization with max-min aggregation	NA	Sustainable network design
Diaz-Barriga-Fernandez et al. [43]	Economic	Multi-objective multi-stakeholder optimization	NA	Strategic planning of the MSWM system
Pouriani et al. [52]		Bi-level mixed-integer LP using a scenario-based robust optimization approach	NA	Facility location and waste allocation

Notes: (1) The authors argued that according to the US Environmental Protection Agency (EPA), SCC represents the damage avoided due to emission reduction and can, therefore, be considered as the social benefit for reducing CO_2 emissions. NA: Not applicable is specified in the table for those papers that did not consider social aspects.

It is important to include any uncertainties in the parameters of optimization models to reach a more robust solution and better represent real-world applications. Uncertainty was explicitly addressed in all the 13 papers reviewed in this section. Multiple methods were applied to characterize uncertainty (Table 7). Likewise, a variety of uncertain parameters were evaluated, with the most common one considered being waste generation, followed by the amount of waste collected. The consideration of uncertainty was motivated by the lack of data available or the difficulty of estimating an exact value for the parameters. For instance, Habibi et al. [40] forecasted parameters such as the quantity of both recyclable and non-recyclable waste produced per customer per year, whereas Pouriani et al. [52] justified the amount of waste collected as being uncertain since it depends on different factors, such as number of residents, family size, level of education and culture, and monthly income.

Table 7. The uncertain parameters and methods used to address uncertainty.

Uncertain Parameters	Method
Waste generation	Chance-constrained programming [44] Scenario-based analysis [40] Fuzzy average function [46] Sample average approximation [47] Fuzzy best-worst method [30] Interval-valued fuzzy numbers [50] Robust optimization [42]
Waste availability	Optimistic, mean, and worst-case scenarios [43]
Prices of products made from recovered waste	Optimistic, mean, and worst-case scenarios [43] Interval-valued fuzzy numbers [50] Robust optimization [42]
Amount of waste collected	Robust optimization [40] Chance-constrained fuzzy programming [45] Fuzzy average function [46]
Purchasing cost of vehicles	Chance-constrained fuzzy programming [45]
Capacity of facilities	
Customer demand	Chance-constrained fuzzy programming [45] Robust optimization [42]
Waste composition	Fuzzy average function [46]
Population growth rate	
Technical-economic parameters	Interval parameter programming [49] Fuzzy optimization [51] Robust optimization [42]
Planning and inventory control (variables and parameters)	Interval parameter programming [48]
Waste distribution process (variables and parameters)	
Waste disposal (variables and parameters)	
Emission factors	Fuzzy optimization [51] Robust optimization [42]

3.2.3. Multi-Attribute Decision-Making and Other Methods

Although this review aims to highlight MODM methods, eight articles focused on MADM, and seven articles that presented other decision support frameworks were included here due to their consideration of the three pillars of sustainability. All of the reviewed articles that addressed MADM methods included economic, environmental, and social aspects. These methods can be categorized into three different streams: (i) value-based methods, (ii) outranking methods, and (iii) distance-based methods. Table 8 shows the specific MADM methods and applications found in the literature.

Table 8. Papers reviewed that applied multi-attribute decision-making.

Author	MADM Stream	Specific Method	Criteria	Application
A. Effat and N. Hegazy [53]	Value-based methods	Analytical Hierarchy Process (AHP)	Economic, environmental, and social	Landfill location sites
Tot et al. [54]				Evaluate key indicators and sub-indicators for sustainable WM
Joel et al. [55]				SWM strategy selection
Sun et al. [56]				Treatment technology selection
Le et al. [57]				Treatment technology selection
Santos et al. [58]	Outranking methods	Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)		SWM strategy selection
Delgado et al. [59]	Distance-based methods	Technique for preference by similarity to the ideal solution (TOPSIS)		SWM strategy selection
Coban et al. [60]		TOPSIS, PROMETHEE I, and PROMETHEE II		Investigate various disposal techniques

The most frequently used MADM method was AHP. Joel et al. [55] discussed that, when compared to other MCDM tools, AHP is the most widely applied in the field of SWM. Some of the advantages of the method include the possibility of using qualitative and quantitative criteria, its structured nature, which allows for traceability, and its quality assurance as given by consistency indices. However, it was recognized that the main challenge is how to measure intangibles.

Table 9 shows the other decision support methods found in the literature, with all of them addressing social aspects. The LCA and CBA methods also benefit from stakeholder participation in terms of gathering information about the criteria and preferences for SWM systems. For instance, Handakas et al. [61] surveyed participants to investigate the societal acceptability of different technological options, and they conducted a SWOT analysis to create the qualitative attributes of such technological options. The approaches that differ from MCDM methods were game theory and machine learning. Game theory can be used for analyzing and modeling decision-making for multiple stakeholders [10], whereas machine learning allows for the analysis of big databases [62]. Velis et al. [62] utilized the Wasteaware Benchmark Indicators (WABI) dataset, which is available and distributed worldwide.

Table 9. Papers reviewed that applied other decision support methods.

Author	Method	Criteria	Application
Tulokhnova and Ulanova [63]	LCA-integrated waste management (LCA-IWM)	Economic, environmental, and social	Identify the most appropriate direction for the current WM
Handakas et al. [61]	CBA and LCA		Sustainably manage MSW and minimize the volume of waste disposed of in landfill sites
Chifari et al. [64]	Network theory		Generate informed deliberations about policies concerning SWM
Rodrigues et al. [65]	Multi-criteria decision aid–constructivist (MCDA-C)		Develop criteria and compare strategic objectives and available performance information
Karmperis et al. [10]	Game-theoretic decision support		Survey/Literature review
Palafox-Alcantar et al. [66]	Hybrid game theory approach and AHP		Encourage co-operation between stakeholders to adopt circular economy principles for SWM in cities
Velis et al. [62]	Random forest and univariate nonlinear regression	Economic and social	Provide a set of indicators and assess the level of progress for 40 countries

3.2.4. Combinations of Methods

Multi-criteria problems are characterized by having opposing preferences, which is the nature of the challenging decision-making process. Over the years, researchers have used a mixture of methods with the objective of making more acceptable decisions. Combinations of methods belong to different categories; for instance, various MADM processes are used together to undertake the same problem, or they are combined with MODM. A total of 11 papers applied these combinations; of these, two included economic and environmental aspects, and nine included economic, environmental, and social aspects (Table 10).

Table 10. Papers reviewed that applied a combination of MADM and MODM methods.

First Method			Second Method				
MADM	**MODM**	**Use**	**MADM**	**MODM**	**Use**	**Application**	**Reference**
AHP		Scenario development and weight of the importance of criteria	VIKOR		Evaluate alternatives and enable ranking of scenarios	Selection of MSWM waste treatment alternatives	Vučijak et al. [67]
TOPSIS		Ranking scenarios	VIKOR		Sensitivity analysis	Selecting optimal disposal options for generated waste	Aghajani Mir et al. [68]
	Multi-objective mixed-integer program	Obtain several alternatives	TOPSIS		Select the most preferable solution	Generate a sustainable configuration for MSWM	Mirdar Harijani et al. [69]
Fuzzy AHP		Determine the relative importance of selected objectives		Multi-objective mixed-integer nonlinear program	Identified the most beneficial set of strategies	Waste-to-energy management strategies	Abdallah et al. [70]
	Multi-objective mixed-integer nonlinear program	Determine the possible locations	AHP		Select a solution	Location of transfer stations	Rabbani et al. [71]
	Multi-objective optimization model	Determine the set of technologies	VIKOR		Search for the final decision schemes	Select technologies for a SWM treatment system	Chen et al. [72]
Delphi and TOPSIS		Assess and grade alternative locations for siting facilities		Multi-objective mixed-integer program	Determine capacities, routes, and recycling and treatment technologies.	Facility location and planning	Asefi and Lim [73]
Fuzzy AHP		Obtain the weights and importance degree of each criterion	Fuzzy TOPSIS		Selection of appropriate alternatives	Selection of treatments and disposal technologies	Govind Kharat et al. [74]
	Multi-objective mixed-integer nonlinear program	Determine the technology alternatives and waste allocation	TOPSIS		Selection of the most preferred solution	Selecting sustainable waste final disposal technologies for MSW treatment	Heidari et al. [75]
Weighted sum model (WSM) and weighted product model (WPM)		Calculate the weights of each criterion	TOPSIS		Ranking of alternatives	Assess the sustainability of SW treatment techniques	Omran et al. [76]
Fuzzy AHP		Calculate the weights of each criterion	Fuzzy TOPSIS		Ranking of suitable scenarios	Selection of treatment technology for MSW	Gaur et al. [77]

Notes: AHP: analytic hierarchy process; VIKOR: Viekriterijumsko Kompromisno Rangiranje: Serbian term for multi-criteria optimization and compromise solution; TOPSIS: technique for preference by similarity to the ideal solution; MSWM: municipal solid waste management.

Some authors have relied on MADM methods to select the social impacts prior to their inclusion into an optimization framework. Mirdar Harijani et al. [69] utilized fuzzy AHP with input from stakeholders and experts to conduct a social impact assessment. Rabbani et al. [78] created a social score for social sustainability and defined a minimum threshold for such a score. Fuzzy simple additive weighting was used to find the scores according to the experts' given opinions on local government and SWM. Govind Kharat et al. [74] proposed a fuzzy Delphi method (FDM) to obtain the critical factors obtained from expert groups working in the field of WM for the evaluation of technology alternatives. Rabbani et al. [71] examined the role of nongovernmental organizations (NGOs) in increasing customer environmental awareness (CEA) to decrease MSW. Thus, a noticeable pattern from this collection of papers is the use of MADM methods to define criteria and collect stakeholders' preferences, a feature that is complicated to achieve when only using MODM methods, making the combination of methods an attractive approach.

Other combinations that are different from the ones mentioned above were used by Gonzalez-Garcia et al. [79], implementing material flow analysis (MFA), LCA, and data envelopment analysis (DEA) to assess and identify the non-sustainable cities in Spain by considering the three pillars of sustainability. Xu et al. [80] developed a multi-objective model to select disposal processes for MSW; LCA was introduced to quantify and evaluate environmental effects. De Souza et al. [81] suggested a multi-criteria decision analysis with LCA to assess sustainability and prioritize system alternatives for WM. MFA, LCA, and cost-benefit analysis were used by Fei et al. [82], along with multi-objective optimization, to select treatment technologies for biowaste management. Nie et al. [83] used CBA for economic performance, LCA to assess environmental impact, and AHP to evaluate social benefit. Gombojav et al. [84] applied LCA and CBA to determine economic and environmental factors. Interviews were used for the social aspect, and then the authors utilized TOPSIS to select the best waste disposal method.

3.3. Social Dimensions

Quantifying the social aspects in terms of SWM is challenging, as it may require significant effort to design unique instruments for gathering data. Further, not all aspects can be captured numerically, and thus, qualitative information is often required to account for the local context of WM systems. In these cases, stakeholders' perspectives are used as input to measure these social aspects. In order to achieve a more comprehensive measure, researchers must consider multiple stakeholder categories (e.g., worker, consumer, local community, and society), as suggested by Benoît et al. [11]. Authors have used a variety of methods to support the quantification and assessment of the social dimension in SWM. The methods found in this literature review are S-LCA, questionnaires or surveys, social network analysis and stakeholder analysis, fuzzy theory, statistical methods, and other theoretical frameworks.

According to Benoît et al. [11], one can choose between quantitative, semi-quantitative, and qualitative indicators. A quantitative indicator describes the impact of using numbers (e.g., the number of people employed); qualitative indicators use words (e.g., a description of WM strategies in a local community), and semi-quantitative indicators translate qualitative indicators into a yes/no form or a scale, such as a scoring system (e.g., the satisfaction with local strategies, yes-no). The social indicators proposed by researchers in the articles reviewed were grouped according to the definitions used in the publications. The review found that the social indicators were most frequently used for the non-optimization methods (Table 11), involving workers and community. Health and safety appeared 12 times in the articles reviewed, and employment potential emerged 11 times. The other popular social indicators were social acceptance (found 10 times) and public involvement (found seven times). The authors used all forms to define these indicators (i.e., quantitative, qualitative, and semi-quantitative), which contributes to the literature on social indicators and facilitates their inclusion in future research.

Social indicators, particularly those that are more qualitative, can be difficult to measure. Consequently, researchers seek information from many different sources to accomplish this task. The most widely popular data collection methods are field observations, document and records analysis, key informant interviews, historical analysis, and focus groups with stakeholders [85–91]. Another common method is the application of questionaries [89,90,92–98]. Some authors have employed survey instruments to guide the data collection process, and these protocols provide insight into the validations and pretesting used before the actual field survey. More time is needed, but these yield higher quality results [99–102]. Other data collection methods include the use of expert score sheets [83,103], reviews of local context and policies [87], assessments of environmental authority reports [104], the gathering of sustainability indicators from national information system databases, municipal or national agencies [104–106], and an examination of newspapers [107].

These data collection methods allow researchers to gather information, but without further processing or analysis, they can, at most, offer evidence for qualitative indicators; this typically provides a starting point for researchers to understand the context and then select general metrics. Then, other methods are used to support the quantification of the social metrics, i.e., to translate qualitative data into semi-quantitative or quantitative data. Stakeholders' opinions and judgments are usually captured by using a Likert scale, for instance, scores from worst (1) to best (6) [94], satisfaction levels from satisfied (1) to dissatisfied (3) [99], an agreement scale from strongly disagree (1) to strongly agree (5) [95], an inter-relationships scale from no influence to a very high influence [89], sustainable behavior scales from never (0) to always (4) [101], sustainability scores from unsustainable to high sustainability [108], among others. Semi-quantitative metrics were used with fuzzy methods due to their nature to transform human judgment into fuzzy linguistic variables [89]. The authors discussed that this approach is appropriate due to the lack of data, uncertainties, and the qualitative character of indicators, and this provides an effective way to include knowledge and gained experience in the process [95,96]. Statistical methods were explored to understand the data, identify significant metrics, and standardize information. These methods are suitable for semi-quantitative and quantitative indicators, depending on the information collected. For instance, when working with historical data from reports, the outcome is a quantitative metric. Another method that supports quantitative metrics was LCA combined with S-LCA; Costa et al. [109] indicated the potential of S-LCA for the social evaluation of SWM systems and the improvement of participatory methods for the selection of categories, sub-categories, and impact indicators.

One characteristic that describes social metrics is whether the quantification is objective or subjective. Those studies that used MODM generally utilized social indicators that are more quantitative (Table 12). Examples include numeric values, such as number of people, distances, and costs. Whenever the quantification becomes challenging, the introduction of factors has proved to be effective. These factors are presented as risk values, damages to health, social scores, or the percentage of compliance with a desired criterion. Factors are considered semi-quantitative when they use a score given by stakeholders. The authors argued that when surveying a population, they generally tend to agree with the options given, which poses a challenge in data collection efforts [95]. It has been suggested to aggregate the responses from a set of questions to define one social metric [74,94,95,110]. The quantification of these metrics allows researchers to include them in mathematical models as part of the objective function or as a possible constraint for WM systems.

Table 11. List of social indicators used with non-optimization methods.

Indicator	Definition (If Any Provided)	Type of Indicator	Data	References
Income-based community well-being	Account for uplifting the living standards of community	Quantitative	Potential employment opportunities, wages, income generation, cost of living	[111] LCA/S-LCA
Health and safety, Damage to human health, Health footprint, Occupational injury potential	Mortality, safety, health status, and risks DALY (disability-adjusted life year), Nonfatal and fatal accidents/injuries, Disease, injuries, infections	Quantitative (DALY) Semi-quantitative Qualitative	Theoretical concept of DALY Expert opinion/survey Survey to residents Previous studies and current practices	[85] Riddle method and Best-worst method [98,103,105,109,111,112] LCA/S-LCA, [113] SWOT, [97] Fuzzy projection-based grey analysis, [96] Interval-valued neutrosophic sets, [114,115] Literature review
Sanitation equipment provision	SWM workers have the appropriate sanitation equipment	Semi-quantitative	Survey to residents	[97] Fuzzy projection-based grey analysis
Employment potential, Employment implication	Number of people employed, Working conditions, Provision of employment/creation, Occupational benefits	Quantitative Semi-quantitative Qualitative	Tons of waste, positions needed per ton of waste Expert opinion/survey Previous studies and current practices	[85] Riddle method and best-worst method [88] Integrated assessment scheme (IAS), [98,103,105,109,112] LCA/S-LCA, [113] SWOT, [114,115] Literature review, [116] Social network analysis (SNA) and stakeholder analysis (SA)
Quality of life, Living satisfaction	Odor, noise, traffic, living conditions, Willingness to continue living in the district	Semi-quantitative Qualitative	Expert opinion Previous studies	[103,109,112] LCA/S-LCA
Salary satisfaction	Satisfaction level of workers with their monthly salary	Semi-quantitative	Expert opinion Survey to workers in WM	[96] Interval-valued neutrosophic sets,
Workers' rights	Freedom of association and negotiation, child labor	Semi-quantitative	Expert opinion Survey to workers in WM	[96] Interval-valued neutrosophic sets
Level of social commitment, Social participation, Source separation level	% of homes separating waste or % of population eager to participate in waste separation, Commitment to sustainable guidelines	Quantitative Semi-quantitative Qualitative	Survey to households/residents Expert opinion	[90,117] Questionnaires and surveys, [91] Importance-Performance Analysis, [96] Interval-valued neutrosophic sets, [118] Literature review, [119] Open-ended interviews

Table 11. *Cont.*

Indicator	Definition (If Any Provided)	Type of Indicator	Data	References
Level of social acceptance, Public acceptance, Social/Public perception, Service quality, Waste technology acceptance	% of citizens not satisfied with SW services Quality of WM Solution and facility distance, Evaluate WM system condition/ facilities, Socio-demographic + pyscho-environmental	Quantitative Semi-quantitative Qualitative	Survey to households/residents Field visits Expert opinion Review of case studies	[85] Riddle method and Best-worst method [89] Fuzzy decision-making trial and evaluation laboratory (DEMATEL), [90,94,101] Questionnaires and surveys [95] Fuzzy logic, [99] Binary logistic regression, [115,118] Literature review, [98] LCA/S-LCA
Community opposition	Residents who disagree with the SWM strategies in place	Qualitative	Review of previous studies	[120] Literature review
Impact of tourism	Waste generated by tourism in places that are tourism-dependent	Qualitative	Review of previous studies	[120] Literature review
Coverage rate	Coverage rate collection of SW in relation to population	Quantitative	Municipality reports of service Municipality indicators	[104] LCA/S-LCA, [106] Evaluation of sustainability indicators
Existence of a collector formal organization	Whether there is a formal organization in charge of waste collection	Semi-quantitative	Municipality indicators	[106] Evaluation of sustainability indicators
Social satisfaction	Number of (health) complaints per year or number of environmental complaints per year	Quantitative	Municipality reports (complaints) Field visits Survey to households/residents	[102] Response surface methodology, [104] LCA/S-LCA
Public participation, Level of institutional acceptance, Governance	Participation in SWM at the organizational level: community programs, Legitimacy to any policies, co-ordination with stakeholders, and institutional coherence	Semi-quantitative	Survey to households/residents Field visits Expert opinion	[88] Integrated assessment scheme (IAS) [107] Socio-ecological model (SEM), [121] Literature review, [90] Questionnaires and surveys [114] Literature review
Perceived roles and responsibilities	Roles of stakeholders (i.e., who should take management actions regarding SW)	Qualitative	Survey to households/residents Expert opinion	[119] Open-ended interviews
Level of social demand Interest	Strong community or public demand and support	Qualitative	Survey to households/residents Field visits	[90] Questionnaires and surveys, [116] Social network analysis (SNA) and stakeholder analysis (SA)

Table 11. *Cont.*

Indicator	Definition (If Any Provided)	Type of Indicator	Data	References
Public attitude and behavior, Level of social interaction, Public involvement, Feedback mechanism	Participating in SWM at the individual level (e.g., involved in the selection of new WM policies), Personal responsibility, Moral obligation, Existence of a reporting system for suggestion	Qualitative Semi-quantitative	Survey to households/residents Field visits Expert opinion	[89] Fuzzy decision-making trial and evaluation laboratory (DEMATEL), [90,94] Questionnaires and surveys, [100] Confirmatory factor analysis and structural modeling, [103] LCA/S-LCA, [110,121] Literature review
Vulnerability, Level of social inclusion	Account for the influence of SW on subpopulations (children, women, and minorities) in terms of health, income, access to services, and environmental justice	Qualitative Semi-quantitative	Survey to households/residents Field visits Federal and state statistics	[90] Questionnaires and surveys, [121] Literature review, [108] Sustainability indicator matrix
Social equity	Equitable distribution of systems benefits and detriments within a community	Semi-quantitative	Survey to households/residents Expert opinion	[87,89] Sustainability indicators, [89] Fuzzy decision-making trial and evaluation laboratory (DEMATEL)
Public awareness, Level of Knowledge	Information on SWM systems, Sources to acquire knowledge	Semi-quantitative	Survey to household/residents Expert opinion	[86] Social network analysis (SNA) and stakeholder analysis (SA), [89] Fuzzy decision-making trial and evaluation laboratory (DEMATEL), [93] Multiple correspondent analysis, [99] Binary logistic regression [100] Confirmatory factor analysis and structural modeling [107] Socio-ecological model (SEM)
Information credibility, Service transparency	Management and operation of facilities, technology credibility clear laws about WM trust in local government	Qualitative	Survey to households/residents	[92,94] Questionnaires and surveys
Willingness to pay	Public willing to pay for SWM system current or new	Semi-quantitative	Survey to household/residents	[99] Binary logistic regression
NMBYS (not in my backyard syndrome)	Acceptance of building facilities 1 km from houses–opposition by residents in proximity to a SWM facility	Semi-quantitative	Survey to household/residents	[87,89] Sustainability indicators, [92] Questionnaires and surveys
Public communication		Qualitative	Review of case studies	[122] Literature review

Table 11. *Cont.*

Indicator	Definition (If Any Provided)	Type of Indicator	Data	References
Personal attributes Demographic factors	Age, sex, marital status, occupation, education level, place of residence, and political orientation	Qualitative	Survey to household/residents	[93] Multiple Correspondent Analysis [101,110], Questionnaires and surveys
Socioeconomic factors	Population, life expectancy, education, income per capita, inequality, and human development	Quantitative Qualitative	Municipality records Survey to household/residents Expert opinion	[123] Delphi Survey, [124] Pearson's correlation and regression analysis
Social factors in terms of the functionality of humans and their responses toward changes in WM	Seasonal variations, religion, culture, ethnicity, local/national events, discrimination, resource consumption patterns, shared norms, rural-urban daily migration, philosophical change, attitude-behavior relationship, and resistance to change	Qualitative	Survey to household/residents Expert opinion	[123] Delphi Survey

Table 12. List of social indicators used with MODM and MADM methods.

Indicator	Definition (If Any Provided)	Optimization Use	Type of Indicator	Data	References
Reused waste	Percentage of reused waste, Linked to the rationale that reusing the process generates jobs	Objective function (OF): Maximization	Quantitative	Reports from national and international environmental agencies	[23]
Safety	Risk associated due to exposure to toxic gases by burning waste and due to leaching expressed as the number of fatalities.	OF: Minimization	Quantitative	Risk analysis reports and government's institutions	[24]
People or population affected	Number of people living within a certain distance from facilities (some authors considered a radius of 1 km)	OF: Minimization	Quantitative	GIS data to measure the amount of residential area affected based on population density data.	[25,26]
Social dis-satisfaction	Includes traffic jams, job creation, social acceptance, and customer satisfaction	OF: Minimization	Quantitative	Municipality databases (e.g., department of statistics, department of construction and development)	[27]
Wealth public benefit	Externality cost per ton for incinerator	Term within financial aspects using future net present value: Maximization	Quantitative	European commission cost-benefit analysis guidelines	[28]
External costs or benefits	Associated with impacts on quality of life, electricity consumption/displacement, compost use, and recycling of materials	Additional term in the cost OF: Minimization	Quantitative	Environmental reports from consultancy agencies (e.g., Eunomia)	[29]

Table 12. *Cont.*

Indicator	Definition (If Any Provided)	Optimization Use	Type of Indicator	Data	References
Social score	Based on S-LCA considering five inventory indicators: job opportunities, social acceptance, damage to worker, annual turnover, and quality of products	Constraint: guarantees that the social score of the network should be greater than or equal to a certain value	Semi-quantitative	Panel of experts	[30,41]
	Use cross-impact analysis (CIA) method considering indicators: people displacement, disturbance to infrastructure, heatwave, health risk, job creation, impact on land value, community acceptance, and local economy development	OF: Maximization			[42]
Visual pollution	Any damage to the population view of the area	OF: Minimization	Semi-quantitative	Questionnaire to people living in the region, latest census information	[40]
Social cost of carbon	Damage avoided due to an emission reduction	Term in the economic OF: Maximization	Quantitative	Technical report from a government agency	[44]
Worker's safety Health and Safety	Lost days caused by work damages, Damage to worker, Health and safety of employees involved	Term in a social impact OF: Minimization	Quantitative	Expert's opinion Municipality records, existing literature	[45,69]
		Criteria for decision-making	Semi-quantitative		[57,74,76,77]
Population-based location risk	Risk factor based on fuzzy FMEA	Term in a social impact OF: Minimization	Semi-quantitative	Expert's opinion	[45]
Job opportunities	Number of jobs created (some authors considered fixed and variable job opportunities), Number of new employees	Term in a social impact OF: Maximization	Quantitative	Expert's opinion Municipality records, existing literature	[45–47,69,75]
		Criteria for decision-making	Semi-quantitative		[57,67,76,84]
Social acceptance Public acceptance	Societal consensus on the planned scenario, and this is determined on the basis of interviews with stakeholders, Technology identified should be accepted socially	OF: Maximization	Quantitative	Expert's opinion Municipality records, existing literature	[69]
		Criteria for decision-making	Semi-quantitative		[57,67,74,76,84]
Reaching objectives	Reaching the objectives of the national strategies	Criteria for decision-making	Semi-quantitative	Expert's opinion	[67]
NGOs role	Expense of NGOs for increasing environmental awareness of people based on the rationale of the NGOs' role in increasing CEA causes a decrease in produced waste	Constraint: guarantees to not exceed the total budget of NGOs	Quantitative	Municipality records	[71]

Table 12. *Cont.*

Indicator	Definition (If Any Provided)	Optimization Use	Type of Indicator	Data	References
Suitability Indicator	Includes proximity to residential areas, land cover, proximity to surface water, groundwater contamination risk, population density nearby, proximity to major roads, soil type, slope, and altitude.	OF: Maximization	Semi-quantitative	Expert's opinion	[73]

3.4. Stakeholders

In this section, we discuss 20 articles that applied specific methods that were used for stakeholder involvement in decision-making for WM. The stakeholders that were usually involved in the decision-making process are listed in Table 13. Similar to the ones listed for social indicators, stakeholder perspectives are captured by using questionnaires [117,125–129], interviews [119,130], literature surveys, and governance [131].

Table 13. Stakeholders that are typically involved in decision-making found in the reviewed literature.

Stakeholder List
Local authorities/politicians (e.g., government officials)
Environmental legislation agencies and other government agencies
Nongovernmental organizations (NGOs)
Community-based organizations (CBOs)/local representatives
Service users/local citizens
Private and formal sector
Manufacturers/industries
Donor agencies
Waste management professionals
Experts/academics/researchers (e.g., in environmental science, economy, sociology, soil science, civil engineering)
Technicians
Policymakers

A common practice is to consider stakeholder input when implementing MADM. In this situation, stakeholders provide criteria and weights to rank WM alternatives and eventually recommend the most preferred one for the given situation [8,56,60,67]. Other studies explored the combination of multi-objective optimization with multi-attribute decision-making [69]. For more applications, please refer to Section 3.2.

A different identified approach uses game theoretic approaches to include stakeholders (e.g., companies, academic institutions, local government, the general public, and consultants) in the decision-making process of WM systems [10,66]. A comprehensive review of game theory in WM decision-making was conducted in [132].

Some authors included stakeholders in SWM decision-making by exploring other methods and frameworks. Methods such as strengths, weaknesses, opportunities, and threats (SWOTs) analysis, questionnaires, and interviews were used. Ozturk and Tonuk [131] proposed the evaluation and prioritization of system options using ranking methods and SWOT (R'SWOT) analysis to ensure the participation of the central government and people in the local area. Feo and Williams [127] used a structured questionnaire focusing on understanding and reporting the views and knowledge of people regarding WM operations and facilities. Other questionnaires were used to determine the level of social satisfaction [129] and social involvement [117]. Nguyen et al. [133] conducted face-to-face interviews and a field survey to investigate stakeholders' opinions from government authorities, workers, the private sector, and WM experts, whereas Fichtel and Duram [119] conducted open-ended interviews to examine the role of the community members and government officials in SWM.

Systematic interviews and qualitative research methods are also presented in the literature. Chen et al. [126] developed an application of FDM based on expert options and then implemented a decision-making trial and an evaluation laboratory (DEMATEL). This methodology aims to analyze the causal relationships among circular economy barriers. Ngullie et al. [128] implemented a conceptual structural equation model (SEM) to identify the critical success factors in MSWM and show their inter-relationships in public-private partnerships. Thakur et al. [134] suggested a total interpretative structural modeling (TISM) approach to analyze stakeholder opinions in the various dimensions of a sustainable SWM system.

Finally, theoretical frameworks were used to analyze SWM by considering stakeholder input. Adam et al. [125] suggested an integrated SWM approach by analyzing the relevant issues on both sides of the market, namely customers and providers. Garnett et al. [130] utilized an empirical framework based on a soft system methodology (SSM) for negotiating the level of public involvement in WM decision-making. Whereas Yukalang et al. [135] proposed an integrated sustainable waste management (ISWM) framework, including the stakeholders affected by or engaged in WM. The authors argued that successful changes in WM require an understanding of the local context, and consequently, extensive community consultation and engagement are important to recognize the challenges of a particular WM system.

4. Recommendations and Perspectives on Future Research in This Area

Based on the articles reviewed and the current developments in SWM decision-making, we propose a closed-loop optimization framework for SWM, as illustrated in Figure 8. This framework presents four stages: (1) model definition, (2) model development, (3) model solution, and (4) post-optimization analysis. It recommends feedback loops to address those issues found in the literature regarding stakeholder involvement. Stakeholders should be consulted in each step of the process; moreover, the results from each stage should be revised and compared against the information from previous stages where the updating or tuning of the parameters needs to be considered. This could help with implementation in practice, as the stakeholders would have a better understanding of the technical models, and the results would be tailored according to their needs. Within the model development stage, the quantification of the criteria highly depends on data availability, and we provide options to adopt this in any case based on the findings derived from this review. In addition, for a model solution, we recommend considering a combination of methods, as is presented in Section 3.2.4; the combination using MODM to generate alternatives followed by MADM to select the most appropriate candidate has been the preferred option selected by several authors. However, we encourage researchers to further explore the combination that works best for the SWM system under study. Finally, for the post-optimization analysis stage, we suggest sensitivity analysis to determine the impact of the parameters on the optimization results.

As developments continue in WM decision-making, we recommend that future studies investigate the definition of frameworks that incorporate and quantify social metrics such that their inclusion in optimization might be streamlined. Social metrics strongly depend on the local context and stakeholders' perspectives; hence, guidelines and protocols to extract such information are necessary. However, these should be as flexible as possible to allow for the customization of each WM system.

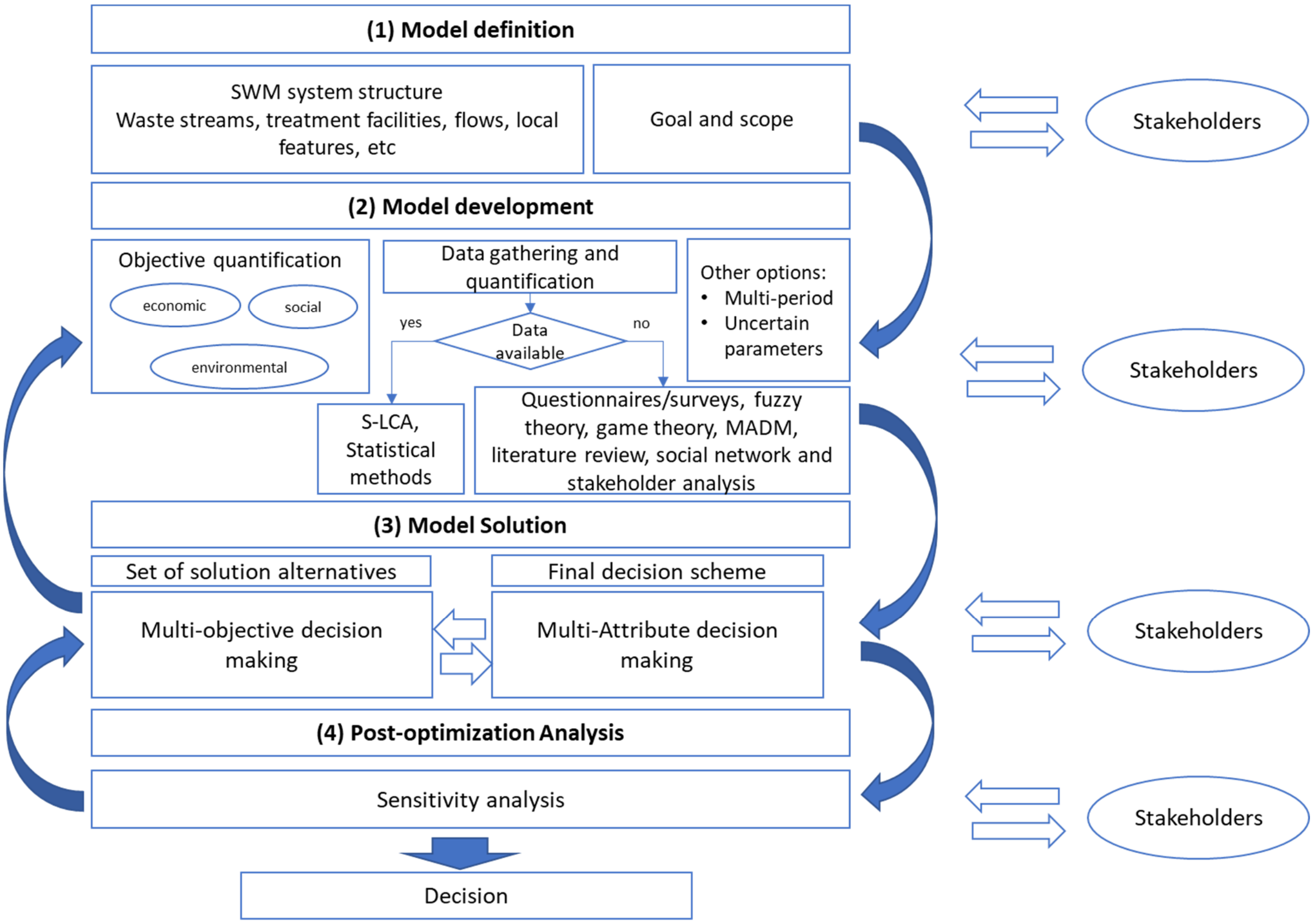

Figure 8. Closed-loop optimization framework for SWM.

A missing link identified in this review is the connection between the decision-making methods and their practical application. Stakeholders in the WM sector are consulted for input to model WM systems, but limited evidence is available regarding the use and implementation of such models in practice. For instance, Ferronato et al. [117] presented the positive effects on a real-world implementation project where practical actions and theoretical methods were introduced in parallel; moreover, several researchers have successfully applied closed-loop approaches to address similar problems in the circular economy [117,136,137]. Hence, future research in WM should explore other frameworks that work on a circular process to consider the feedback loops that keep stakeholders engaged. This review has engaged the initial steps by suggesting a closed-loop optimization framework (Figure 8). A simple tool integrating several criteria as well as stakeholders' perspectives is much needed to allow for the practical application of these theoretical perspectives in the decision-making area.

5. Conclusions

In this paper, we have reviewed 125 articles that account for the developments in MODM methods found in the literature, with an emphasis on sustainability criteria and stakeholder involvement in the context of SWM. The findings of this review offer key information to aid researchers in their understanding of the complexities of social aspects in waste management; furthermore, a full list of social metrics, along with definitions and information on the data used for the optimization methods and non-optimization methods applied in previous studies is presented.

The central theme of this review showed that the incorporation of social indicators with MODM is a rather recent occurrence in the literature, with the majority of the studies appearing from 2017 onwards, and these are concentrated in Asia. Network design was a popular application of these MODM methods, with the authors considering the location of treatment facilities, the transportation methods, the selection of technology, and the allocation of waste to the facilities. Moreover, the networks analyzed included both recycling and disposal.

Additionally, three challenging topics for MODM and social indicators have been found: the availability of qualitative versus quantitative data for social indicators, the extension of MODM methods to account for social aspects, and the consideration of stakeholders in all stages of the development of decision-making models. The first two challenges have practical implications for future research considerations and invite waste management professionals and local governments to consider the means of data collection in their facilities. The last challenge lies more in the realm of policy analysis and encourages more focus on the practical implementation of decision-making research.

Finally, we provided answers to the research questions that motivated this review.

RQ1: What multi-objective decision-making methods have been utilized in SWM studies that consider the three pillars of sustainability?

This literature review revealed different MODM methods used in SWM, considering the economic, environmental, and social criteria. In the category of MODM methods, the inclusion of the social pillar of sustainability was most frequently implemented in the objective function; it was rarely used as a constraint that "must" be satisfied. This provided some practical and policy implications for social metrics since the use of constraints could enforce the satisfaction of thresholds based on local law or regulations for the social values instead of a general and open goal of maximizing or minimizing a function.

In these searches, we also found MADM and other methods, as they are useful for developing social indicators; the most frequently used method for this purpose is AHP. The other techniques are PROMETHEE I and II and TOPSIS. All these abbreviations are defined in Table 8. Additionally, the Delphi method has been utilized to select criteria to evaluate WM strategies. Other methods (CBA, LCA, and game theory) have been utilized, albeit less frequently than MODM or MADM.

WM systems are complex in nature, and better results in decision-making have been obtained when using a combination of methods. The strategy identified is the use of methods in a linear process (e.g., MADM, followed by MODM or vice versa). We hypothesize that the process should be transformed into a circular process using a feedback loop, similar to the application of such concepts in the development of closed-loop supply chains in a circular economy [136]. This could allow for an adjustment of the parameters and help update information based on previous results. Moreover, this loop can provide an organic path to keep stakeholders involved and generate a useful solution that has a greater chance of being implemented.

RQ2: How have the authors quantified and assessed the social dimension in SWM?

Unlike economic indicators, which can be unmistakably expressed in costs and dollars and are commensurate from system to system, the social dimension has been articulated differently by the authors. These differences are driven by the setting, the research questions, the decision envelope, and the availability of the data. Consequently, there is no standard form for defining and selecting a set of social indicators. These features make the social dimension unique and worthy of further research.

One key feature during the quantification process of social indicators is stakeholders' involvement (see RQ3 below). The authors relied on interviews, focus groups, and field observations to obtain relevant information. The quantification process could be represented as first collecting information from the stakeholders to determine which social indicators are suitable for the system under study, then determining the importance of such indicators by means of, again, using stakeholder input, translating the information obtained into a quantitative measure, and finally introducing that measure into a SWM system.

Frequently, when there was information available, the authors opted for statistical methods to identify SWM indicators. Contrarily, with a lack of data, fuzzy theory, questionnaires or surveys, social network analyses, and stakeholder analyses were the preferred methods. These methods captured the current dynamics, roles, and needs of the system and provided alternatives to translating the qualitative data into semi-quantitative data. Because these field-based data are costly to acquire in terms of logistics, time, travel, and analysis, there is an availability bias of data accounting for social dimensions: the data that are most easily attained are those that are included. Data limitation is a constraint in the social dimension definition due to the project-specific input needed; however, it was found that on certain occasions, the local, national, and international databases are useful sources of information. This motivates the sharing and integration of databases, as well as the need for waste management facilities to keep records of measurable information for data analysis.

RQ3: How have the authors introduced stakeholders' perspectives in waste management?

Stakeholders' perspectives are generally included in the optimization framework through MADM. In these situations, multi-objective optimization is utilized along with techniques such as TOPSIS and AHP. MADM has been demonstrated to be an effective instrument for considering stakeholders' preferences about WM strategies. These preferences might come from selecting the criteria to assess such strategies, then ranking the alternatives, and eventually recommending the most appropriate one. Stakeholder perspectives are context-dependent. The other techniques used for stakeholder involvement in WM include SWOT analysis, questionnaires, interviews, and game theoretic approaches.

The authors agreed that to successfully manage a waste system, it is vital to understand the local context where a WM system is located, and hence, community consultation is essential for recognizing the potential challenges and improvements to a WM system.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151813316/s1, PRISMA 2020 Checklist [19].

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