Review Article

WM&R

Waste Management & Research
2014, Vol. 32(6) 461–473
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DOI: 10.1177/0734242X14535653
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Assessment methods for solid waste management: A literature review

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Abstract

Assessment methods are common tools to support decisions regarding waste management. The objective of this review article is to provide guidance for the selection of appropriate evaluation methods. For this purpose, frequently used assessment methods are reviewed, categorised, and summarised. In total, 151 studies have been considered in view of their goals, methodologies, systems investigated, and results regarding economic, environmental, and social issues. A goal shared by all studies is the support of stakeholders. Most studies are based on life cycle assessments, multi-criteria-decision-making, cost-benefit analysis, risk assessments, and benchmarking. Approximately 40% of the reviewed articles are life cycle assessment-based; and more than 50% apply scenario analysis to identify the best waste management options. Most studies focus on municipal solid waste and consider specific environmental loadings. Economic aspects are considered by approximately 50% of the studies, and only a small number evaluate social aspects. The choice of system elements and boundaries varies significantly among the studies; thus, assessment results are sometimes contradictory. Based on the results of this review, we recommend the following considerations when assessing waste management systems: (i) a mass balance approach based on a rigid input–output analysis of the entire system, (ii) a goal-oriented evaluation of the results of the mass balance, which takes into account the intended waste management objectives; and (iii) a transparent and reproducible presentation of the methodology, data, and results.

Keywords

Assessment methods, benchmarking, cost benefit analysis, life cycle assessment, mass balance, material flow analysis, multi criteria decision making, risk assessment, waste management

Introduction

The primary goals of sustainable waste management are to protect human health and the environment and to conserve resources. Additional goals include prevention of the export of waste-related problems into the future (e.g. ‘clean’ cycles and landfills requiring little after care (Brunner, 2013)) and socially acceptable waste management practices (Wilson et al., 2007). A key precondition is affordable waste management costs. To reach these goals, decision makers apply integrated strategies that consist of a multitude of connected processes, such as collection, transportation, treatment, recycling, and disposal (Al Sabbagh et al., 2012). As a result, decision makers expect practicable waste management at an acceptable cost, balancing environmental, economic, technical, regulatory, and other social factors (Barton et al., 1996).

Because the number of available options for waste collection and treatment is always growing and because the economic boundary conditions are changing often, decision makers are constantly confronted with the following questions: Is the current waste management system the most cost effective method for reaching the goals of waste management? Are there other and better combinations of more advanced processes that can provide an identical service at lower costs (Rogge and De Jaeger, 2012)? When answering these questions, decision makers on one hand are under pressure of different stakeholder groups that ask for more sustainability, new technologies, or for cheaper waste management (Wilson et al., (2007). On the other hand, the decision makers experience the methodological dilemma in the choice of the evaluation tool to assess present and new waste management systems.

This situation is a particular challenge because of the many and diverse approaches that promise support for strategic or policy decisions, for waste management planning, and for waste management optimisation on all levels (companies, municipalities, and governments) (Finnveden et al., 2007).

Decision support models were first applied to waste management in the late 1960s (Karmperis et al., 2013). These early

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approaches, which primarily focused on individual functional elements, such as collection routes or facility locations (Tanskanen, 2000), were followed during the 1980s by studies assessing entire waste management systems. Computer-aided decision support began in the 1980s (Banar et al., 2009). Regarding the economic impacts of waste services, the first study dates back to 1965 (Hirsch, 1965), with a rapid development and increasing number of publications peaking between 2000 and 2010 (Simões and Marques, 2012).

At present, many published assessment methods for waste management systems are quite advanced and sophisticated because waste management is considered a strategic sector of public service (Coelho et al., 2012). The high goal to provide sustainability as a balance between society, economy, and ecology requires an integrated approach. Hence, for an evaluation of the many effects of waste management systems, it is necessary to consider all of the processes involved (Diaz and Warith, 2006). An assessment method as discussed in this review should be understood as a cornerstone within such a decision framework. The method should be goal oriented and provide an overview of the advantages and disadvantages of different options, while being objective, transparent, and comprehensible.

Aim and scope of this article

The objective of this article is to support decision makers when choosing assessment methods for waste management. Commonly used assessment methods are reviewed and categorised, and conclusions are drawn that consider the selection of methods for decision support. For this purpose, 151 studies have been examined considering their goals, methodologies, systems investigated, and results regarding economic, environmental, and social issues. Similar reviews have been previously performed. These reviews usually included studies concerning municipal solid waste (MSW) or single assessment methods (Beigl et al., 2008, Cleary, 2009, Morrissey and Browne, 2004). Other overviews concerning assessment methods have compared different assessment methods and discussed their weaknesses and strengths; have looked at the historical development of assessment methods; or have presented a new combined approach (Finnveden and Moberg, 2005; Finnveden et al., 2007; Karmperis et al., 2013; Pires et al., 2011).

This study focuses on stakeholders and decision makers on the one hand, and the research community on the other hand. The purpose is to present a survey of assessment methods, to show their potentials and to provide guidance for the application of, and for future research into, methods for the assessment of waste management systems. In contrast to other reviews, this study focuses less on the assessment methodology itself, but on the actual content of the assessment. The objects of investigations, specific addressees, and goals of the studies are characterised to indicate why and for whom assessments are performed. In addition, we examine the data quality of the studies using the mass balance principle. Finally, key elements within waste management assessment methodologies are addressed to provide suggestions for future developments within the research community.

Materials and methods

The current study is based on a thorough literature search that was composed of articles in journals through September 2013 in the Science Direct database and in specific SAGE Publications journals. The keywords used for the literature search included ‘waste’, ‘assess’, and ‘different assessment methods’ according to the state of the art. Some further studies were identified through the reference list of these articles and Google was used to find special reports or conference proceedings. After a pre-review of the collected articles, 151 studies were selected for this review (Supplementary Table, available online). This database allows a systematic examination of the goals and scope of investigations: How did the investigations assess the impacts of waste management systems on technical, economic, environmental, and social levels? Which system boundaries, waste treatments, waste streams, and compositions were considered? Was there a weighting step included in the assessment, and how and by whom was the weighting performed? Which novelties concerning the assessment method were introduced? The results of the review are categorised and discussed to answer the following questions.

- What were the objectives of the studies?
- Which assessment methods were used?
  - Which software/tools were applied?
  - Were there any novelties with respect to the assessment tool?
- Which scales were observed?
- Which waste streams were considered?
- Which aspects were considered?
  - General goals of waste management.
  - Economic aspects (business economy or national economy).
  - Environmental aspects.
  - Social aspects.
- Were weighting steps performed?
- Did the study contain information concerning the impact of the study?

Rounding and rough categorising were used to simplify the results. Categories with a contribution <5% were grouped under the term ‘others’. Differences to 100% in the figures were caused by rounding errors.

Results and discussion

Overview of different assessment methods, software, and novelties

Table 1 provides an overview of the different assessment methods used in the 151 reviewed studies.

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Table 1. Description of the reviewed assessment methods.

Assessment method	Description
Benchmarking	Benchmarking is a continual comparison of products, services, methods, or processes to identify performance gaps, with the goals to learn from the best and to note out possible improvements (Gabler, 2014).
Cost benefit analysis (CBA)	The essential theoretical foundations of CBA are defining benefits as increases in human wellbeing (utility) and costs as reductions in human wellbeing. All benefits are converted to monetary units. The cost component is the other part of the basic CBA equation (Pearce et al., 2006).
Cost effectiveness analysis (CEA)	CEA evaluates alternatives according to both their cost and their effect concerning producing some outcome (Levin and McEwan, 2000). CEA allows the consideration of intangible effects.
Eco-efficiency analysis (Eco-Eff)	Eco-efficiency analysis (Eco-Eff) denotes the ecological optimisation of overall systems while not disregarding economic factors. The Eco-Eff analysis by BASF quantifies the sustainability of products and processes, considering the environmental impacts and economic data concerning a business or national economic level (Saling et al., 2002).
Emergy analysis (EA)	Emergy is the amount of available energy that is used up in transformations, directly and indirectly for a service or product. The EA is an evaluation method that considers both environmental and economic values (Song et al., 2012; Yuan et al., 2011).
Environmental impact assessment (EIA)	EIA is a method that has to be performed before consent is given to a project. Significant effects on the environment by virtue, inter alia, of their nature, size, or location are made subject to a requirement for development consent and for an assessment concerning their effects (Directive 2011/92/EC).
Exergy analysis	The exergy method evaluates the qualitative change from the available energy to the unusable one in the form of work (Hiraki and Akiyama 2009; Szargut, 2005).
Life cycle assessment (LCA)	LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (ISO 2006).
Life cycle costing (LCC)	LCC is an economic analysis method in combination with LCA. This method is a tool for accounting the total costs of a product or service over a long life span (Carlsson Reich, 2005; Langdon, 2007).
Multi-criteria-decision-making (MCDM)	MCDM is a decision-making tool that facilitates choosing the best alternative among several alternatives. This tool evaluates a problem by comparing and ranking different options and by evaluating their consequences according to the criteria established (Hermann et al., 2007; Hung et al., 2007; Karmperis et al., 2013).
Risk assessment (RA)	RA is an integral part of the overall organisation's performance assessment and measurement system for departments and for individuals. The goal is to provide a comprehensive, fully defined, and fully accepted accountability for risks (ISO 2009).
Statistical entropy analysis	The statistical entropy analysis is a method that quantifies the power of a system to concentrate or to dilute substances (Brunner and Rechberger, 2004; Rechberger and Brunner, 2002).
Strategic environmental assessment (SEA)	SEA is a method to provide a high level of protection to the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and programmes, with an aim to promote sustainable development by ensuring that an environmental assessment of certain plans and programmes, which are likely to have significant effects on the environment, is performed (Directive 2001/42/EC).

Most of the reviewed studies used existing assessment methods and models. However, new approaches have also been developed to evaluate waste management systems, and often, existing assessment methods have been modified or supplemented. Figure 1 shows the percentage distribution of the assessment methods used in the reviewed articles. Approximately 41% of the 151 reviewed studies have used life cycle assessment (LCA) as a method to evaluate waste management systems. Particularly since the 1990s, the interest in LCA has rapidly grown (Finnveden et al., 2009), and in the recent years, it has become popular to analyse MSW management systems with LCAs (Cleary, 2009). Since 1990, attempts have been made to develop and to standardise the LCA methodology (Burgess and Brennan, 2001), and since the publication of the guidelines for LCA (ISO 2006), an international standard has been defined. Commonly used software tools for LCAs include EASEWASTE and SimaPro software programs. Approximately one-third of the reviewed studies using LCAs performed their evaluation with one of these software programs. One of the reviewed studies linked economic information to a LCA in a so-called life cycle cost (LCC) assessment. To evaluate the positive and negative effects of waste management scenarios, cost-benefit analysis (CBA) was used by 6% of the reviewed articles. For assessing the socio-economic implications of waste to energy (WtE), a social CBA was developed on one study (Jamasb and Nepal, 2010). Approximately 14% of the reviewed studies were performed as benchmark studies. Benchmarking is commonly used to compare countries, regions, or cities to identify the best

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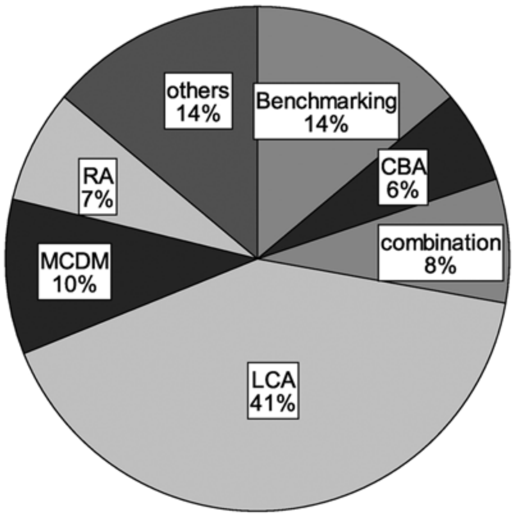

Figure 1. Assessment methods in the reviewed studies (n = 151).
CBA: cost-benefit analysis; LCA: life cycle assessment; MCDM: multi-criteria-decision-making; RA: risk assessment.

practice, with the aim of learning from each other. Approximately one-tenth of the reviewed articles assessed waste-related topics with multi-criteria-decision-making (MCDM). Commonly used MCDM software tools include analytic hierarchy process, ELECTRE, and PROMETHEE (Achillas et al., 2013). In the reviewed studies that were performed with MCDM, one-quarter was performed using ELECTRE. Approximately 7% of the researchers adopted risk assessment (RA) for the assessment, primarily for the evaluation of local environmental impacts through waste treatment plants.

The analysis of the assessment methods LCA, MCDM, and CBA by Karmperis et al. (2013) shows that all frameworks have shortcomings. The main weaknesses of a LCA are the assumptions required by the researchers. The required number of assumption within a LCA is large and leads to diverging results (Heijungs and Guinée, 2007). Moreover, a review concerning a LCA of sewage sludge by Yoshida et al. (2013) shows that the different assumptions made (e.g. energy and chemical consumption) vary greatly between the LCA studies. The results of MCDM are difficult to interpret because the choice of the criteria and the weighting are highly subjective. Additionally, using a CBA method, the valuing of intangible goods is not possible and the selection of the discount rate is a critical issue (Karmperis et al., 2013). Cost effectiveness analysis (CEA) can circumvent some of these disadvantages. Future methods and models should combine different methods to maximise their strengths and/or to minimise their weaknesses. Combinations of different assessment methods have been used to provide a more comprehensive picture (Finnveden and Moberg, 2005). In the reviewed studies for example, the Cumulative Energy Demand and the Centrum voor Milieukunde Leiden CML method (LCA impact assessment) have been combined for the evaluation of energetic and environmental impacts (Giugliano et al., 2011). Furthermore, combinations of LCA, RA, emergy analysis (EA), or the joint application of geographic information system (GIS) to MCDM have been performed (Benetto et al., 2007; Gómez-Delgado and Tarantola, 2006; Song et al., 2012). Overall, 12 studies have used a combined approach to investigate waste management-related topics. Some of the reviewed studies report novelties according to the assessment methods. On-going methods and supplementary software tools have been modified to enhance the quality of the methods and of the results. Different assessment methods have been modified, such as the MCDM methodology TOPSIS for the selection of appropriate disposal methods (Ekmekçioğlu et al., 2010) or the MCDM software ELECTRE III to help decision makers more objectively negotiate alternatives that rank close to each other (El Hanandeh and El-Zein, 2010). In few assessments, new indices have been developed or used for the first time in the context of waste management. Examples are the *Cleaner Treatment Index*, which aggregates several indicators based on operational parameters to assess the environmental performance of waste treatment technologies (Coelho et al., 2012); the *Net Recovery Index* to assess the capacity of a MSW management system for converting waste into resources; the *Transport Intensity Index* with the aim of minimising transport requirements for managing specific waste flows (Font Vivanco et al., 2012); or the *Resource Conservation Efficiency* to benchmark the ecological sustainability of waste management practices across multiple locations with minimal data (Kaufman et al., 2010).

Aims of the reviewed studies

The general goals of all the reviewed studies were to support stakeholders by (i) noting the current state of waste management systems and/or (ii) naming best waste management options for a specific local situation. Hence, one comprehensive aim of the reviewed studies is the simplification of the complex waste management processes and their environmental, economic, and social impacts to provide a basis for adequate decision making. Although there are many reasons for assessing waste management systems, in this article the reviewed studies are classified into four categories according to their aims.

- 'Scenario-based': an evaluation of different scenarios to find the best scenario for a single project/company or for a whole waste management system.
- 'Comparison-based': a comparison of countries/cities/regions or companies to determine the best in a defined category.
- 'Performance-based': an evaluation of the performance of a single project (e.g. treatment plant) or strategy (waste management system) with the goal to increase efficiency.
- 'goal-based': an evaluation of the current status of a project or strategy concerning provided goals or regulations.

The reviewed studies show that it is common to compare the current situation with different scenarios. Approximately 60% of

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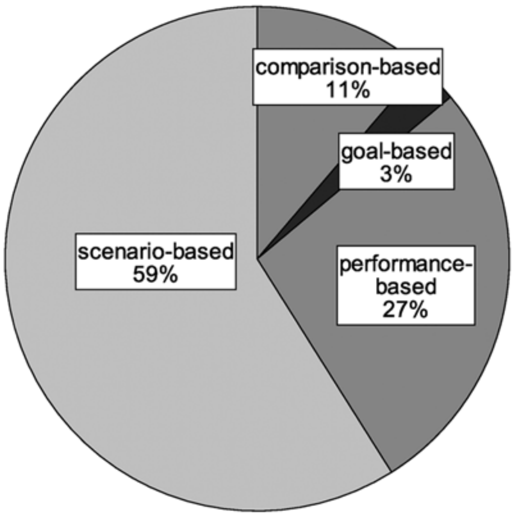

Figure 2. Aims of the reviewed studies (n = 151).

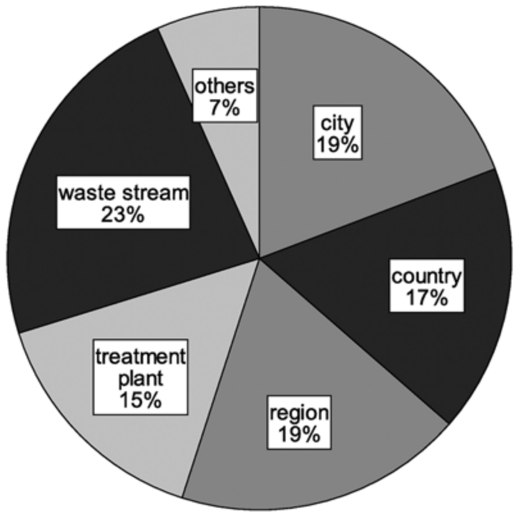

Figure 3. Observed scale in the reviewed studies (n = 151).

the studies were 'scenario-based'. Often, three or four scenarios were compared; however, the range of the considered scenarios in the reviewed studies was from one to 19. One-third of the studies used the 'performance-based' approach, and approximately 10% were 'comparison-based'. Only four studies compared the efficiency of current waste management systems with provided goals or laws (see Figure 2).

As already mentioned, the reviewed studies were performed with the overall goal to support decision makers in developing new laws, to provide the decision makers with a base for decisions concerning current waste management and for future projects, or to note new assessment methods. The target group of the reviewed studies were primarily official institutions. Only a few studies were performed to provide direct support for citizens or to introduce new methods or software tools.

Scale of the reviewed studies

The scale refers to the boundaries and functional unit observed in the reviewed assessments. The scales used in the studies were (i) one unit of a specific waste stream (e.g. 1 tonne organic household waste), (ii) the entire waste input and output of a treatment plant, or (iii) the waste management system of a city, country, or region. In a few cases, household waste or waste generated through the demolition of buildings was investigated.

This review shows that more than half of the studies geographically defined their system boundaries by assessing the waste management of a city, region, or country, and that approximately 25% of the 151 studies investigated one unit of a waste stream. The waste input and output streams of a treatment plant were evaluated in 15% of the reviewed studies (see Figure 3).

Only approximately one-fifth of the reviewed studies used the mass balance principle (Brunner and Rechberger, 2004) to identify the inputs and outputs of the investigated system. More commonly, only the outputs of the systems were considered.

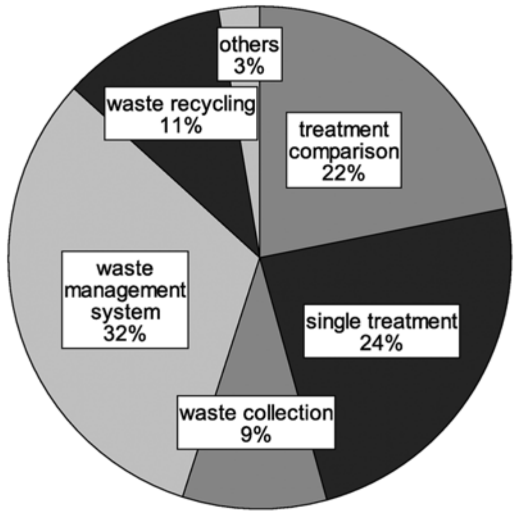

Figure 4. Object of investigation of the reviewed studies (n = 151).

Objects of investigation

Categorising the reviewed articles by their objects of investigation shows that many studies assessed entire waste management systems. The life cycle of a product ends with waste management, which includes the waste management system from waste generation, waste collection, recycling, and treatment to final disposal. Therefore, the efficient planning of waste management systems requires an accounting of complete sets of effects caused by the entire life cycle of waste (Emery et al., 2007). One-quarter of the reviewed works assessed either one treatment plant or compared different treatment options to determine the best available alternative (Figure 4.). In particular, the performances of incinerators or landfills were often the objects of such investigations.

Comparing system boundaries with the object of investigation shows that studies evaluating waste management systems, waste

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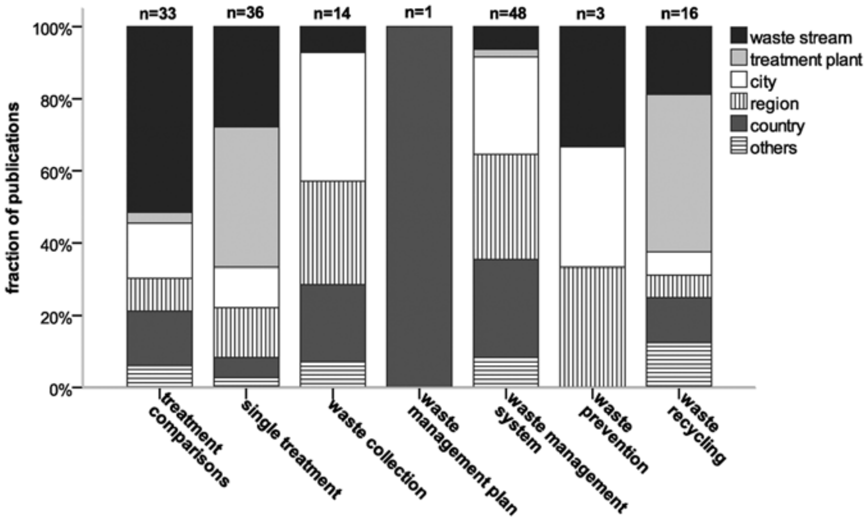

Figure 5. Comparison of the objects of investigation and scales used (n = 151).

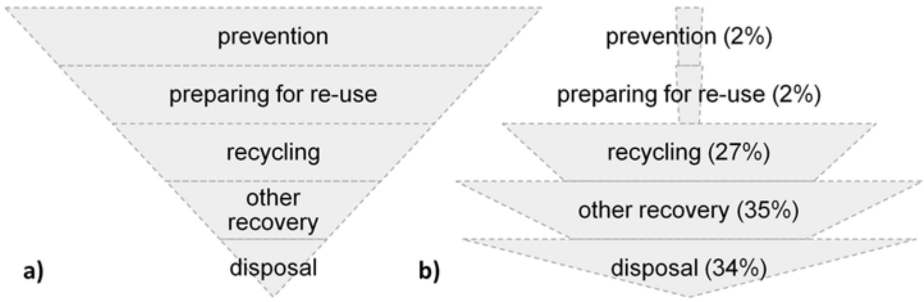

Figure 6. (a) Waste hierarchy of solid waste management (Directive 2008/98/EC). (b) Objects of investigation of the reviewed studies according to the EU waste hierarchy.

collection systems, and waste prevention options often used geographic boundaries (country, region, or city). The reason is that these boundaries most likely coincided with administrative boundaries. The functional unit to compare different treatment options was primarily one unit of a specific waste stream, and the evaluation of single treatment often referred to the inputs and outputs of the investigated plant (Figure 5).

According to the European Union waste hierarchy (Directive 2008/98/EC), waste prevention is ranked as the highest goal in waste management (see Figure 6(a)). The allocation of the reviewed studies to the five steps of the EU waste hierarchy (without considering the categories of waste management system and waste collection) shows that waste prevention is not ranked among the top issues by the waste management assessment community (see Figure 6(b)).

In only 4% of the reviewed studies, the main object of the investigations was waste prevention or re-use; however, approximately 25% assessed waste recycling systems. Most frequently, other recovery methods, such as incineration, with energy recovery or disposal methods, such as landfills, have been the objects of investigations.

The investigated waste stream can be categorised as solid waste, MSW, different waste fractions (mixed), or a single waste fraction (organic, plastic waste, paper waste, aluminium waste, construction and demolition waste (C&D) waste, glass waste, or other single waste streams). Over 50% of the reviewed articles assessed waste management systems considering MSW, and 12% investigated the combined solid waste of a region or the solid waste applied to a specific waste treatment plant (see Figure 7).

Because of the growing production and consumption of electronic products, the question of how to manage e-waste has become important (Song et al., 2012). Approximately 6% of the articles attempted to determine the best e-treatment option. The increasing attention to climate change and the diversion of organic waste away from landfills lead to the fact that 6% of the studies specifically observed organic waste.

Figure 8 shows that benchmarking methods were often used for assessing MSW management. However, benchmarking does not seem common for investigations of single waste streams. Compared with the other assessment methods, LCA, MCDM, and RA were more often performed for assessing single waste streams. Associated with risk management, e-waste was often the topic of investigations. Many RAs were performed in China to evaluate the risks concerning e-waste treatment plants.

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Considered aspects

For a comprehensive assessment of waste management systems or processes, it appears necessary to examine all three aspects associated with the term sustainability: social, economic, and environmental aspects. However, depending on the goal of a study, sometimes only one or two aspects were considered.

Economic aspects are an important factor because money, in combination with available technology, is generally the limiting factor for a sophisticated, properly functioning waste management system. Economic aspects are mentioned on a business (micro-economic) level or on a public (macro-economic) level. In the reviewed articles, on the business level, the investment and operational costs were usually evaluated. Macro-economically, the costs for waste management are labelled as a percentage of the gross domestic product, or the total costs of a waste management system of a region or country are calculated and evaluated. However, many studies did not consider the economic aspects. This lack may be a common reason why different waste management strategies, scenarios, and plans are not implemented.

The purpose of considering environmental aspects in waste management (from waste generation over collection, recycling, and treatment to the final disposal) is to evaluate the impacts on air, soil, and water, as well as on resource consumption (Su et al., 2010). To protect humans, flora, and fauna, it is necessary to know the environmental aspects of a service or a process. Studies using LCA methodology for an assessment often evaluate environmental impacts by examining the following categories: global warming potential; stratospheric ozone depletion; acidification; terrestrial eutrophication; aquatic eutrophication; photochemical ozone formation; human toxicity; and ecotoxicity.

Social sustainability can be classified under three different perspectives (den Boer et al., 2005): social acceptability (the waste management system must be acceptable); social equity (the equitable distribution of waste management system benefits and detriments between citizens); and social function (the social benefit of waste management systems). Public health and safety are important factors within society, with a close link to the economy and to the environment. Social aspects also refer to the employment market, governance, ethics, security, education systems, and to culture (European Commission, 2009).

In this article, to categorise the reviewed studies depending on the economic, environmental, and social impacts, a modified classification of the 'Impact Assessment Guidelines' that was provided by the EC was used (see Table 2). Notably, many evaluated impacts can not only refer to one of the three pillars of sustainability, but also interactions between social, economic, and environmental sustainability are frequent. For example, human health can be associated with the social sustainability, depending on the DALY (disability-adjusted life years), the economic

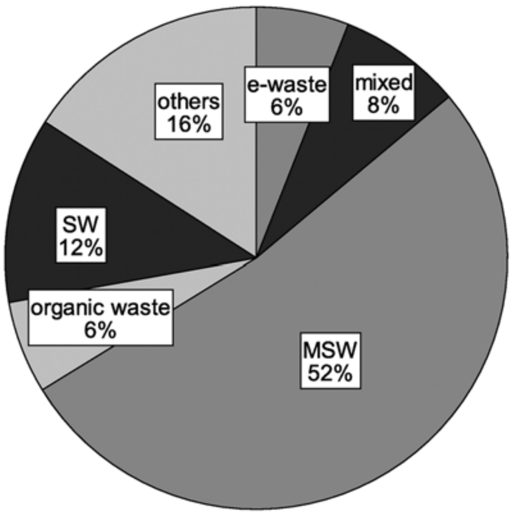

Figure 7. Observed waste streams in the reviewed studies (n = 151).
MSW: municipal solid waste; SW: solid waste.

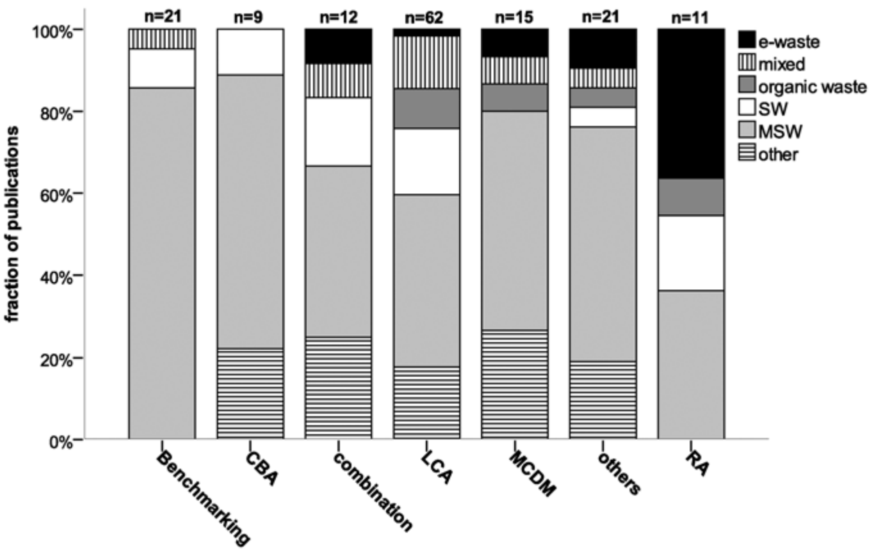

Figure 8. Investigated waste streams as a function of the assessment methods (n = 151).
MSW: municipal solid waste; SW: solid waste.

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Table 2. Economic, environmental, and social impacts of waste management, based on European Commission (2009).

Economic impacts	Environment impacts	Social impacts
– Function of the internal market – Investment costs – Operating costs – Administrative burdens – Public authorities – Property rights innovation and research – Economic effects on consumers and households – Economic effects on industry and business	– Climate – Energy – Air quality – Biodiversity, flora, fauna, and landscapes – Water quality and resources – Soil quality or resources – Land use – Renewable or non-renewable resources – Environmental consequences of firms and consumers – Likelihood or scale of environmental risks – Animal welfare	– Employment and labour markets – Social inclusion and protection of particular groups – Non-discrimination – Individuals, private and family life, personal data – Governance, participation, good administration, access to justice, media, and ethics – Public health and safety – Security – Access to and effects on social protection, health, and educational systems – Culture

sustainability with the future costs of different toxic impacts, and on the environmental sustainability as the cause for future diseases. Particularly as a function of time, environmental aspects can influence the economy and society.

The categorisation of the reviewed articles shows that common environmental impacts were investigated. Approximately 90% of the reviewed studies considered environmental impacts; 45% of the reviewed studies considered economic impacts; and only 19% of the reviewed studies considered social issues. Few studies considered environmental, and/or economic, and/or social aspects. However, only 28 of the 151 reviewed studies analysed the impacts on all three pillars of sustainability. Studies assessing the economic aspects more often considered macroeconomic than micro-economic effects.

A comparison of the different aspects in the reviewed studies with respect to the assessment methods (Figure 9) shows that, in particular, LCA and RA often evaluated a waste management system by only considering the environmental impacts. According to LCA guidelines (ISO 2006), economic and social aspects are typically not considered within a LCA. MCDM and the category 'others' (different methods, e.g. CEA, EA, exergy analysis, strategic environmental assessment (SEA)) appear to be the most complete methods regarding the comprehensive evaluation of social, economic, and environmental aspects.

Weighting

Weighting is defined as converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data before weighting should remain available (ISO 2006). The weighting steps are based on value-choices of the stakeholders, and are not scientifically based (ISO 2006). This lack of a scientific basis is the reason why weighting is prone to criticism (Finnveden et al., 2007). For comparison or for converting different indicators, approximately 50% of the reviewed studies performed a weighting step.

Conclusions and recommendations for the application of assessment methods and for future research

In total, 151 studies have been reviewed to compare goals, methods, object of investigations, considered aspects, and system boundaries. The results of this review show the heterogeneity within the published studies. The results also show that any investigation of waste management systems requires an individual assessment methodology, depending on the goal of the assessment, the object of investigation, system boundaries, and on addressees. For a complete knowledge of a waste management system, an assessment is fundamental (Zurbrügg et al., 2014) for providing reliable results and data for decision making.

Based on the results of this review, the following recommendations are suggested for the future evaluation of waste management systems.

1. Goals are important and must be clearly stated. This concerns two types of goals: (i) First, the *objectives for waste management*, as provided by the legislative framework, policy statement, or regional guideline, must be considered. It is important to focus on these objectives because these objectives can be manifold and even contradictory and because these objectives have a determining influence on the methodology that must be chosen for the evaluation. (ii) Second, the purpose, scope, and the *goals for the assessment* must be clearly defined, considering the addressees and the objectives of waste management stated in (i). It is important to select an assessment method, or, most often, a set of assessment methods, that is capable of addressing all the criteria necessary for characterising the goals established in the first step. To meet these expectations, numerous studies have been published. Table 3 summarises why, and for whom, assessments are performed, and presents the reviewed assessment methods in relation

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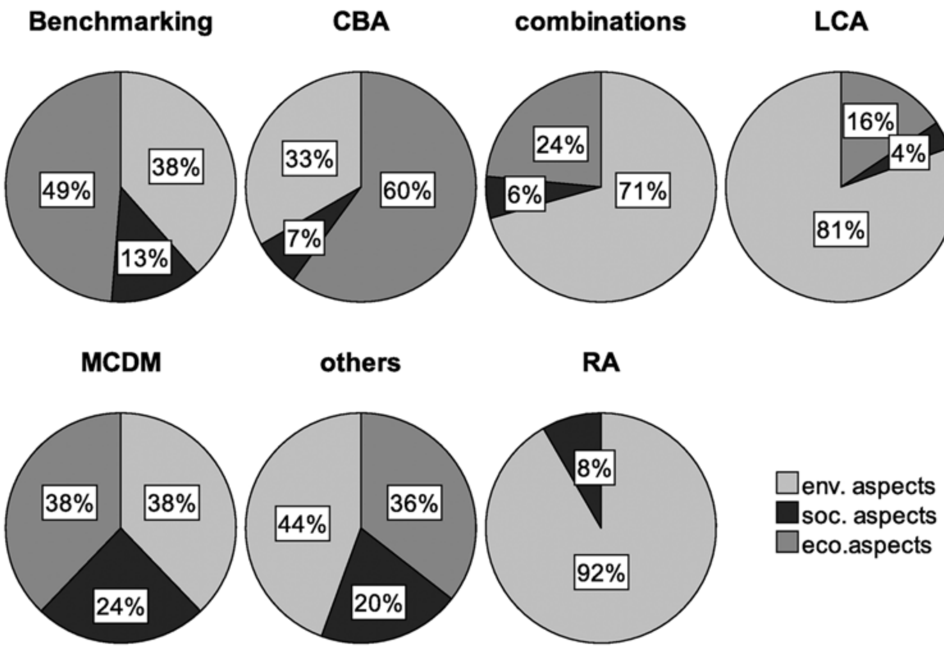

Figure 9. Considered aspects in the reviewed studies with respect to the different assessment methods (n = 151).
CBA: cost-benefit analysis; LCA: life cycle assessment; MCDM: multi-criteria-decision-making; RA: risk assessment.

to the receivers of the studies, objects of the investigation, and aspects considered.

If only a part of the goals are to be considered, for example environmental protection such as in a LCA, this consideration must be clearly stated to allow for the comparison of different studies. Regarding goals of waste management, it is recommended to choose comprehensive social, environmental, and economic goals that meet the requirements of sustainability. In specific terms, this recommendation suggests affordable and acceptable waste management of proven reliability that protects humans and the environment, conserves resources, and minimises after-care. According to the purpose of the assessment, it may be necessary to address additional issues, such as the value of previous investments and of existing waste treatment components. It is evident that such a comprehensive evaluation is a demanding task requiring reliable methodologies, sound data, and experienced evaluators.

2. Often, waste management systems are assessed by evaluating the impacts caused by selected single outputs, for example emissions. A comprehensive evaluation must consider all direct and indirect impacts. Waste management should be perceived as a ‘throughput economy’, with inputs from the market and with outputs to the market and to the environment (Figure 10).

Taking this view, the complexity of the economic system is apparent. It becomes evident that sophisticated assessment methods are required. Only such methods are able to evaluate the economic, ecological, and social effects of a waste management system. The choice of the starting point and end point of an assessment can have a decisive impact on the results. The scope and system boundaries have to be selected carefully, because changing the boundaries can have a key influence on the results. Particularly in the case of recycling, it is important to consider not only emissions but also all the risks. The fate of hazardous substances that are not released to the environment, but that are retained in the recycling goods, must be followed as well. If not, then an ‘after-care-free’ waste management cannot be established because these hazardous substances will have to be managed after x cycles (Velis and Brunner, 2013). Hence, when recycling processes are assessed, waste composition, process characteristics, emissions, and recycling product qualities must be known. In summary, inputs must be linked with outputs.

3. The application of the mass balance principle is crucial for an impartial, comprehensible evaluation. As stated before, assessment methods can be divided into two groups: methods that are based on the mass balance principle and other methods that do not require this strict precondition. The establishment mass balances of the total waste management system is recommended as a base for any subsequent evaluation step. Such mass balances on the level of goods and substances represent required and highly useful tools for evaluation because these tools allow the cross-checking plausibility of available information (Brunner and Rechberger, 2004). When evaluating waste management systems, data availability and data quality are often limiting steps. Wastes contain many products that are made from complex mixtures of elements and that are composed of countless substances, yielding highly heterogeneous combinations. In fact, wastes may contain everything because their content cannot be completely controlled. Thus, to analyse waste inputs over longer periods for real situations

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Table 3. Overview of the 151 reviewed studies and their classifications (percentages in bold indicate the most commonly used assessment method in relation to the criteria for each column).

Methods	Receiver									
	Government	Government/ citizens	Government/ operators	Government/ researchers	Citizens	Municipalities	Operators	Operators/ researchers	Researchers	Not named
Benchmarking	**76%**	5%	0%	0%	0%	**5%**	5%	0%	0%	10%
CBA	44%	11%	22%	0%	**11%**	0%	11%	0%	0%	0%
combinations	42%	0%	8%	8%	0%	0%	**17%**	0%	**25%**	0%
LCA	56%	0%	5%	6%	0%	0%	5%	2%	18%	8%
MCDM	40%	7%	7%	**27%**	0%	0%	7%	0%	13%	0%
RA	9%	**27%**	**27%**	18%	0%	0%	0%	**9%**	0%	9%
others	52%	5%	5%	5%	0%	0%	14%	5%	14%	0%
Methods	**Object of investigation**									
	Different treatments	Treatment	Waste collection	Waste management plan	Waste management system	Waste prevention	Waste recycling			
Benchmarking	5%	10%	29%	0%	**48%**	5%	5%			
CBA	0%	44%	**33%**	0%	11%	0%	11%			
Combinations	17%	33%	0%	0%	33%	0%	17%			
LCA	**39%**	23%	6%	0%	24%	2%	6%			
MCDM	20%	7%	7%	0%	47%	**7%**	13%			
RA	0%	**64%**	0%	0%	0%	0%	**36%**			
Others	14%	19%	0%	**5%**	52%	0%	10%			
Methods	**Aspects**									
	Eco. aspects (macro)	Eco. aspects (micro)	Env. aspects	Soc. aspects						
Benchmarking	**86%**	5%	71%	24%						
CBA	67%	**33%**	56%	11%						
Combinations	17%	17%	**100%**	8%						
LCA	15%	5%	**100%**	5%						
MCDM	60%	**33%**	93%	**60%**						
RA	0%	0%	**100%**	9%						
Others	57%	19%	95%	43%						

CBA: cost-benefit analysis; LCA: life cycle assessment; MCDM: multi-criteria-decision-making; RA: risk assessment.

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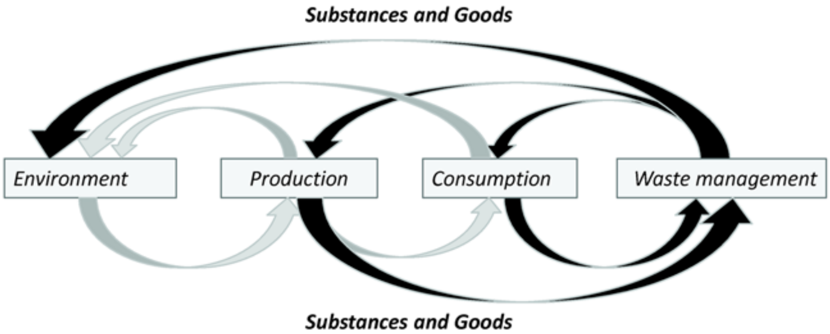

Figure 10. Waste management as a 'throughput economy'.

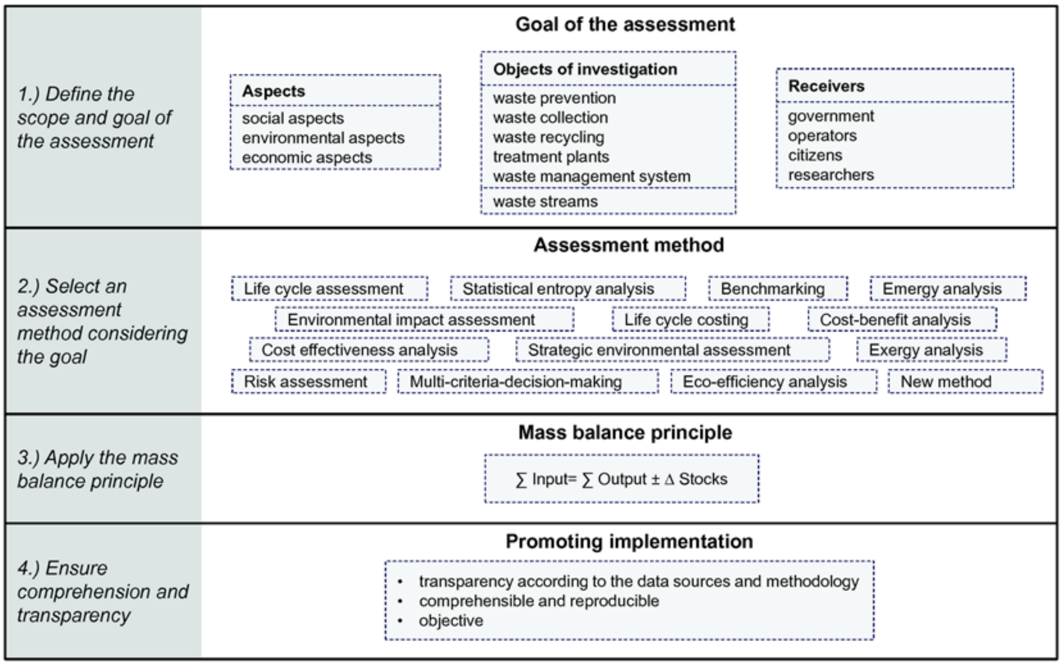

Figure 11. Key elements of a waste management assessment methodology.

is a non-trivial, time-consuming, and costly endeavour. A more effective means is output-oriented analysis. If inputs and outputs of waste treatment systems are monitored and balanced, then the law of conservation of matter allows the comparison of information concerning material flows from the input side with the output side. Hence, data can be cross-checked, deviations can be detected, and additional investigations can be performed, if necessary. The products of waste treatment are generally more homogenous and easier to analyse, and the accuracy of waste composition data calculated from the products of waste treatment is usually higher (Brunner and Ernst, 1986). This advantage becomes even more pronounced when, in addition to the level of goods, the level of substances is considered. Mass balances on the level of goods ensure that the total input (wastes) and total output (products, residues, emissions) match. Substance balances go one step further; these balances ensure that inputs and outputs correspond on the level of individual elements or chemical compounds (e.g. carbon or CO_2). Thus, if an array of valuable and hazardous substances is balanced together with the flow of inputs and outputs of goods, then the resulting information serves as a reliable and comprehensive base for subsequent evaluation steps. Hence, a mass balance approach based on a rigid input–output analysis of the entire waste management system should be taken. Well suited for this purpose is material flow analysis, a systematic assessment that considers all processes, flows, and stocks in a defined system, delivering a complete and consistent set of information concerning a waste management system (Brunner and Rechberger, 2004).

4. Assessments must be reproducible, comprehensible, and transparent regarding methodology and data. Methods based on mass balances must be favoured and applied that promote these characteristics. Good, impartial, and reliable data sources with known uncertainty are crucial. Objectivity, transparency, and confirmability are not only necessary during the assessment step; these qualities are also of key importance when the results are presented, for example policy decisions.

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Politicians, stakeholders, and decision makers generally require results that these individuals can grasp with little effort. If informative and convincing text, figures, and tables are produced in a transparent and reproducible manner, then the results of the assessment are likely to have a larger impact.

Figure 11 summarises the conclusions of this review. As a framework for waste management decisions, assessment methods depict the strengths and weaknesses of different management alternatives. An approach based on mass balances and on a goal-oriented evaluation of impacts is a powerful means to ensure comprehension, objectivity, rigidity, and transparency. Applying this approach for assessing waste management systems will result in better and more comprehensive support for decision makers.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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