



Review

How is the performance of waste management systems assessed globally? A systematic review

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ABSTRACT

How is the performance of waste management systems (WMS) assessed globally? In order to answer this question, 366 peer-reviewed research articles in English, which assessed the WMS of cities or countries focusing on municipal solid waste (MSW), are systematically reviewed to 1) identify existing correlations between country income group and different considered issues that indicate possible future trends, and 2) categorize assessment methods concerning the suitability for decision makers and for different country income groups and based on this 3) determine the evolution of WMS assessment for the different country categories since the 1980s. The considered issues are the used assessment methods, investigated WMS components, assessment aspects, funding support and outcome of the study. For this systematic review three databases (Web of Science, ScienceDirect and Technik und Management – TEMA) as well as snowballing were used to identify relevant articles. The results show that the assessment of WMS is a crucial and still relevant topic according to the increasing number of publications in the last 40 years. 40% of all reviewed studies used life cycle approaches and their combination with other assessment methods to assess the performance of WMSs. Environmental aspects are the most investigated aspects. Only four studies assessed all defined WMS components. Three different method categorizations are defined: A) data generating methods (e.g. surveys), B) simple assessment methods (e.g. benchmarking) and C) complex assessment methods (e.g. LCA, MCDM, DEA). Type B methods are mostly suitable for decision makers as well as for all investigated country types, regarding the needed data and the simplicity of the methods. Based on the review results, future research should focus more on the development of simple, quick and user-friendly methods with great potential for WMS optimization by ensuring a holistic view to assess the performance of WMSs.

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Abbreviations

AHP	Analytical Hierarchy Process	LMI	Lower-middle income
CBA	Cost-benefit analysis	MCDM	Multi-criteria decision-making
CEA	Cost effectiveness analysis	MFA	Material flow analysis
DEA	Data envelopment analysis	MSW	Municipal solid waste
EIA	Environmental impact assessment	RA	Risk assessment
GHG	Greenhouse gas	RDF	Refuse derived fuel
GIS	Geographic information system	SD	ScienceDirect
HI	High-income	SEA	Strategic environmental assessment
IFI	International funding institutions	SFA	Substance flow analysis
LCA	Life cycle assessment	SLCA	Social life cycle assessment
LCC	Life cycle costing	UMI	Upper-middle income
LCSA	Life cycle sustainability assessment	WM	Waste management
LI	Low income	WMS	Waste management system
		WMSs	Waste management systems
		WOS	Web of Science

1. Introduction

In any society a well-functioning management of municipal waste is a central element for a good quality of life, a clean environment and the conservation of natural resources. However, the implementation of a well-operating waste management system (WMS) for municipal solid waste (MSW) is still a challenge for many countries in the world, particularly for developing and emerging countries. The United Nations Environment Programme assumes that around two billion people worldwide are excluded from municipal waste collection (UNEP, 2015). Consequently, this promotes wild dumping into the environment (water, soil) or open burning. As shown by Kaza et al. (2018), these are the mainly used disposal practices in countries that do not have a well-functioning WMS. The consequences are serious: impacts on human health, loss of valuable resources and climate gas emissions. Besides that, a lot of other factors influence the sound implementation of WMSs as Governance (Marshall and Farahbakhsh, 2013), which is crucial for building up a WMS (Filho et al., 2016) as well as lack of financial resources (Wilson and Velis, 2015). Moreover, social factors as rapid urban growth, which in turn lead to an increased amount of waste, and poverty are other aspects which complicate the sound implementation of WMSs and thus the handling of waste (Kaza et al., 2018; UNEP, 2015). Hence, it should be a principle goal to be pursued by countries to improve their WMS by enabling a proper disposal, recycling and recovery of waste and to promote waste prevention. So, they are able 1) to cope with the increasing waste quantities, especially in fast-growing regions, 2) avoid the irreversible loss of valuable resources (Georgescu-Roegen, 1971), 3)

decouple the resource use from population growth as well as economic growth (Matthews et al., 2000) and 4) to keep the negative risks as low as possible.

For improving the performance of waste management in a country, different stakeholders and decision makers have to cooperate or to be coordinated: notably municipal and/or regional administration, national authorities, experts for waste collection and technological treatment, but also consumers and local population. Due to the importance of waste management for sustainable development but also to face the challenges in developing and emerging countries, international development agencies and funding organizations contribute to national efforts. However, owing to the complex set of problems interacting in waste management, it is a challenge to conceive targeted measures for improvement as well as to invest money efficiently, because of the following reasons. Firstly, there are multifold expectations what a WMS should provide: a safe disposal of (dangerous) waste, health protection, resource recovery, climate mitigation, creation of jobs, etc. Consequently, the improvement or optimization of WMS pose a multicriteria decision problem. Secondly, a WMS is a complex system, with interconnections between the single system components (Seadon, 2010) where often it is not clear whether measures affect the system as a whole or only single components (Finnveden et al., 2007). Thus, for efficient improvement of WMSs it is desirable to use clear assessment methods to characterize the performance of a WMS in view of its multiple targets and components in order to 1) identify existing problems or improving potentials and 2) control the successfulness of measures after implementation.

Different reviews identified assessment methods for decision

Table 1
Summary of methods for WMS assessment.

Assessment methods	Finnveden et al. (2007)	Pires et al. (2011)	Karmperis et al. (2013)	Zurbrügg et al. (2014)	Allesch and Brunner (2014)
Benchmarking					X
Business canvas and business environment assessment				X	
Clean development mechanism				X	
computer based multiple sustainability assessment				X	
Cost effectiveness analysis (CEA)	X				X
Cost-benefit analysis (CBA)	X	X	X	X	X
Eco efficiency analysis					X
Emergy analysis					X
Energy analysis	X				
Entropy analysis	X	X		X	X
Environmental impact assessment (EIA)	X	X			X
Environmental management system	X				
Environmental technology assessment				X	
Exergy analysis	X	X		X	X
Forecasting models				X	
Integrated modelling system				X	
Investment analysis	X				
Life cycle assessment (LCA)	X	X	X	X	X
Life cycle costing (LCC)	X			X	X
Management information system, decision support system and expert systems		X			
Material flow analysis (MFA)	X	X		X	X
Multi-criteria-decision-making (MCDM)			X		X
Optimization models				X	
Risk assessment (RA)	X	X		X	X
Scenario development		X			
Simulation models				X	
Social and organisational network analysis				X	
Socioeconomic assessment		X			
Stakeholder analysis				X	
Strategic environmental assessment (SEA)	X				X
Substance flow analysis (SFA)	X				
Sustainability assessment by success and efficiency factors		X		X	
Sustainability assessment of technologies				X	
Technology appropriateness				X	

support in the context of waste management. Pires et al. (2011) evaluated system analysis techniques for waste management in European countries. Finnveden et al. (2007) and Allesch and Brunner (2014) provided a guidance for the selection of appropriate assessment methods for decision makers, while Zurbrügg et al. (2014) analyzed the general applicability of different assessment methods for developing countries and identified their strengths and weaknesses. Karmperis et al. (2013) surveyed decision support models that are commonly used in the solid waste management area.

Table 1 presents a compilation of the assessment methods identified in the referred reviews:

Additionally, some reviews focused on single assessment methods such as Goulart Coelho et al. (2017), who evaluated and compared different Multi-criteria-decision-making (MCDM) applications as well as their use in the context of waste management for developing countries and rapidly growing regions. The authors determined that existing approaches and available technologies for urban waste management are not fully exploited. Bani et al. (2009) reviewed different Decision Support System (DSS) applications and described the evolution of the DSS development starting from 1996. Over time, DSS models and applications included more waste management aspects translated in different variables and mathematical formulations as well as combining DSS models with other tools like Geographical Information Systems (GIS). Consequently, DSS tools got more complex. The authors saw a big opportunity with the technological evolution of computing power and software applications, which can help to optimize DSS tools to reduce uncertainties in the results.

Life Cycle Assessment (LCA) has received special attention in literature considering the assessment of WMSs. Ekvall et al. (2007) described LCA as tool for the assessment of waste management, but also discussing limitations. Winkler and Bilitewski (2007) compared six different LCA models concerning specific criteria (i.e. user friendliness, adjustability, interpretability, the covered LCA-elements). Cleary (2009) compared 20 LCA studies of MSW, focusing on the methodological transparency, used LCA computer models, impact categories, weighting, sensitivity analysis, etc. Laurent et al. (2014) evaluated 222 LCA studies of solid WMSs regarding the LCA methodology phases (goal definition, scope definition, inventory analysis, impact assessment, interpretation). Khandelwal et al. (2019) reviewed 153 LCA studies of MSW management systems by analyzing time evolution, geographical distribution, and the applied methodology. The review summarized the use of the functional units, LCA model, LCIA method, MSW management options, and other findings concerning MSW composition, income group, and possible application gaps.

In spite of a broad literature and many methodological approaches, practical application is still limited and it is an open question, how helpful these approaches are for practical application. As can be seen in Table 1 many different methods exist and are used in the literature to assess WMSs. Regarding the suitability of assessment methods for developing countries, Zurbrügg et al. (2014) concluded that the use of comprehensive assessment methods is very limited, because most of them are designed from academia for academic purposes and so, they are too complex for the existing local capacities and thus for decision makers. Also, not all assessment tools are able to evaluate different aspects, such as

economic, environmental, social, technical, organizational, or Governance. Frequently, only the combination of different tools and approaches may enable a holistic and comprehensive assessment of various aspects. A further point is the necessary data for different methodological approaches, where data availability is a far higher challenge in developing compared to industrial countries. Summing up, in order to promote the benefits of using assessment methods in practice, a much more scrutinized analysis of methods for the assessment of WMS in developing countries is needed than can be found in literature up to now.

1.1. Research question and scope of the study

The general question of this study is: *How is the performance of waste management systems assessed globally?* By answering this general question another interesting question emerges regarding the suitability of assessment methods for different income countries as well as the applicability for decision makers. So, the second important question is: *How can the applicability of assessment methods for WMS be described?* Based on these two questions, the analysis of assessment methods goes along with the issues of investigated cities and countries, assessment of WMS components, used assessment methods and investigated aspects, the outcome of the assessment and the funding of the research study.

In this study, 366 scientific peer-reviewed publications in English are reviewed systematically by analyzing the issues mentioned above. For this purpose, some analysis criteria from the above-mentioned existing reviews are used along with new criteria to enhance the results.

The novelty of this study in comparison to the foregoing reviews is:

1. Firstly, it focuses on the assessment practices in combination with the country categorization by income group according to the World Bank (low (LI), lower-middle (LMI), upper-middle (UMI) and high income (HI) countries) (World Bank, 2019). Furthermore, this analysis determines more precisely existing correlations between the specific income group of the investigated countries and assessment methods, investigated aspects, WMS components, funding and decision makers. By linking the results of the current research in combination with the World Bank's income related country categories, correlations are expected that indicate possible trends or developments in the respective country category. Along the whole study, a special emphasis will be given to low and middle income countries.
2. Secondly, the analyzed assessment methods are categorized regarding their suitability for different countries according to their income group and applicability for decision makers.
3. Thirdly, the evolution of WMS assessment in the context of MSW emphasizing on cities and countries over the last 40 years for the different country categories is evaluated.

2. Material and methods

The literature research for this paper was carried out in line with the PRISMA guidelines for systematic reviews (Liberati et al., 2009; Moher et al., 2015). The completed PRISMA-checklist as recommended from PRISMA et al. (2009) has been attached as supplementary material (see SM1). First, the search strategy, the screening process including the eligibility criteria and the information sources are described. Subsequently, the data extraction and the analysis criteria for the systematic review are presented.

2.1. Search strategy

For the systematic literature review, databases and information sources as Web of Science (WoS), Technik und Management (TEMA®) and ScienceDirect (SD) were used. SD was used as one database, due to the missing full access of the Scopus database. The following keywords were used for the search in the three databases: "waste management", "assess", "assessment", "evaluation", "evaluate", "classification" and "classify". In WoS and SD the keywords were used to identify matching titles, abstracts and keywords; in TEMA only the search for titles and abstracts was possible. The limits of the search are defined as follows: only peer-reviewed research articles in English published or available in early access status before the 31st of May 2019. Some journals have different types for naming peer-reviewed research articles, e.g. country reports (Waste Management Journal) or case studies (Waste Management and Research). These types of articles were also included for further analysis. Review articles, conference papers, books, preliminary works and grey literature were excluded during the search process. The Boolean operators AND/OR/NOT were used in WoS and TEMA to separate the keywords and to specify the results. The same was done for SD with the exception of using only AND/OR operators in the search query, due to the restricted use of Boolean operators (max. 8) in the advanced search. In WoS the possibility to refine journals, which evidently do not address the issue (e.g. Nuclear, Water, Medicine Journals), was applied. The described search strategy resulted in a total of 6.100 search findings. The used search query, the refining search criteria (limits) and the associated search results for each database are listed in Table A1 (see Appendix). In addition, 64 relevant articles, which did not result from the defined search strategy, but had been identified using "snowballing" or suggested after the article downloading process (especially in SD), were also included in the screening process to select the relevant studies for review.

2.2. Screening process

The screening process was performed by the corresponding author. The search results of WoS, SD and TEMA (including the reported limits and the refined criteria) were, 2.980, 2.303 and 817 findings, respectively. The literature information was exported to the reference management program Citavi Version 6.1. Citavi was used to perform the study selection process. 1.801 duplicates were detected by Citavi during the import of the reference information. Although proceedings, book chapters or grey literature were excluded in the first step, 200 were still found in the list of matching articles. All these references were removed before the start of the title and abstract screening phase.

To make sure that only relevant articles are analyzed in the final reviewing step, first the title and then the abstract of 4.163 articles were further checked by using the following eligibility criteria:

- The screened article is a research article and not a review article.
- The authors investigated MSW streams in combination with the assessment of waste treatment/disposal technologies, waste policies, waste management concepts, plans or strategies.
- The authors investigated the MSW stream as a whole and more than one waste component.
- The authors assessed these issues for cities, regions or countries (case study).

In this study the components of a WMS are defined as follows:

- waste control and regulation (incl. Governance and Management)

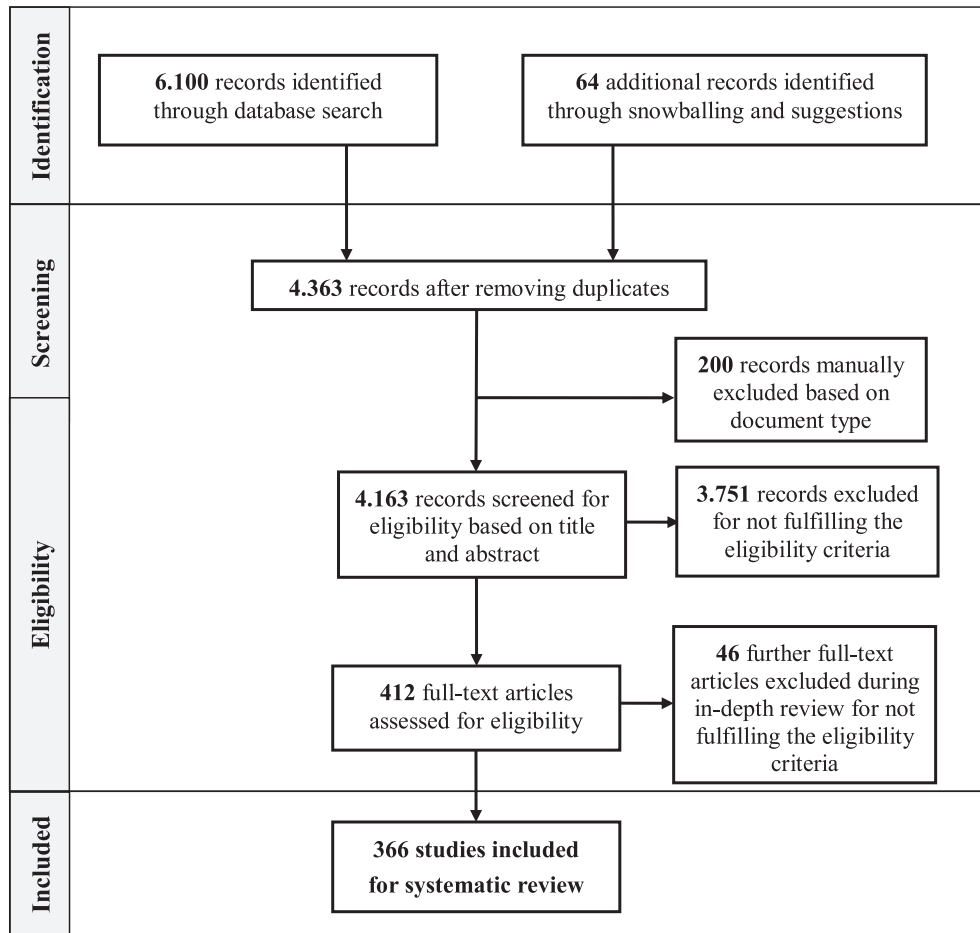


Fig. 1. Overview of the screening process to identify relevant publications for review adapted from Liberati et al. (2009).

- waste market (incl. trading and broking)
- waste collection and transport
- waste prevention and re-use
- waste recycling
- energy recovery
- waste disposal (landfilling, dumping, open burning)

According to Wilson et al. (2012), the components are distinguished into physical components (collection, prevention, recycling, recovery and disposal) and Governance components (waste market, waste control and regulation). The description of the single WMS components is specified in Table A2 (see Appendix) and the investigated assessments aspects in Table A3 (see Appendix).

If at least one criterion was not fulfilled, the article was excluded. 412 articles were identified as relevant. As next step, the digital or print versions of the relevant papers were acquired via the university library of the Technical University of Darmstadt. Four articles were not accessible and could therefore not be further investigated. After the complete reception of all other articles, they were checked again according to the eligibility criteria. The second screening excluded 46 articles, because only after reading the full article it was evident that the eligibility criteria were not fulfilled. Other reasons for exclusion were that the full text of some papers were in a different language (e.g. Portuguese, Spanish), but contained an English title and abstract, so they were not excluded in the first screening procedure. Papers, which analyzed fictitious cities or regions or, which turned out to be methodological papers

without referring to a case study were excluded as well. Fig. 1 shows the overview of the screening process for the identification of relevant articles.

2.3. Data extraction and analysis

Finally, 366 articles were identified as relevant and subsequently analyzed in detail. For managing the data of these articles an excel sheet was developed (see SM2). The following descriptive information: title, author(s), year of publication, abstract, investigated location(s), World bank country classification and funding information, were extracted from the included studies and documented in the developed sheet.

In order to give an answer to the research questions (1. "How is the performance of waste management systems assessed globally?" and 2. "How can the applicability of assessment methods for WMS be described?"), the 366 studies were analyzed according to the following questions grouped in four topics:

Topic 1: Investigated cities and countries.

1. Which income group were the investigated cases assigned to?
2. Was the case study comparing the WMS of different cities or countries?
3. Did the research receive funding? If yes, by whom?

Topic 2: Assessment of WMS components.

4. Which components of the waste management system were analyzed?

Topic 3: Used assessment methods and investigated aspects.

- 5. What assessment method was used?
- 6. Which aspects were assessed?
- 7. Did the study only assess a case study or present also a new assessment tool?
- 8. If a new tool was presented: Who can use the newly developed tool?

Topic 4: Outcome of the assessment.

- 9. Was the result of the study a less advanced or more advanced WMS?
- 10. Were measures proposed to improve the WMS for the investigated case(s)?
- 11. Did the authors categorize the WMS of the investigated cases after assessment?

Besides the descriptive information, the coding for each question as well as the complete results of the analysis are included for each study in the developed excel sheet named "Review Analysis Documentation", which is available as supplementary material (see SM2).

2.4. Data synthesis

For each of the 366 relevant studies, the four topics and the corresponding questions were examined. The results are presented and discussed in chapter 3, including the use of graphical charts. Correlations between the specific income group of the investigated countries and assessment methods, investigated aspects, WMS components, funding and decision makers are described. On this basis, the results of the assessment of WMS as well as developments and possible trends are summarized for each country category by highlighting similarities and differences between the different categories. Due to the existing similarities, the categories LMI and LI are presented in one section. Moreover, the analyzed assessment methods are categorized regarding their suitability for different countries according to their income group and applicability for decision makers.

3. Results and discussion

In this section, the results based on the systematic review of 366 peer-reviewed research articles are presented. The following chapter is subdivided into the four identified topics from the previous chapter, i.e. investigated cities and countries, assessment of WMS components, used assessment methods and investigated aspects, and outcome of the assessment.

3.1. Investigated cities and countries

The increasing number of publications over the last four decades regarding the assessment of WMSs in cities and countries shows that this research topic is still important and necessary (Fig. 2). Most of the identified studies assessed WMS of HI (n. 161; 44%) and UMI countries (n. 120; 33%), while only a small part of the studies focuses on LMI (n. 53; 14%) and LI countries (n. 12; 3%). 20 studies assess and compare countries from different income groups (Note: This category is termed "mixed" in the subsequent text). Fig. 2 presents the publication year of the scientific papers and the investigated countries (HI, UMI, LMI, LI, or mixed). Regarding the results, the first relevant study was found in 1984. While at the beginning the number of studies assessing HI countries are dominating, from 2014 on, studies investigating UMI countries are predominating the statistics. In comparison with the country categories, LI countries are rather underrepresented. Generally, since 2009 the amount of publications regarding assessment of WMS for MSW increased in comparison to the past years. From 2016 on, the number of published studies rises annually. A further growth in the number of publications is quite conceivable due to the trend shown in Fig. 2, not only for HI and UMI countries, but especially for LMI countries due to the rising number of published studies since 2015.

In Fig. 3 the identified publications are assigned to the World Bank classification by region (World Bank, 2019). However, 23 studies examine cities and countries of different regions. The highest number of WMS assessment studies concerns China (n. 35), followed by Italy (n. 33) and then India, Brazil and Iran with 15 studies each (see Table A4).

84% of all the reviewed studies assess only one city; the remaining assess more than one city/country by comparing them (Fig. A1). The ratio of comparison to non-comparison studies is for HI: 1:7, UMI: 1:10; LMI: 1:6 and LI: 1:11). The exception is for mixed regions, for which the comparison is the determining criterion.

Nearly 46% of the reviewed studies have mentioned in the acknowledgment or funding chapter that their research was

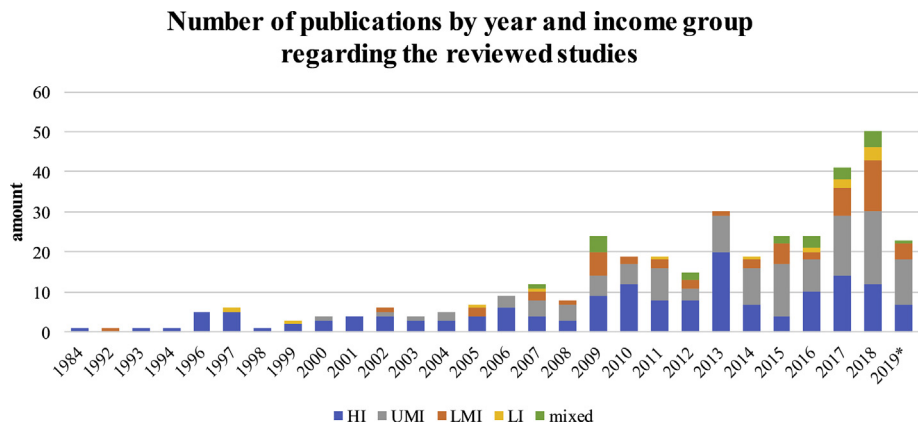
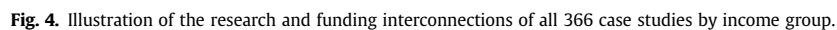
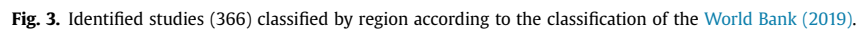


Fig. 2. Number of publications by year and income group regarding the 366 reviewed studies. *Note: Only studies until May 2019 were considered.



higher income as well as organizations like the United Nations or the European Union. The same can be observed for LI countries. For those studies, which included funding information (50%), we can say that studies in LI countries are not financed by LI countries. Studies in LI countries are mainly carried out from foreign countries and rarely in cooperation with local research institutions. However, this does not necessarily mean that no local experts were involved in the assessment. In the study of [Halla and Majani \(1999\)](#), which was carried out by a local university with the aim to investigate innovative ways for solid WM in Dar-Es-Salaam, Tanzania no help from foreign countries is mentioned.

WMSs consist of different components, which are essential for its functionality. But as can be seen in Fig. 5 the WMS components are not assessed in an equal share. A large number of studies analyze treatment (recycling and energy recovery) and disposal options (n. 278), by comparing them with each other, whether by using LCA (n. 74) or combinations of different methods (n. 90). Most of these investigations include the collection and transport of waste (n. 214). In 143 and 91 studies, respectively, the components “waste

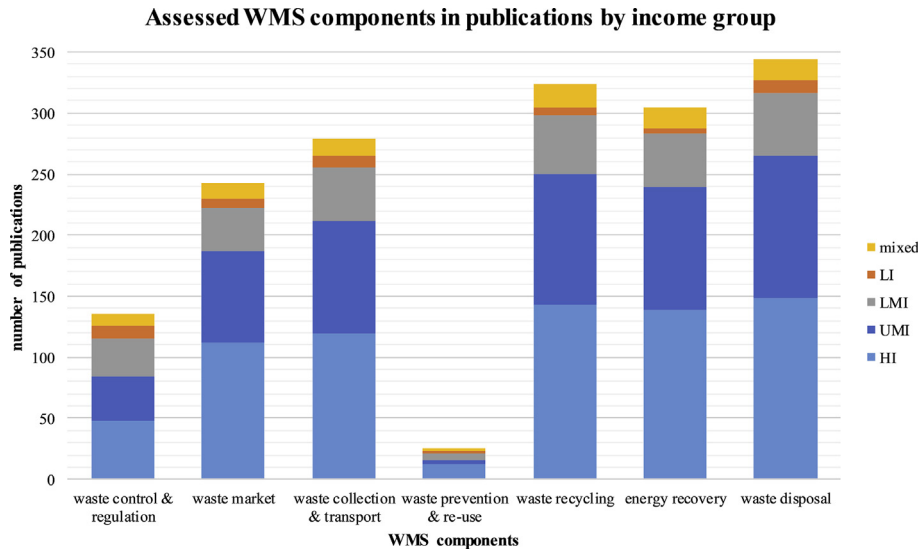


Fig. 5. Assessed WMS components of the 366 reviewed publications classified by income group.

market” and “control and regulation” are investigated in combination with treatment and disposal options. As already determined by Allesch and Brunner (2014), waste prevention and reuse is yet the least assessed WMS component. Although it has the highest priority in the waste hierarchy for several regions as the European Union (EC, 2008) and waste recovery helps to promote the decoupling of resource use from economic growth (Matthews et al., 2000). The most significant difficulty here is the assessment of avoided waste, which is often very difficult to quantify (Gentil et al., 2011), though it shows high environmental benefits (Cleary, 2014; Gentil et al., 2011). In total, only 25 studies take the examination of waste prevention into consideration. Waste prevention is mostly examined in HI countries.

Just four studies assess all defined WMS components. Al-Khatib et al. (2007) used surveys to evaluate the WMS of seven Palestinian districts to determine trends and problems of the current system. Zaman and Lehmann (2013) measured the waste management performance in Adelaide, Australia using the Zero Waste Index and additionally they conducted online surveys with local waste experts to identify the most important priority areas for future waste management strategies. Arushanyan et al. (2017) analyzed environmental impacts of several policy instruments including fees and taxes for Sweden by using a LCA. Fuldauer et al. (2019) proposed an integrated methodology for long-term waste management planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals.

Studies, which used life cycle approaches alone or in combination with other methods are in most all cases considering physical components, without including waste prevention, market concerns and waste control and regulation in their assessment. In pure LCA studies, only three consider prevention in their environmental evaluation (Cleary, 2014; Mohareb et al., 2008; Morais Lima et al., 2019) and only two considered waste control and regulation (Corsten et al., 2013; Liamsanguan and Gheewala, 2008). Studies, which included control and regulation aspects are those, which combined life cycle approaches with other methods as policy analysis (Arushanyan et al., 2017; Deus et al., 2017; Falzon et al., 2013; Jaunich et al., 2019; Liu et al., 2017), MCDM (Su et al., 2010), SEA and performance indicators (Salhofer et al., 2007) or also single score index with Analytical Hierarchy Process (AHP) (Aleisa and Al-Jarallah, 2018).

In case studies using benchmarking only three out of 32 studies

investigated some physical and Governance components by integrating also waste prevention in the analysis (Barron and Ng, 1996; Zaman, 2014; Zaman and Swapan, 2016).

In Fig. A2 the assessed WMS components are put in relation to the publication year. It indicates that the evaluation of waste collection, recycling, recovery, disposal and market has been always of great interest. Since 2007, the consideration of waste control and regulation has been included in some studies. For waste prevention there is no significant change so far.

3.3. Used assessment methods and investigated aspects

For the assessment of WMSs diverse methods have been identified. To guarantee a concise overview, these methods are clustered into eight categories (i.e., life cycle approach, benchmark and indicators, MCDM, data-envelopment analysis (DEA), surveys, mathematical models, other and the combination of different methods). Methods categorized as “other” are methods as energy, exergy, emergy, economic and policy analyses as well as MFA/SFA, GHG-analysis, rapid impact assessment or SEA. Studies for which no precise method was described or identifiable have been classified in the group “no method”. In Fig. 6 the nine categories indicating the total findings are presented. Methods based on life cycle approaches and the combination of methods are largely applied. The category “combination” represents the largest group, since it enables a consideration of different assessment aspects. Of all studies using life cycle approaches, 87 are exclusively LCA studies assessing environmental aspects; the remaining five are social LCA (SLCA) (Ibanez-Fores et al., 2019), life cycle sustainability assessment (LCSA) (Wang et al., 2018; Zhou et al., 2019), dynamic life cycle-based optimization and decision support tool (Roberts et al., 2018) as well as iWaste a simulation model based on LCA (Corsten et al., 2013). But including the LCA studies allocated to the category “combination,” the number of studies combining LCA with other methods (e.g. LCC, material flow analysis - MFA, cost or policy analysis, MCDM) rises up to 146. This result shows that LCA is firstly, a commonly used method in literature to perform environmental investigations and secondly, a suitable tool to combine it with other methods.

Methods as benchmarking (n. 32), MCDM (n. 27) or DEA (n. 3) allow the evaluation of multiple aspects. Nevertheless, these methods are also combined; 21 studies used benchmarking or

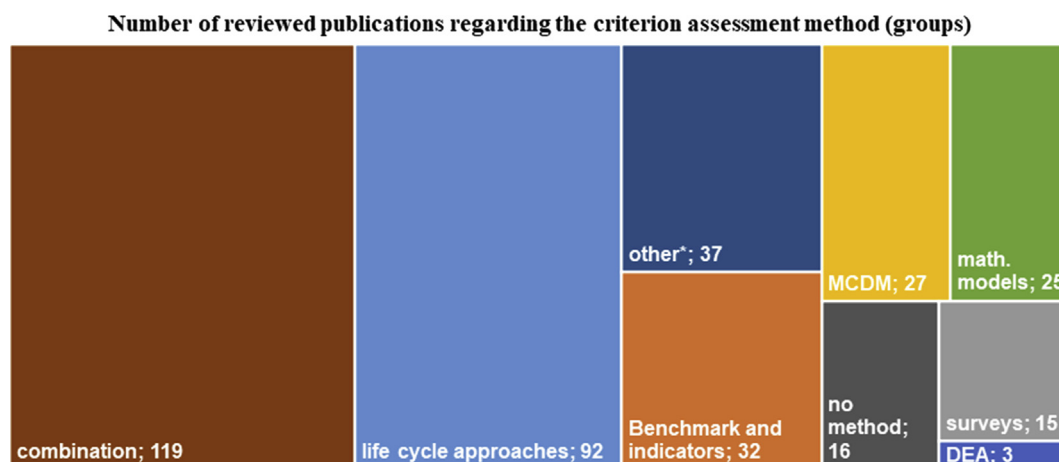


Fig. 6. Number of reviewed publications (366) regarding the criterion assessment method (groups).

performance indicators, 15 MCDM and 4 DEA in combination with other methods.

There are various methods in the review analysis that are not mentioned separately in the upcoming diagrams, because they are almost entirely used in combination with other methods. MFA for example is used in 16 studies in combination with methods as LCA, policy or cost analysis, environmental indicators or MCDM, while only three made use of it without combining it with other methods (Allesch and Brunner, 2017; dos Muchangos et al., 2017; Markic et al., 2019). The approach strategic environmental assessment (SEA) is used in three studies in combination with multi-criteria evaluation (Josimović et al., 2015), performance indicators (Federico et al., 2009) and LCA (Salhofer et al., 2007). Cost-benefit analysis (CBA) can be found eleven times in combination with other methods as for example cost effectiveness analysis (CEA) (Döberl et al., 2002; Weng and Fujiwara, 2011), LCA (Chang et al., 2012; Chang and Lin, 2013a; Nguyen and Matsui, 2012), GIS (Chang and Lin, 1997), MCDM (Abou Najm et al., 2002; Chang et al., 2012; Chang and Wang, 1996; Chang and Davila, 2007; Chang and Lin, 2013b) or as variation as in the study of Jamasb and Nepal (2010), who used social CBA.

As already mentioned, since 2009 the amount of publications regarding the assessment of WMS is growing. From 2004 on, LCA is applied extensively to assess WMS, which proves that it has established as a good tool for environmental evaluation. The combination of methods increased since 2010 and the use of benchmarking and performance indicators since 2012.

All assessment methods require specific type of data as metrics (e.g. population, waste composition, recycling rates, landfill rates, number of waste pickers) or literal descriptions (e.g. service quality, level of awareness). The depth of detail and the type of data, which is needed for application can vary depending on the investigated aspects and system components. Quantitative data is mostly needed for the assessment of environmental, economic as well as technical aspects by using metrics from impact assessment (e.g. GHG-emissions, resource depletion), financial data (e.g. costs, revenues) or various rates (collection or recycling rates, etc.) or efficiency indicators (Halkos and Petrou, 2019; Kaufman et al., 2010; Yang et al., 2018) as well as indices (Yadav and Samadder, 2018a; Zaman and Lehmann, 2013). Whereas qualitative data is usually used to assess organizational, Governance and social aspects. The generation of this non-numerical data is done for example by the utilization of methods as structured interviews or group discussions (Dangi et al., 2017; Kassahun and Birara, 2018; Lalitha and Fernando, 2019).

Methods, like mathematical modelling, MCDM, DEA and life cycle approaches for example, need a big amount of robust data for calculations to guarantee valid results. These mostly complex methods need a lot of data, which has the positive effect that they can go more into detail regarding WMS assessment, then for example benchmarking tools can do. Life cycle approaches need specific data, which are often not available in countries, where data collection is lacking (Zurbrügg et al., 2014). That is why these methods are mainly used to evaluate WMSs in HI and UMI countries. However, twelve studies performed LCA for LMI countries (Batool and Chuadhry, 2009; Islam and Moniruzzaman, 2019; Majeed et al., 2018; Menikpura et al., 2012; Nguyen and Matsui, 2013; Tseng and Lin, 2009; Ogundipe and Jimoh, 2015; Rana et al., 2019; Sharma and Chandel, 2017; Singh and Basak, 2018; Syeda et al., 2017; Wang et al., 2018; Yadav and Samadder, 2018b). Only three studies examine the WMS in LI countries using LCA (Oyoo et al., 2014) and MCDM (Kapepula et al., 2007; Makarichi et al., 2018). When developing countries use data-rich methods, the validity of the results must be viewed critically. In the case of LCA, it is possible that for assessing WMSs in developing countries for example data from HI countries (e.g. from databases) is used and many assumptions have to be included to calculate the environmental impacts. Subsequently, uncertainties cannot be avoided (Finnveden et al., 2007). So, the validity of the calculated results and the representativeness are not assured anymore. The more detailed data are needed, the less applicable they are for countries in which waste relevant data are not systematically collected or the access is not provided due to for example uncooperative institutions (e.g. authorities or private companies).

In contrast, surveys and interviews are more appropriate methods for such circumstances, because they generate data. Surveys, interviews and waste analyses have been found in 15 studies, which investigate WMSs of mostly LMI or LI countries, due to the existing lack of data (see also Fig. 7). For 16 studies in mostly LMI countries no clear assessment method was described in the publication. Sometimes the authors mentioned the use of literature or management analysis without going into detail regarding the methodological approach.

Benchmarking tools and indicators are generally user-friendly with the goal to simplify the assessment in order to give a first overview. The needed data for assessment can be quantitative or qualitative, that is why, these assessment methods are suitable for all country types as well as for decision makers. To increase the investigation depth more complex methods (e.g. LCA, MCDM, DEA, etc.) can be used.

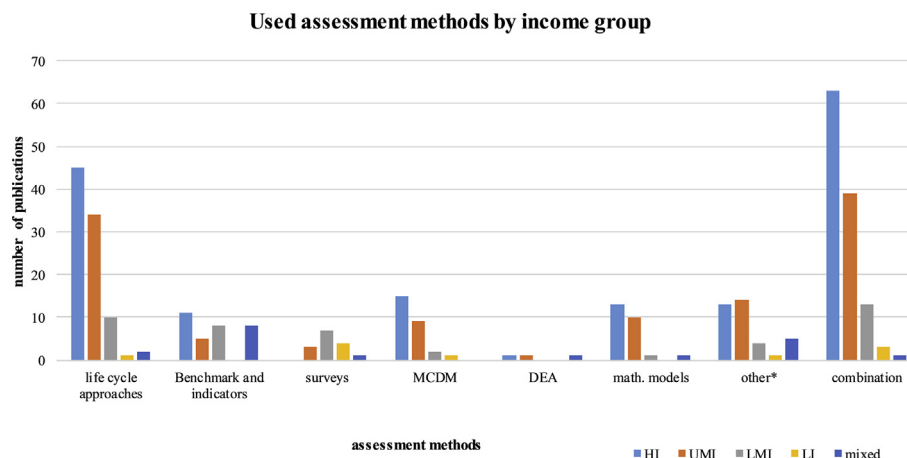


Fig. 7. Used assessment methods of the 366 reviewed publications classified by income group.

For the comparison of different case studies, performance indicators for benchmarking (e.g. wasteaware benchmark indicators (Wilson et al., 2012)) or composite indicators (e.g. Zero Waste Index (Zaman, 2014)) as well as LCA, DEA and other mathematical models are frequently used.

Generally, assessment methods can be described with regard to their applicability for assessment aspects (environmental, economic, etc.), system components, the data situation, the different country groups and the users of the methods. In order to ensure a clear overview of the methods, the identified one are categorized into the following three clusters regarding the needed data and the applicability for the users and country groups:

Type A: “Data generating methods” Methods, which are used to generate quantitative and qualitative data, for example surveys, interviews, waste analysis or field investigations. Type A methods are mostly applied by academics and less usable for decision makers. These methods are suitable in countries in which waste related data is lacking (e.g. mostly low and middle income countries).

Type B: “Simple assessment methods” Benchmarking and performance indicators can be summarized in one group due to the amount of data needed and due to the fact that they are simplified assessment methods, which can be applied either by academics or by decision makers, as for example waste planners. These methods are suitable for mostly all country categories, since the assessment needs quantitative and/or qualitative data.

Type C: “Complex assessment methods” System analysis methods, which are complex, because of the big amount of data needed (databases, in-depth analysis), the work with algorithms or due to the applicability are clustered here. Life cycle approaches, MCDM, DEA, mathematical models and the combination of complex methods are categorized to type C. Usually, these methods are applied by academics, but these complex models can also be simplified to get applicable for decision makers. Since, a big amount of data can be necessary these methods are more suitable for countries with a good and reliable data record in waste management (e.g. mostly the case in HI or UMI countries).

Since 1980es, many new methodologies have been developed for WMS assessment (focusing on MSW). While 137 of the reviewed studies publish new methods, tools, frameworks or innovative combinations of already existing methods, the remaining 229 studies assess WMS by applying the existing methods. The majority of the newly developed methods are still too complex and mostly suitable for academic purposes, which underlines the findings of Zurbügg et al. (2014). 37 new methods have been

described as applicable for decision makers or waste planners. Out of this, twelve methods are type B methods as benchmarking tools (Aleluia and Ferrão, 2016; ElSaid and Aghezzaf, 2018; Ilic and Nikolic, 2016; Lavee and Khatib, 2010; Wilson et al., 2012; Zaman and Lehmann, 2013) and performance indicators (Cifrian et al., 2015; da Silva et al., 2019; Fragkou et al., 2010; Fuss et al., 2018; Mendes et al., 2013; Rigamonti et al., 2016). The remaining are type C methods in combination or in a simplified way to be also applicable for decision makers. For example, Edalatpour et al. (2018) developed a waste management model based on a mathematical model, which can be applied by decision makers to gain a better performance of their WMS. Federico et al. (2009) presented an approach by using indices for public administration, which enables an integrated analysis of WMS in the framework of SEA. den Boer et al. (2007) developed a decision support tool for sustainability assessment based on LCA as well as Kirkeby et al. (2006), which developed a computer based model to perform the environmental assessment of WMS. Both studies simplified the LCA approach to be also applicable for decision makers. Besides, Inglezakis et al. (2018) designed a user-friendly decision support tool by combining MFA and MCDM for the evaluation of waste management plans. Also Vučijak et al. (2016) linked MCDM with AHP used for defining criteria weights and scenario analysis to support decision-making processes for the selection of sustainable WM alternatives. Le ThiKimOanh et al. (2015) as well as Hasome et al. (2001) combined cost analysis with performance indicators. While Le ThiKimOanh et al. (2015) is focusing only on the economic aspect, Hasome et al. (2001) integrated also environmental and technical aspects. Chifari et al. (2017) made an approach to generate well-founded considerations about policies over MSW management useful for researchers and decision makers by ensuring the quality of the process of generation and use of quantitative science. This approach is based on a metabolic network theory and multi-scale integrated analysis of societal and ecosystem metabolism including performance indicators. Bergeron (2016) designed a multi-method assessment regarding household waste management mainly for policy makers, which combines MFA policy analysis and SWOT-analysis with the goal to formulate new waste management strategies for policymakers and other decision makers.

As already mentioned, the aspects of investigation can be a relevant factor for choosing a specific method or to combine them. The reviewed papers predominantly assess environmental and economic aspects, followed by technical, organizational, Governance and social aspects (Fig. 8). Often the studies examine more

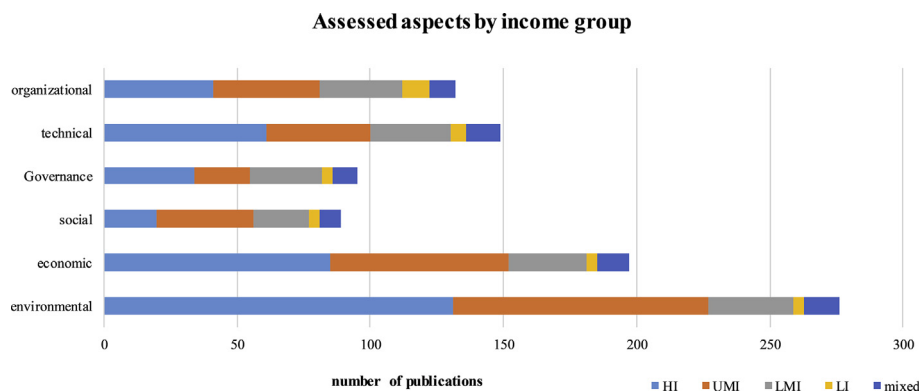


Fig. 8. Assessed aspects of the 366 reviewed publications classified by income group.

than one aspect by combining them in different ways (Table A6): 2 aspects (74 studies), 3 aspects (67 studies), 4 aspects (53 studies), 5 aspects (27 studies). 20 studies examine all investigated aspects. Out of these, ten use the wasteaware benchmark framework from Wilson et al. (2012). The remaining studies use other benchmarking approaches and indicators (AlHumid et al., 2019; Marques and Simões, 2009; Mendes et al., 2013; Parekh et al., 2015; Topic and Biedermann, 2015), MCDM (Tseng, 2009; Tseng and Lin, 2009; Vučijak et al., 2016) as well as integrated approaches (Fuldauer et al., 2019; Shekdar, 2009). Fuldauer et al. (2019) is yet the only study, which consider all WMS components and assessed all investigated aspects.

However, the scope of 125 studies is the assessment of one single aspect. Among these, 112 focus on the environmental assessment of WMS, where mainly LCA is applied as a tool. The combination of environmental and economic aspects is widespread in literature with around 33 studies. Wherefore, mostly LCA (n. 21) is used combined with LCC (n. 3) or cost analyses (n. 16). 15 studies do a sustainable assessment concerning environmental, economic and social aspects, whereas most of them used LCA or MCDM.

3.4. Outcome of the assessment

The assessment of WMSs is a useful method to evaluate the actual state and identify potentials for improvement, by providing recommended actions. The depth of detail of the proposed measures to optimize the WMS varies significantly from study to study. For this reason, the analysis was divided into three categories: “concrete measures”, “unspecific measures” and “no measures” (see detailed description of these codes in SM2). For each category, some studies will be given as examples. Concrete measures are often mentioned in the discussion (Lima and Paulo, 2018) or conclusion chapter (Ali et al., 2019). Some studies (Lalitha and Fernando, 2019; Sharma et al., 2018) even contained an extra chapter only concerning optimization measures. Unspecified measures have been identified, if the study analyzed for example different scenarios and presented their findings only referring on the “best” and “worst” scenario regarding the analyzed aspects (Liikanen et al., 2017; Milutinovic et al., 2017). But, beyond this, no extra measures are proposed, which are required e.g. for the real implementation of the scenario or across all scenarios. Some studies did not mention any improvement measures, either because the focus of the paper concerned the used methodology (Bergeron, 2017; Hasome et al., 2001) or they describe merely problems and challenges of the status of WMS without providing any solutions or at least to point out existing strengths of the WMSs (Damanhuri et al., 2009). However, only 44% of the studies specify

concrete recommendations for improvement on the basis of the gained results. 46% of the studies did not specify concrete measures. 10% do not have any optimization measures or suggestions for improvement.

In two-thirds of the studies investigating LI and LMI countries concrete recommendations for action are included, whereas, for UMI and mixed countries, it was the case for around 50%. The situation is different for WMS assessment studies in HI countries; only around 30% suggest concrete improvement measures.

22% of the studies indicate whether the WMS is less or more advanced. In comparative studies, 39 out of 60 make such a statement by comparing the condition of the different WMSs. Of these, the study of Yang et al. (2018) clusters the investigated case cities based on the obtained results. Yang et al. (2018) investigate the management effectiveness and efficiency of MSWM by using a DEA model. The obtained efficiency results from DEA are clustered to enable a comparison of the investigated cities. Cucchiella et al. (2014) presents a new framework using mathematical programming to assess the effectiveness of waste management quantitatively. Cucchiella et al. (2014) cluster the Italian regions in different groups with similar waste management indications, which can be used to optimize the waste treatment in the clustered regions better. Parfitt et al. (2001) describes a new system of classification for local authorities using hierarchical cluster analysis to compare the local waste collection and provision of recycling infrastructure performance.

Ranking or clustering the efficiency or the performance of WMS can be a good method for the comparison of cities, regions or countries. However, the comparison of WMS should not pursue the goal of judging systems that deserve improvement, but rather serve to gain important information from high performing WMSs.

4. Developments and trends for WMS assessment

In this part, the developments and trends for WMS assessment in HI, UMI, LMI, and LI countries are described based on the results of the systematic review. Moreover, the applicability of WMS assessment methods are described considering the type and amount of investigated aspects as well as WMS components.

4.1. WMS assessment for LI and LMI countries

The assessment of WMS in LI and LMI countries show similar trends and developments, that is why, they are discussed in one section. LI countries are the least analyzed country category followed by LMI countries. Influencing factors for this can be the lack of data and also non-existent or little financial support. Half of all LI

studies received external funding, while for LMI studies it is nearly 45%. The research was mostly funded from national funds of HI or UMI countries (e.g. European Commission, the United States of America, Republic of China) or through foreign Ph.D. scholarships, but infrequently from the investigated countries themselves. The case studies from LMI countries are mostly investigated by LMI countries or in cooperation with or completely by HI or UMI countries. For LI countries the situation is quite different. The studies analyzing LI countries are rarely done lonely by local research institutions, but rather by HI or UMI countries or at least in cooperation with them.

Regarding LI countries, the number of published articles between 2016 and 2018 show a slight increase, while it nearly doubled for LMI from 2017 to 2018. Due to the existing challenges in these countries, an increase in the number of published articles can be expected in future. With 15 studies India is up to now the most investigated country for the LMI category. While for LI countries the analysis of the waste collection, disposal, market and regulation are predominant, waste disposal, recycling, collection and energy recovery are relevant WMS components for LMI countries. Unfortunately, prevention and reuse are largely neglected in both cases. For LI countries only Halla and Majani (1999) and dos Muchangos et al. (2017) consider this component in their analyses and, whereas for LMI countries Oduro-Kwarteng et al. (2016), Al-Khatib et al. (2007), Khatib and Al-Khateeb (2009), Papargyropoulou et al. (2015) and Ahsan et al. (2014) included it in their investigations.

In developing countries, lack of data is a known problem. Consequently, the applicability of methodologies is very limited (Zurbrugg et al., 2014). This is also confirmed by our results. Both country categories rarely applied type C methods, which need a significant amount of data. It is noticeable that for LMI countries, benchmarking, life cycle approaches as well as interviews and surveys are often utilized to evaluate WMSs. For LI countries, type A methods as surveys and interviews (incl. field investigation and waste analyses) are common used techniques, because they generate data and can be used to build up a database. In order to develop databases and statistics for waste management, those countries could, for example, follow the guidelines of UN solid waste accounting framework (United Nations, 2014). In both country categories those type A methods are commonly applied focusing mostly on Governance, technical and organizational aspects. In 70% of all studies improving measures for LI and LMI countries are formulated.

4.2. WMS assessment for UMI countries

In comparison to the previous country categories, the number of publications for UMI countries regarding the WMS assessment for MSW is constantly high since 2013. The average of published articles since then is about 12 articles per year. In contrast to HI countries, this means that more publications are addressing UMI countries. The most studies are done for China (n. 35), followed by Iran and Brazil with 15 publications each. Unlike to LMI and LI countries, type C methods as life cycle approaches and combinations of methods are used the most. Relevant assessment aspects are environmental (n. 96) and economic (n. 67) aspects. 50% of the studies propose concrete measures for improving the WMS in UMI countries. Nearly half of all studies received grants for research. Contrasting to LI and LMI countries, the research for UMI studies was mostly financially supported by national research programs and through national funded Ph.D. fellowships from UMI countries and also from HI countries. The investigations are mainly carried out by UMI countries and to a certain extent in cooperation with HI countries.

4.3. WMS assessment for HI countries

Since 1984 a mean of around six studies per year concerning the assessment of WMS in HI countries have been published. Interestingly, studies addressing Italian WMS are published the most (n. 33). With regard to the applied methods, there are similarities with UMI countries. Type C methods as life cycle approaches and combinations of methods are also frequently used for HI countries, mainly assessing environmental (n. 131), economic (n. 85) and technical (n. 61) aspects. Unlike to UMI countries, type B methods as benchmarking and the use of indicators is also a utilized method for assessment. Concerning the recommendations for action, only a third of the studies propose concrete measures for improving WMSs. 69 studies out of 161 got financial funding almost entirely from national governments and national funded Ph.D. fellowships with the exception of studies concerning Taiwan, which are financially supported by the Republic of China. Where information on funding was available, it can be stated that the financing of the studies derives exclusively from HI countries. The assessment is completely done by HI countries, with little exceptions. Due to the expertise in some waste related research topics, some assessment studies of HI countries are focusing on cities or countries with middle or low income.

4.4. Applicability of WMS assessment methods

A lot of assessment methods are actually in use, whose applicability is still limited for LI and LMI countries, mostly due to the high amount of data needed, which cannot be provided for those countries (see Fig. 9). Therefore, it is essential that a database is created to enhance WMS in these countries. Surveys, structured interviews as well as field investigations are methods, which can generate missing qualitative as well as quantitative data. Especially for those countries, for which waste relevant data is not available, due to lack of related statistical records (e.g. waste amount, waste composition), these methods are suitable.

Only a part of the new developed assessment methods addresses waste planners and other decision makers, which are the main target group, who need these tools the most. The biggest part of innovative methods is still designed for academic purpose and often with the goal to inform decision makers about the assessment results.

Table 2 summarizes some identified methods according to method type, the amount of investigated aspects, which could be found in the reviewed literature as well as the applicability for decision makers (municipal or regional administration, national authorities, experts for waste collection and technological treatment and international funding organizations) and academics. Notable is that benchmarking is applicable to investigate one single aspect up to all six aspects. Life cycle approaches as LCA, LCC or SLCA are limited regarding the investigated number of aspects, whereas life cycle variations as LCSA or combinations based on life cycle approaches are able to evaluate more aspects. Generally, MCDM, DEA models are used in the waste management context to investigate more than one aspect.

40% of all studies chose a classic life-cycle approach or the combination of them with other methods for WMS assessment. In general, environmental aspects (n. 112) are the most studied ones in this context, which is due to the fact that LCA (n. 87) is mainly used to assess environmental impacts. Besides, the combination of environmental with economic aspects (n. 33) and all six aspects (n. 20) are the most identified aspect combinations (see Table A6). Furthermore, Table A6 shows, which methods are used in the literature to investigate single or multiple aspects.

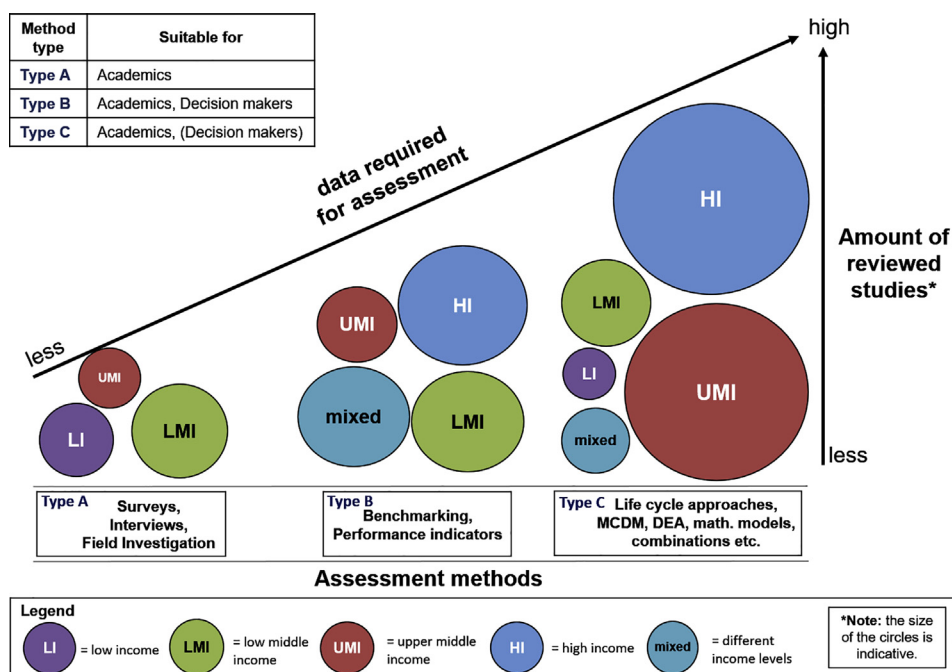


Fig. 9. Used assessment methods in studies according to the required data and the income groups.

Table 2

Assignment of methods with regard to the possible amount of examined aspects, method type and suitability for stakeholders.

		Investigated aspects					
Methods type	Suitable for	1	2	3	4	5	6
Type A	Academics	Surveys & interviews					
Type B	Decision makers & academics	Benchmarking & performance indicators					
Type C	Academics, (decision makers)	LCA, SLCA, LCC		Life cycle variations			
			MCDM				
					DEA		
		Mathematical models					

4.5. Limitations of the study

This systematic review might have missed some assessed cases, especially the ones which are published in proceedings or grey literature or are not written in English language. Also method papers, which did not contain a case study are not examined and are therefore not considered in this review. A further limitation is that individual waste streams are not examined, but only the MSW stream as a whole is considered. However, we searched three different databases to address as many different peer reviewed journals as possible. Moreover, it must be emphasized that this systematic review contains a wide range of peer-reviewed articles concerning the assessment of WMS in cities or countries.

5. Conclusion, challenges and recommendations for future research

In this systematic review 366 peer-reviewed research articles in English assessing WMS of cities or countries were analyzed. Assessment of WMS does not always mean that all relevant system components are addressed in the studies. For example, waste

prevention is still the WMS component which is considered the least in all country types, although it has the highest priority in the waste hierarchy. So, future research should focus more on this component in the context of assessing WMSs. The component control and regulation is the second least assessed component, which is very fundamental for WMSs. Therefore, additional research regarding WMS components are recommended, to ensure a holistic view and to assess the performance of WMSs. There is a gap regarding the methods for clustering of WMS of cities and countries regarding their WMS performance including all relevant WMS components, which can be applied by decision makers.

Generally, the assessment consists of two essential parts 1) assessment of the status quo and 2) formulating measures for improving. The performance of WMSs is mostly assessed using life cycle approaches and combining them with other assessment methods. Due to this fact, environmental aspects are the most investigated aspects for mostly all country types. Sometimes recommendations for WMS are not included in the research studies. Especially, for LCA studies it is noticeable that some of them only assess different scenarios (e.g. treatment options) and discuss results without subsequently proposing concrete recommendations

for action. This should be improved for further research, so that results of assessment studies can be directly used as basis for decision-making processes.

Based on the results, three different method clusters are defined regarding the needed data, the applicability for users and suitability for country groups:

Type A: Methods to generate qualitative and quantitative data as surveys and interviews; mainly used by academics and crucial for countries with high lack of data (e.g. LI and LMI countries).

Type B: Simple assessment methods as benchmarking and performance indicators; suitable for decision makers and academics as well as for mostly all country types.

Type C: Complex assessment methods with high amount of data as LCA, MCDM, DEA, mathematical models; mostly suitable for academics, if there are no simplified alternatives; they are mostly used in UMI and HI countries due to the needed specific data.

The biggest challenges will be problematic in those countries with high data deficiency in the MSW sector in the context of assessing and improving WMSs. This is mainly the case for low and middle income countries. The same challenge exists also for decision makers, who want to rely their decision on robust WMS assessment, which is made difficult due to lack of data. Therefore, future research should focus more on the development of simple, quick and user-friendly methods with great potential for WMS optimization. This could be an option, so that waste related challenges most of all in low and middle income countries can be overcome without wasting precious time.

Due to the existing challenges regarding lack of data, we expect that in future mainly type A and B methods will be used for LI countries. Whereas an increase of type C methods in LMI as well as LI countries is quite conceivable, under the condition that the data situation improves. For UMI countries, type C assessment methods will probably continue to be an essential assessment method. In comparison to UMI countries, besides type C also type B methods will be relevant options in HI countries regarding WMS assessment. The ranking or clustering of the efficiency or the performance of WMS can be a good method to compare cities, regions or countries.

The assessment of WMS is crucial and still a relevant topic in the research field of waste management. The number of publications increased in the last 40 years for all country categories. But, studies addressing LI countries are still underrepresented. The review results show that the country categories developed similarly, but with a time shift. So, considering the future challenges low and middle income countries will meet, more assessment studies for these categories are expected to come. However, development aid in terms of funding support and research cooperation is needed to fasten the research in LMI and especially in LI countries for improving WMS and in order to be able to meet the existing and future challenges more effectively.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2020.122986>.

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