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REVIEW

Solid waste indicators and their implications for management practice

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Abstract
This study analyzed, through bibliometrics, state-of-the-art municipal solid waste indicators by consulting key articles on the subject from prominent authors and institutions. A content analysis was used to identify main indicators for municipal solid waste performance along with their corresponding sustainability dimensions and implications for the practice of its management. The environmental dimension is the most significant, followed by the economic and social dimensions, because it was found in more papers along time. Emphasis is given to the following indicators related to life cycle: energy indicators (also analyzed with emergy tools); landfill volume or percentage of waste sent to it; waste generation; and rates of composting, recycling, and incineration (may involve the rate of separation at the source). Indicators categorized by the economic dimension are primarily understood by their direct relation to the costs of municipal solid waste management systems, as implementation, maintenance, and operation. Concerning the social dimension, indicators are incipient and present in fewer studies. Among the indicators of this dimension, collection coverages and services (including quantity, types, and rates) are more frequently featured in publications. It is important to highlight that municipal solid waste indicators should be comparable across countries and cities and that international standards for quality management in companies must be established. These standards should be easy to interpret and apply and should include all dimensions of sustainability.

Keywords Municipal solid waste · Performance indicators · Decision-making support · Sustainability · Content analysis

Introduction

Population growth, industrialization, economic development, and rapid urbanization have accelerated the production of municipal solid waste (MSW), especially in developing countries (Guerrero et al. 2013). About 2.3 billion tons of MSW was generated globally in 2012, and it is expected that by 2025, about 2.2 billion tons will be generated worldwide (United Nations Publications 2013).

Hoornweg et al. (2013) created three scenarios projecting data for up to the year 2100. In the first, most optimistic scenario, the 7 billion population is 90% urbanized and sustainable development goals are reached, resulting in greater environmental awareness and the reduction in fossil fuel consumption. In the second, less optimistic scenario, the population is estimated to reach 9.5 billion people with 80% urbanization. In this scenario, high-income countries in East Asia and the Pacific contribute the most to generating waste, but they tend to stabilize after 2020. From 2080 on, sub-Saharan Africa will primarily be responsible for waste production, and South Asia joins in 2100. The most pessimistic scenario predicts a population of 13.5 billion people with 70% living in cities and sustainable development goals not fully achieved, which results in extreme poverty and moderate wealth (Hoornweg et al. 2013).

Because MSW management needs improved urban infrastructure to operate, indicators can contribute to creating a measure, which would help with decision-making support, allow comparison between performances of the waste management systems, and direct the creation of new policies for the development of effective and sustainable solid waste management (Greene and Tonjes 2014).

Scientific literature on waste management discloses several indicators to use for performance analysis, comparisons between municipalities or technologies, and support to make decisions that enforce positive environmental, political, economic, and social effects (Zaman 2014a).

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Zaman (2014a) provides a list of studies involving MSW management indicators, listing 17 studies the author considers to be essential findings on these indicators. The waste indicators include generation, composition, separation, recycling, recovery, final disposal methods, costs, capacity, service coverage, service satisfaction, environmental and socioeconomic factors, institutional and political impacts and performance, composting, collection frequency, performance, eco-efficiency, carbon footprint, treatment technology, transportation, human health, and other indicators.

According to Greene and Tonjes (2014), indicators can be classified and sorted into four layers: absolute, indexed, relative, and aggregate. These authors show that classification differs substantially when different indicators are used. They argue that care should be taken when using comparison assessments based on indicators, especially those aimed at assessing environmental quality, because a given indicator can only measure one environmental aspect. However, despite the inadequacies of indicators for comparison purposes, they do provide relevant information for decision-making support and continuous improvement (Greene and Tonjes 2014; Ferreira et al. 2017).

Indicators can also be divided into efficiency and effectiveness indices, with efficiency relating to the input and output resources of a system and effectiveness evaluating the objectives achieved according to the capacity of the system (Koushki et al. 2004). Some examples of efficiency indicators include cost per truck, cost per ton of solid waste, cost per ton km of distance, and cost per ton km^2 of the service area. Examples of effectiveness indicators include the rate of the population receiving the service (people per cost) and coverage area (km^2 per cost) (Koushki et al. 2004).

Koushki et al. (2004) cover indicators involving cost–benefit factors, which allow comparisons between public or private service costs and performances of the systems. The indicators portrayed in the layers explained by Greene and Tonjes (2014) do not involve costs, but the indexed layer can be used with the effectiveness indicators described by Koushki et al. (2004), because it is expressed as percentage with respect to the total. This combination of indicators directly affects waste management systems and can be applied to municipalities and industries (Freitas and Magrini 2017).

Sanjeevi and Shahabudeen (2015) compiled a chronological literature review of 387 research studies on performance indicators for MSW management and highlighted five key indicators that capture the essential parameters: collection costs, transportation costs, social perception, social participation, and environmental impacts. It should be emphasized here that there are several indicators, such as multiples indicator with a diversity of variables, but due to their complexity, they are not feasible for the use of public managers who need simple tools.

The indicators therefore allow public managers to monitor the services provided to the population (Wilson et al. 2012), the sustainability of landfills (Ghanbari et al. 2012), collection and transportation costs (Sanjeevi and Shahabudeen 2015), and social and economic impacts (Deus et al. 2017).

Monitoring with indicators facilitates the identification of best practices and of new opportunities for continuous improvement and essential changes in public policies (El Said and Aghezzaf 2017).

This study uses bibliometric analysis, but the way academic impact is measured and evaluated has undergone rapid changes. Such research impact measures play an increasingly important role in the way individuals, research groups, institutions, and countries are classified. For example, clustering techniques are applied to bibliometric data sets, allowing lines of research to be identified (van Eck and Waltman 2017). Bibliometric studies on solid waste reinforce the importance of this subject and demonstrate its tendency to increase in scientific publications (Deus et al. 2015).

The objective of this study is to analyze the state-of-the-art indicators involved in MSW management by studying key articles on the subject from authors and institutions of different countries by means of bibliometric indicators and the bibliographic survey that occurred in July 2017. The study also aims to conduct a content analysis to identify the main MSW indicators used in scientific literature to verify these approaches in the three dimensions of sustainability and to highlight real implications in management and practice.

Materials and methods

This research first follows a rigorous sequence within a process of systematic literature review, as described by Brereton et al. (2007) in three major phases: (1) create a review plan, (2) conduct the review, and (3) document the review. Figure 1 shows the steps followed for the systematic bibliographic review in more detail. This approach provides an exhaustive summary of the literature, improving the review process and reaching more accurate and reproducible results. To complement the systematic review, quantitative and qualitative methods were combined.

First, the research question was established: “What is the state-of-the-art relationship between indicators and solid urban waste?” Although Sanjeevi and Shahabudeen (2015) have reviewed articles on MSW management systems with a focus on performance indicators, unlike this proposed method, they did not use bibliometric analyses or software for their analysis.

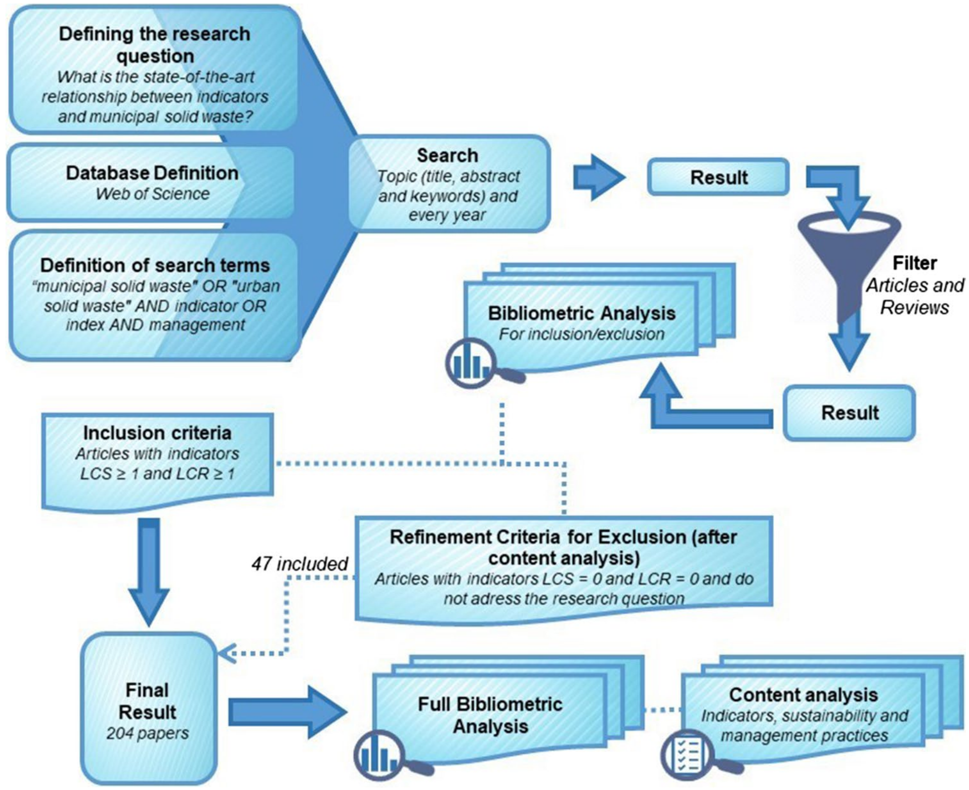

Fig. 1 Process flow for bibliometric and content analysis

The Web of Science database was chosen for this research because it currently indexes the most relevant journals.

While establishing the research question, the English search terms were defined with Boolean operators: "municipal solid waste" OR "urban solid waste" AND "indicator" OR "index." The search was performed in the topic field, generating a list of results with search terms present in the titles, abstracts, or keywords. No restrictions were imposed on publication dates. In addition to these filters, the search was limited to only return articles and reviews, resulting in 829 total sources.

Bibliometric analysis

A bibliometric analysis was performed using VOSviewer to verify clustering of researches. Document grouping uses a mathematical process that classifies documents into meaningful document clusters, grouping documents that are similar to each other within the same cluster (van Eck and Waltman 2017). This process revealed the need to enter the word "management" as a search term. The search was carried out again for the first stage using the Boolean operator, AND, with "management." After this new filter was applied, the search returned 269 articles.

These results were submitted for bibliometric analysis using HistCite software version 12.03.17. This analysis included indicators for the local cited references (LCR), which identified the number of shared citations in the reference list of a particular article with other articles in the sample, and the local citation score (LCS), which identified the number of times a particular article was cited within the sample. Both of these indicators identified the importance of each article within the returned results. Thus, all articles with an LCS of one or greater and an LCS of one or greater were included in the final analysis of 157 total articles. The remaining articles (112) underwent a content analysis, meaning the titles and abstracts were analyzed to verify whether or not they fit the theme of this study. Of the articles that underwent content analysis, 65 were excluded and 47 were included. A total of 204 articles were therefore submitted for bibliometric analysis and final content analysis.

It should be noted that the bibliographic survey occurred in July 2017. The results were exported for analysis with all information available in the database in the form of text files (.txt). The bibliometric analyses were performed using HistCite version 12.03.17, VOSviewer version 1.6.5, and CitNetExplorer version 1.0.0.

Bibliometric indicators

The citation indicators analyzed by the HistCite software are highlighted in Table 1.

Another indicator adopted in this study was an efficiency index using the data envelopment analysis (DEA) method

Table 1 Bibliometric indicators adopted. *Source*: Adapted from the HistCite software glossary

Indicator	Initials	Description
Global citation score	GCS	Shows the total number of citations for an article in the Web of Science database
Local cited references	LCR	Shows the number of citations in the reference list of an article for other articles within the collection of sample
Local citation score	LCS	Shows the citation count for an item within the collection
Local citation score per year	LCS/t	Local citation for a year from the publication of the article until the end
Global citation score per year	GCS/t	Global citation scores per year from the publication of the article to the end of the collection

in SIAD software (Meza et al. 2005). This index considers each of the amount of publications as input elements for analysis and indicators from Table 1 as output elements. It is worth mentioning that DEA is a nonparametric method and is a great alternative to aggregating partial indicators, such as those returned by HistCite. The DEA method allows the incorporation of all available information as an aggregate of the most varied indicators. In general, DEA defines a reference border to analyze the performance of the whole set, and performance is represented by the distance to the built boundary. This study used a border composed of the production of productive units.

Content analysis

The main indicators of MSW are identified using content analysis to examine the main approaches for the three sustainability dimensions (environmental, economic, and social) and highlight their implications in practical management.

Generally, content analysis is conducted by codifying texts to analyze qualitative data, a process that can be divided into data collection, data coding, and analyzing using specific software (Gaur and Kumar 2017).

In this case, summaries of the 204 selected papers were submitted to coding analysis software to verify which sustainability approaches have been commented on by authors over a period of time. The coding steps followed rules established by Weber (1990): (1) define the recording units; (2) define the categories; (3) test coding on sample of text; (4) assess accuracy or reliability; (5) revise the coding rules; (6) return to Step 3; (7) code all the text; (8) assess achieved reliability or accuracy. The codes for each dimension are listed in Table 2. These analyses were run through KH Coder 3.

Among the 204 articles, those with a local citation score greater than or equal to one (LCS $\geq$ 1) were selected for in-depth analysis of the methods and conclusions; a total of 90 articles initially met this criterion, but 17 were excluded because they did not include the full text or relevance to express the indicators, leaving a total of 73 articles. Thus, the relevant articles were selected from the sample to identify the most frequently used indicators and their implications for management practice.

Table 2 Coding for dimensions of sustainability

Dimension of sustainability	Coding
Environmental	"environmental" ǀ "environment" ǀ "greenhouse gas" ǀ "ghg" ǀ "emission to air" ǀ "emission to water" ǀ "emission to ground" ǀ "fuel saving" ǀ "energy saving" ǀ "energy recycling" ǀ "energy recovery" ǀ "wastewater generation" ǀ "water consumption" ǀ "hazardous solid waste" ǀ "hazardous waste" ǀ "hazardous residues" ǀ "noise pollution" ǀ "air pollution" ǀ "water pollution" ǀ "global warming" ǀ "damage to human health" ǀ "damage to ecosystems" ǀ "damage to resource" ǀ "climate change" ǀ "ozone depletion" ǀ "human toxicity" ǀ "ecotoxicity" ǀ "acidification" ǀ "eutrophication" ǀ "photochemical ozone formation" ǀ "radioactivity" ǀ "waste heat" ǀ "odor" ǀ "noise" ǀ "heavy metals" ǀ "ecological footprint" ǀ "carbon footprint" ǀ "groundwater quality" ǀ "air quality" ǀ "water quality" ǀ "environmental quality" ǀ "health damage" ǀ "ecological toxicity" ǀ "material recovery" ǀ "environmental impact" ǀ "life cycle assessment" ǀ "lca"
Economic	"economic" ǀ "economy" ǀ "capital expenditure" ǀ "operation and maintenance cost" ǀ "operation cost" ǀ "maintenance cost" ǀ "revenues from products" ǀ "land requirement" ǀ "market prospect" ǀ "market product" ǀ "environmental externalities" ǀ "external costs" ǀ "external benefits" ǀ "recycling market" ǀ "composting market" ǀ "cost assessment" ǀ "cost life assessment" ǀ "cost saving" ǀ "net cost" ǀ "life-cycle cost" ǀ "life cycle cost" ǀ "lcc" ǀ "financial" ǀ "tax" ǀ "investment"
Social	"social" ǀ "social acceptance" ǀ "visual impact" ǀ "risk perception" ǀ "employment" ǀ "life quality" ǀ "quality of life" ǀ "creation of new jobs" ǀ "new jobs" ǀ "job" ǀ "jobs" ǀ "social inclusion" ǀ "inclusivity" ǀ "waste picker" ǀ "cooperative" ǀ "social service" ǀ "recycling picker" ǀ "human dignity" ǀ "human rights" ǀ "human security" ǀ "human well-being" ǀ "public health"

Results and discussion

Evolution analysis and origin country

Figure 2 shows the annual number of articles related to MSW research published in the Web of Science database. The first published articles were from 2001, which reinforces the idea that this is a relatively new area of research, evidenced also by the total of 204 articles found.

A publishing peak was reached in 2016, while 2017 already reached 9.3% when data were collected, showing the potential to exceed the percentage of the previous year. This provides further evidence of the growing importance of MSW indicators in the literature. Understanding the bibliographic behavior, through bibliometric tools, helps to understand the state-of-the-art of MSW and to identify the gaps in scientific literature. This research has significant potential to contribute to the field.

A bibliometric study conducted by Fu et al. (2010) on the more general term of "solid waste" demonstrated that the cumulative number of publications featuring this search term increased from 152 in 1993 to 5688 publications in 2008. Similarly, results from Deus et al. (2015) showed the growth of research on solid waste in Brazil.

Note that there is generally a positive growth rate for peer-reviewed publications in various fields of knowledge, but growth occurs at different rates (Larsen and von Ins 2010). Growth rate of general knowledge is also covered across several databases, such as Web of Science, Scopus, and Google Scholar. Larsen and von Ins (2010) conclude in their temporal study on the publication rates of various areas of knowledge that Web of Science covers an area of traditional scientific literature that has declined, and coverage of some scientific areas with higher growth rate, such as computer science and engineering sciences, is included less often in Web of Science. Perhaps this is a limitation of this study, but it is worth emphasizing that although there are differences between the databases, in terms of both coverage and citations, many types of research and bibliometric tools are widely and deeply adapted to the Web of Science (van Eck and Waltman 2017).

Concerning languages used in these published articles, the majority are in English (97.5% of publications), followed by Portuguese (1.5%), and then Russian and Croatian (0.5% each). Although a lack of English language knowledge is a significant barrier to publishing in international journals, especially those indexed in Web of Science (Vasconcelos et al. 2009), published research from many countries comes from authors who do not speak English as their first language.

Table 3 shows the countries with the highest number of publications. The first four are countries non-native to the English language: Italy (16.2%), Spain (10.3%), China (9.8%), and Brazil (5.9%). Italy has high indicators of global and local citations, but Austria has demonstrated a more efficient scientific impact; although they have produced fewer publications, they produce higher results from local and global citations.

It is worth mentioning that the article with the highest GCS and LCS is from an Austrian researcher, published along with two Italian researchers, entitled "Life Cycle Assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration" by Cherubini, Bargigli, and Ulgiati. The authors of this paper performed an LCA of four waste management strategies and applied these scenarios to the municipality of Rome (Italy) (Cherubini et al. 2009).

Published research is concentrated in Europe, which presents itself as a leading continent in taking actions aimed at the management of solid waste. Since Directive 94/62/EC, Europe has taken measures to manage packaging waste with the aim of preventing or reducing environmental impacts of waste (Magrinho et al. 2006). The directive has undergone several changes over time, and recently Europe has proposed initiatives to create a circular economy, highlighting waste

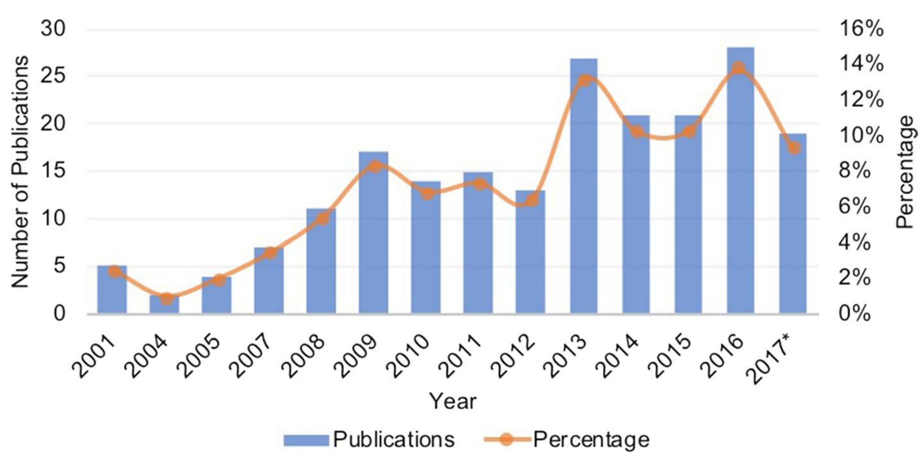

Fig. 2 Annual number of articles related to MSW research published in the Web of Science. *July/2017

Table 3 List of countries with the highest publishing rates and their respective indicators

Country	Amount	%	% rank	LCS	CLS rank	GCS	GCS rank	DEA	DEA rank
Italy	33	16.2	1	70	1	859	1	0.727273	7
Spain	21	10.3	2	33	2	301	3	0.668367	12
China	20	9.8	3	9	7	136	5	0.559902	21
Brazil	12	5.9	4	8	8	62	15	0.582608	19
USA	9	4.4	5	10	6	128	7	0.631521	16
UK	9	4.4	5	6	10	67	14	0.571428	20
Japan	9	4.4	5	3	13	62	15	0.571428	20
Taiwan	8	3.9	6	6	10	121	8	0.637755	15
India	8	3.9	6	6	10	76	13	0.607142	18
Serbia	8	3.9	6	4	12	44	17	0.559129	22
Portugal	7	3.4	7	10	6	60	16	0.653061	13
Will	7	3.4	7	9	7	110	9	0.650000	14
Austria	6	2.9	8	28	3	345	2	1,000,000	1
Canada	6	2.9	8	18	4	168	4	0.821428	2
Netherlands	6	2.9	8	15	5	134	6	0.767857	5
Australia	6	2.9	8	15	5	99	10	0.767857	5
France	5	2.5	9	5	11	60	16	0.680434	9
Thailand	5	2.5	9	7	9	84	11	0.623671	17
Sweden	4	2	10	5	11	83	12	0.607142	18
Romania	4	2	10	4	12	35	19	0.571428	20

LCS local citation score, *GCS* global citation score, *DEA* data envelopment analysis

management as a central role in this process (European Commission 2015).

Content analysis

The traditional concept of sustainable development aimed to satisfy the needs of the human population in the present without committing to sustainability for future generations (World Commission on Environment and Development 1987). Although sustainability is a multi-dimensional system (Cabezas et al. 2003), it primarily consists of three main variables known as a triple bottom line: economic, social, and environmental (Elkington 1994).

In line with these variables, this study proposed to identify the three main dimensions of sustainability in articles that involve MSW indicators over published time. After drafting the sustainability dimension codes given in Table 2, abstracts from all sample articles were submitted for analysis in KH Coder 3. Figure 3 shows the frequency that each code could be applied to documents published in the corresponding years.

The results show that the environmental dimension was treated with higher importance than other dimensions were treated; this fact is also given in Table 4. The environmental aspect is generally better understood in industrial and commercial organizations, with the economic aspect following closely behind, while many organizations struggle to articulate their social impacts and responsibilities (Hubbard 2009).

Some economic indicators intertwine with the environmental and social indicators, such as energy/emergy (possible overlap with an LCA); recovery, demand, or material flow (valorization); and the net recovery index and transport intensity index (specific to particular research). In general, these factors imply a cost-effective view. Policymakers must be aware that the impact of an integrated MSW management system is highly dependent on the various economic, environmental, and social facets.

Other economic indicators are specific, addressing questions of financial costs and returns. They help identify strategies that maximize environmental benefits and minimize economic costs. Usually, these indicators involve investment costs and operating costs and can also use the life cycle cost tool. These indicators quantify the financial return on the investment (Table 4).

Social indicators have an impact on end users and governance, involving the political legitimacy of inclusion, coordination with stakeholders, institutional coherence, oversight, transparency, public participation, and managerial structuring.

The social aspect can be observed in the analytical framework of Integrated MSW Management and the set of UN-Habitat indicators, as explained by Wilson et al. (2015). These structures integrate the three dimensions of sustainability as well as other aspects, such as the physical system with its technological components and the various stakeholder groups involved. Sim et al. (2013) also applied

Fig. 3 Categorization of the articles sustainability dimensions. The numbers in the rectangles and the intensity of the color green reflect the frequency of dimension codes

in their study the following UN-Habitat indicators: (1) collection coverage, (2) controlled disposal, (3) recycling rate, (4a) the inclusion of end users, (4b) the inclusion of suppliers, (5) financial sustainability, and (6) institutional coherence. These indicators reinforce the idea that, in addition to acquiring the physical components, a local MSW management system must also have effective governance. To produce sustainable results, it is also necessary to include all stakeholders in decisions related to the development of waste management and management strategies.

The study by Mendes et al. (2012) mainly addresses the social dimension using 24 key performance indicators, which have been developed and summarized in a scorecard addressing the categories of clients, internal processes, learning and growth, and finances, according to the needs of the public administration service in the waste sector. They emphasize that the public administration service is required to serve the public's best interests and ensure the satisfaction of public needs and welfare by following principles of legality, impartiality, morality, and efficiency. In this way, it is crucial that the service analyzes its systems to seek out adequate and effective management that the stakeholders find suitable. The social dimension of sustainability and its indicators are also addressed in an article by the same main author, Mendes et al. (2013), which applied in client perspective the citizen satisfaction index.

Concerning the social dimension, Baud et al. (2001) examine the combinations of new alliances in MSW management systems contribute to human quality of life using a nine-point indicator system involving coordination, financial viability, employability, and legitimacy. As a management practice, informal actors must be integrated into the official system through the mediation of non-governmental organizations (NGOs); this can promote positive results in terms of socioeconomic and ecological sustainability and public health. The same authors also point out that trade and waste recycling contributes to cleaner neighborhoods, financial viability, the reduction in disposable waste in volumes through recycling, reuse, and composting, and job creation, especially for low-income areas.

Bringhenti et al. (2011) also focus on the social dimension along with its connection to the economic dimension. The authors highlight six indicators, which include cost, scale, operation, and social participation. The authors emphasize that the selected indicators are considered to be universal because they were used in several countries. These indicators were selected for ease of understanding and practical application, including municipal solid waste selective collection for social inclusion in developing countries. Because of this, the existence of a validated reference indicator is of fundamental importance. An indicator that integrates social and economic dimensions includes the evaluation of informal reverse logistics (Fehr and Santos 2009).

Other authors also consider integrative approaches to social indicators to evaluate the MSW management system (Polaz and Teixeira 2009; Font Vivanco et al. 2012; Menikpura et al. 2012a, b, 2013; Gamberini et al. 2013; Milutinović et al. 2014; Pubule et al. 2015; Chong et al.

Table 4 Classification and definition of indicator layers. *Source*: Prepared by the authors

General indicators	Dimension of sustainability	Authors	Implications for management practice
Based on the life cycle, focusing on categories of impact (climate change, acidification, ecotoxicity, depletion of the ozone layer, eutrophication, GHG emissions, etc.)	Environmental	Beccali et al. (2001), Consonni et al. (2005), Thorneloe et al. (2007), Chen and Lin (2008), Cherubini et al. (2008, 2009), Gohlke (2009), Rigamonti et al. (2009, 2010), Brambilla Pisoni et al. (2009), Cleary (2009), Bovea et al. (2010), Abduli et al. (2011), Giugliano et al. (2011), Zhao et al. (2011), Gunamantha and Sarto (2012), Menikpura et al. (2012a, b, 2013), Nessi et al. (2013), Ning et al. (2013), Leme et al. (2014), Teixeira et al. (2014b), Bueno et al. (2015), Chong et al. (2016)	LCA is a powerful tool for assessing the environmental impacts of MSW management systems. It is a means of evaluating the impacts of the integrated systems to determine how these impacts change when assumptions are modified during the modeling of different parts of the system. Integrating management and complementing the LCA with multi-criteria analysis for decision making is crucial. The LCA measures environmental performance. It shows that the problem is complex and that the solution cannot be achieved through technological improvement alone, thus requiring the involvement of entrepreneurs and consumers interested in the conception of new patterns of sustainable production and consumption
Landfill volume or forwarded percentage of waste	Environmental	Beccali et al. (2001), Hasome et al. (2001), Consonni et al. (2005), Suttibak and Nitivattananon (2008), Bovea et al. (2010), Mendes et al. (2012), (2013), Cifrian et al. (2013), Zaccariello et al. (2015), Chong et al. (2016)	The need to allocate less waste to landfills and to seek the hierarchy of waste indicates an order of preference for action: waste prevention, product reuse, recycling, biological treatment, thermal treatment, and landfilling (McDougall et al. 2003)
Environmental cost	Environmental	Hellweg et al. (2005), Polaz and Teixeira (2009), Menikpura et al. (2012b, 2013), Pubule et al. (2015)	Environmental cost evaluates the ratio of net environmental benefits to the cost difference of a given management technology. It also concerns unlawful provisions and hence their environmental liabilities
Ecological/carbon footprint	Environmental	Cherubini et al. (2009), Cifrian et al. (2012), Herva and Roca (2013), Herva et al. (2014)	It measures human consumption of natural resources. The indicator should be used cautiously with awareness of the limitations of the estimates while taking advantage of their integrated nature
Index of pollution and air/water quality	Environmental	Singh et al. (2008), Kale et al. (2010)	The 3-R (reduce, reuse, and recycle) principle is an appropriate methodology for solid waste management and for the reduction in groundwater pollution induced by leachate. The construction of leach lines and ponds helps prevent the transport of leachates to the aquatic environment underground. It analyzes water and air impact (including odor)

Table 4 (continued)

General indicators	Dimension of sustainability	Authors	Implications for management practice
Waste generation (may involve classification)	Environmental	Buenrostro et al. (2001), Sufian and Bala (2007), Polaz and Teixeira (2009), Dahlén and Lagerkvist (2010), Fragkou et al. (2010), Lebersorger and Beigl (2011), Katpatal and Rao (2011), Mendes et al. (2012), (2013), Rimaitytė et al. (2012), Cifrian et al. (2012, 2013), Inglezakis et al. (2012), Abbasi et al. (2013), Antanasijević et al. (2013), Milutinović et al. (2014), Bueno et al. (2015), Kawai and Tasaki (2016)	It includes MSW monitoring. Several socioeconomic factors may be correlated with this indicator. It is essential that landfills are monitored on a regular basis and that the waste received is weighed to maintain a more efficient record. Monitoring the generation of waste also allows verification of its reduction in the face of waste prevention
Composting, recycling, or incineration (rate and separation at source)	Environmental	Hasome et al. (2001), Suttibak and Nitivattananon (2008), Cifrian et al. (2010, 2012, 2013), Bovea et al. (2010), Bringhenti et al. (2011), Mendes et al. (2013, 2012), Gamberini et al. (2013), Sim et al. (2013), Milutinović et al. (2014), Wilson et al. (2015), Zaccariello et al. (2015), Bueno et al. (2015), Chong et al. (2016)	Recycling and composting lead to high environmental benefits and material recovery
Risk and impact assessment, including treatment and control	Environmental	Singh et al. (2008), Laner et al. (2012), Menikpura et al. (2013), Sim et al. (2013), Milutinović et al. (2014), Pubule et al. (2015), Wilson et al. (2015)	Following a post-treatment assessment, results should be used to integrate aspects of different approaches to ensure no unacceptable risk, such as heavy metal release, is associated with the landfill
Zero waste (interlinked with other indicators)	Environmental	Zaman and Lehmann (2013), Zaman (2014b)	It reveals the number of resources that are recovered from waste streams and replaced with virgin materials. In addition, it contributes to the replacement of energy, water, and emissions in waste management systems
Gaseous emissions (not included in LCA)	Environmental	Cadena et al. (2009), Eriksson et al. (2014), Milutinović et al. (2014), Pubule et al. (2015)	Values obtained can be useful for comparing different composting technologies and other biological treatments applied to organic waste in terms of environmental performance indicators
Energy/emergy (possible overlap with an LCA)	Environmental and ECONOMIC	Beccali et al. (2001), Marchettini et al. (2007), Thorneloe et al. (2007), Cherubini et al. (2008, 2009), Rigamonti et al. (2009), Cadena et al. (2009), Gohlke (2009), Cleary (2009), Cifrian et al. (2010), Consonni and Viganò (2011), Agostinho et al. (2013), Milutinović et al. (2014), Herva et al. (2014), Pubule et al. (2015)	It supports the cost–benefit view. A sound waste management policy should be based on the principles of sustainable development where waste is not simply regarded as something to eliminate but also as a potential resource. Policymakers should be aware that the impacts of an integrated MSW management system are highly dependent on assumptions made in modeling material recovery as well as modeling energy recovery

Table 4 (continued)

General indicators	Dimension of sustainability	Authors	Implications for management practice
Recovery, demand, or material flow (valorization)	Environmental and economic	Beccali et al. (2001), Cherubini et al. (2008, 2009), Polaz and Teixeira (2009), Fehr and Santos (2009), Cifrian et al. (2010, 2012), Fragkou et al. (2010), Bringhenti et al. (2011), Mendes et al. (2012), Stanisavljevic and Brunner (2014), Herva et al. (2014), Zaccariello et al. (2015)	The cost of improving raw material quality often outweighs the benefits of such improvement. This indicator shows the complexity of this problem and the need for community involvement. It monitors MSW flows and cycles from generation to final disposal
Net recovery index and transport intensity index (specific to particular research)	Environmental, economic, and social	Font Vivanco et al. (2012)	Both indicators can be useful in assessing key strategies, such as increasing recycling (sustainability principle) or minimizing transport by locating treatment facilities closer to the source (proximity principle), for MSW management policies
Economic cost	Economic	Baud et al. (2001), Hasome et al. (2001), Thorneloe et al. (2007), Suttibak and Nitivattananon (2008), Polaz and Teixeira (2009), Bringhenti et al. (2011), Zhao et al. (2011), Huang et al. (2011), Menikpura et al. (2012b, 2013), Mendes et al. (2012, 2013), Gamberini et al. (2013), Sim et al. (2013), Milutinović et al. (2014), Leme et al. (2014), Cucchiella et al. (2014), Pubule et al. (2015), Chong et al. (2016)	It helps identify specific strategies that maximize environmental benefits and minimize costs. This indicator involves investment costs and operating costs. It can also use the life cycle cost tool
Equipment (distance, fuel consumption, time, etc.) and personnel (workers)	Economic	Hasome et al. (2001), Polaz and Teixeira (2009), Mendes et al. (2012, 2013), Teixeira et al. (2014a, b)	It evaluates the vehicles used, the size of the MSW management team, and the training provided. It provides appropriate methodologies to evaluate and improve intermunicipal general waste management systems and contribute to an effective analysis benchmark and evaluation database. It can involve frequency of collection, evaluation and regulation of technical and operational activity, years of operation, and capabilities
Financial return (sales of recyclables, energy production, collections, etc.) and financial income	Economic	Bringhenti et al. (2011), Milutinović et al. (2014), Teixeira et al. (2014b), Pubule et al. (2015), Chong et al. (2016)	It quantifies the financial return on investment
Coverage of collection and services (including quantity, types, and rates)	Social	Hasome et al. (2001), Suttibak and Nitivattananon (2008), Polaz and Teixeira (2009), Bringhenti et al. (2011), Huang et al. (2011), Gamberini et al. (2013), Sim et al. (2013), Aliu et al. (2014), Wilson et al. (2015)	It evaluates the municipality's performance of the efficient use of its resources and social return. It also evaluates the public–private partnership based on the operational quality of the service provided
User satisfaction	Social	Mendes et al. (2012, 2013), Milutinović et al. (2014), Pubule et al. (2015)	Evaluates the citizens' return on the services provided

Table 4 (continued)

General indicators	Dimension of sustainability	Authors	Implications for management practice
Governance aspects	Social	Baud et al. (2001), Gohlke (2009), Polaz and Teixeira (2009), Sim et al. (2013), Pubule et al. (2015), Chong et al. (2016)	It involves legitimacy to any policies for inclusivity, coordination with stakeholders (integration and inclusion of people, suppliers, etc.), institutional coherence, oversight, transparency, public participation, and management structuring
Employability	Social	Baud et al. (2001), Menikpura et al. (2012b), Milutinović et al. (2014)	In cases where informal actors are integrated into the official system through the mediation of NGOs, there are positive results in terms of socioeconomic and ecological sustainability and public health aspects
Damage to human health (quality of life)	Social	Menikpura et al. (2012b, 2013)	It involves quality of life aspects, and while these aspects may be part of an LCA, they may also fit into other indicators that involve risks to human health

2016). In general, the indicators can be useful to evaluate the main strategies of MSW management policies, with consideration for the dimensions of sustainability.

The LCA, while not an indicator itself, is an evaluation technique that uses several indicators to evaluate the impacts associated with the different subunits that comprise an MSW management system (Rigamonti et al. 2010). Table 4 highlights the importance of each indicator based on life cycle along with the main articles that address it most frequently. This tool makes it possible to evaluate the environmental impacts of MSW management systems, whether integrated or not, and determine how these impacts change when assumptions raised during the modeling of the different parts of a system are modified (Rigamonti et al. 2009). Greene and Tonjes (2014) classified the LCA as an aggregate depictions indicator. The LCA leads to challenges because as a modeling tool, there is the possibility of achieving different outcomes, making it complex, time and resource intensive, and difficult in application for most managers (not user friendly). Life cycle indicators allow for an assessment of environmental impacts, assisting in the assessment of alternative scenarios and comparing different types of systems with different treatments, consequently sensitivity in changing any aspect. Table 4 shows the importance of complementing these indicators with a multi-criteria analysis.

Figure 3 and Table 4 demonstrate the impact of indicators for the environmental sustainability dimension. Studies on this dimension are recurrent and important contributions to scientific literature. Indicators based on life cycle include various categories of impact that may be related to the subject, such as climate change, acidification, ecotoxicity, depletion of the ozone layer, eutrophication, greenhouse gas (GHG) emissions, and other impacts. The energy issue, which can be analyzed using emergy tools, also has strong evidence of use, and it can also be considered in an LCA. These indicators support a cost-effective view. Policymakers must be aware that the impact of an integrated MSW management system is highly dependent on the assumptions made in the modeling of material retrieval as well as the modeling of energy recovery.

Landfill volume also includes evidence for the generation of waste based on the number of articles that cite the issue. This is due to the need to allocate less waste to landfills and to seek the waste hierarchy: waste prevention, product reuse, recycling, biological treatment, heat treatment, and the landfill (McDougall et al. 2003). This is associated with pollution or the air quality index, which implies the adoption of the 3-R principle (reduce, reuse, and recycle) (Singh et al. 2008; Kale et al. 2010).

Examining the whole survey, it is important to note that several studies indicate that recycling leads to greater environmental benefits, requiring selective collection to be well planned, especially for metals, glass, paper, and high-quality plastics such as PET and HDPE (Rigamonti et al. 2010; Giugliano et al. 2011; Zaccariello et al. 2015), and this selection needs to be continuously monitored (Bringhenti et al. 2011). The separation of organic materials (bio-waste) at the source can offer some benefits, especially when these materials are treated in anaerobic digesters (Rigamonti et al. 2010); however, Consonni et al. (2011) argue that the energy, environmental, and economic advantages of composting are questionable. Rigamonti et al. (2010) also emphasize that the residual waste should be sent to a high-performance waste-to-energy (WTE) plant operating in the combined heat and energy mode.

Some authors seek to create their own indicators by aggregating others, using more traditional indicators, or developing their own methodology. Font Vivanco et al. (2012) developed two indicators for fractioning bio-waste, the net recovery index and the transport intensity index, which were applied to a case study in Catalonia. Both indicators can be useful in assessing key strategies, such as increasing recycling (sustainability principle) or minimizing transport by locating treatment facilities closer to the source (proximity principle), for MSW management policies. These indicators attempt to overcome some of the major deficiencies identified in official biological waste recovery indicators, which tend to have simplified methodologies from systematic accounting.

Another indicator developed is the zero waste index, which estimates potential energy, greenhouse gases, and water conservation for municipal solid waste management. This index is an innovative tool to evaluate the performance of waste management and the replacement of materials by waste management systems. It can also provide a clearer representation of a city's overall waste management performance than indicators that simply give rates (Zaman and Lehmann 2013; Zaman 2014b).

Zaman's (2014a) list of indicators derived from 17 studies confirms indicators listed in this study, such as waste generation, recycling, recovery, final disposal, costs, service coverage, service satisfaction, environmental and socioeconomic impacts, institutional and political impacts, collection frequency, performance, carbon footprint, treatment technology, transportation, human health, and others. However, the present study exhibits indicators compiled from top-cited studies in the Web of Science database that are classified and identified within sustainability dimensions, with consideration for the practical managerial impacts on the managers.

Unlike Sanjeevi and Shahabudeen (2015) who only highlight the five key indicators of collection costs, transportation costs, social perception, social participation, and environmental impacts, the authors understand that coupling indicators (as given in Table 4) highlights the importance of multivariate and different facets used to measure the performance of diverse MSW management practices while assessing impacts and monitoring development of MSW management. Thus, it is also necessary to establish a global indicator standard that is easy for managers to interpret and apply, allowing consistent comparison across different municipalities and countries equitably and involving the three dimensions of sustainability: environmental, economic, and social.

Conclusion

Variations exist in the indicators used to categorize MSW management practices, but those studied here are relevant and can be practically applied to one or more of these three dimensions of sustainability: environmental, economic, and social. These indicators are based on performance measurements, with a goal of efficiency and effectiveness when implementing them in an MSW management system.

This study analyzed how state-of-the-art these indicators were in the management of MSW by compiling key articles from a variety of authors and institutions from different countries using established keywords, while identifying articles' interrelationships and co-citations through bibliometric indicators.

The most relevant articles were selected from the sample to identify the most used indicators and determine their implications for management practices. Through a content analysis, the main indicators used in the scientific literature for solid urban waste were identified as well as main approaches to sustainability according to the three sustainability dimensions and implications for management.

This study shows that the environmental dimension is treated with the most importance in the literature, with economic and social dimensions following, respectively. Studies on the environmental dimension highlight life cycle indicators, evidenced by the various impact categories related to this area of study, including climate change, acidification, ecotoxicity, depletion of the ozone layer, eutrophication, greenhouse gas emissions, and others. Energy issues, which can be analyzed using emergy tools, are also widely featured in the literature, but some of these topics can be categorized by the LCA indicator. Landfill volume and waste generation indicators were also widely covered in the articles compiled.

The life cycle indicators allow an assessment of the environmental impacts through scenario analysis, which integrates several types of systems with different treatments and can measure the sensitivity in the change in any parameter of analysis. The results of this study show the importance of complementing the life cycle indicators with a multi-criteria analysis. These indicators reflect the multifaceted nature of the subject, since they involve complex problems. In this way, the use requires an integration of several areas and stakeholders and a holistic view of the system by the manager.

The indicators also imply the constant need to search for the waste hierarchy to prevent waste generation and finally, send to landfill, which is in accordance with the 3-R principle. Monitoring the generation of waste is important to allow the verification of waste reduction in the face of waste prevention.

The environmental indicator covering composting rates, recycling, and incineration as well as the preceding indicator for recovery, demand, and material flow of waste both yielded significant results as well.

Some economic indicators intertwine with environmental and social indicators, but others are specific, especially when they address issues of financial costs and returns.

The social indicators have an impact on end users and on governance, involving the political legitimacy of inclusion, coordination with stakeholders, institutional coherence, supervision, transparency, public participation, and managerial structuring.

The indicators, in their various dimensions, are useful for comparing different technologies, treatments and environmental–social–economic performances. They also help in the creation of quality public policies maximizing the indicators adopted. Therefore, integrating several indicators is important to provide a holistic view of the performance of the entire solid waste management system in the municipality.

This study was limited to articles retrieved from the Web of Science database. Repeated using other databases, other researchers may be able to identify more authors, indicators, and practical implications for MSW management. This article only includes documents with an LCS of one or greater ($LCS \geq 1$). While the whole sample could have been analyzed, the objective of this study was to only perform content analysis on the most relevant articles, informing the decision to classify articles in this way.

New research must be carried out to verify how applicable indicators are for different municipalities because the question of ease of use and understanding for managers and residents is crucial in evaluating several indicators. Further research should also seek to establish a global standard, including international standards for quality management across companies, that is easy for managers to interpret and apply, allowing consistent comparison across municipalities and countries and involving the three dimensions of sustainability: environmental, economic, and social.

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