Chapter 35
LCA of Solid Waste Management Systems

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Abstract The chapter explores the application of LCA to solid waste management systems through the review of published studies on the subject. The environmental implications of choices involved in the modelling setup of waste management systems are increasingly in the spotlight, due to public health concerns and new legislation addressing the impacts from managing our waste. The application of LCA to solid waste management systems, sometimes called “waste LCA”, is distinctive in that system boundaries are rigorously defined to exclude all life cycle stages except from the end-of-life. Moreover, specific methodological challenges arise when investigating waste systems, such as the allocation of impacts and the consideration of long-term emissions. The complexity of waste LCAs is mainly derived from the variability of the object under study (waste) which is made of different materials that may require different treatments. This chapter attempts to address these challenges by identifying common misconceptions and by providing methodological guidance for alleviating the associated uncertainty. Readers are also provided with the list of studies reviewed and key sources for reference to implement LCA on solid waste systems.

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35.1 Introduction

Over the past century, both material use and waste generation have been constantly increasing in quantity and complexity at an unsustainable pace. Globally, waste generation from all sources amounts to around 17 billion tonnes, and is expected to reach 27 billion tonnes by 2050 (Karak et al. 2012). Municipal waste generation has also been increasing and, in Europe, only a few examples exist of decoupling municipal waste generation from economic growth, although recently efforts towards waste prevention are undertaken (EEA 2014). Currently, it is estimated that about 1.3 billion tonnes of municipal solid waste is generated worldwide and trends show that this number will increase in the future due to population increase, urbanisation and socioeconomic development of low-income populations (Hoornweg and Bhada-Tata 2012).

The organised and systematic collection and central treatment of waste originally begun for reasons pertaining to public health and safety, e.g. for combating diseases or reducing odours in public space. Only in recent years has waste been associated with environmental concerns, such as climate change, toxicity to humans and ecosystems or resource depletion. The links between waste management activities and emissions that cause specific environmental impacts have now been proven, e.g.: methane emissions from landfills contribute to climate change, halocarbons in discarded cooling systems or in-use foams contribute to stratospheric ozone depletion, while insufficient or inefficient recycling leads to increased resource depletion.

In light of these environmental concerns, pieces of legislation around the world have attempted to regulate waste management activities and to promote more sustainable systems for waste handling (e.g. Directive 2008/98/EC). The regulations may address technical issues, such as quality standards for recyclables or management issues, such as the promotion of recycling and the reduction of landfilling. In recent years, the role of waste as a pool for material resources extraction has been acknowledged and waste is now more and more viewed as a valuable resource instead of unwanted materials. Along these lines, new legislation and initiatives attempt to integrate waste management into a new vision of a circular economy, with increased quantity and quality of recycling.

In order to conform with legislation, but also to tackle significant environmental considerations, and motivated by issues around the effectiveness and cost of waste treatment, public authorities have started designing integrated management systems that comprehensively address waste generation and that are differentiated according to waste source or waste material (fraction). Although, there are relatively few options to consider regarding waste treatment (the three main ones being recycling—or biological treatment for organic waste, incineration and landfilling), their combinations for each waste type (defined by source of waste) and waste fraction are numerous. Therefore, the complexity of integrated waste management systems has become significant, highlighting the need to adopt systems approaches.

It is thus necessary to use appropriate tools that address activities related to waste management in a systematic and comprehensive manner. LCA can credibly assess the full environmental consequences of waste management, in particular accounting for the interlinks between the waste sector and other sectors of the economy. For example, the energy produced in an incineration plant or processed scrap metals feed respectively into the energy and metal manufacturing sectors. Life cycle thinking helps map all exchanges with other sectors and estimate environmental impacts accurately.

LCA applied to waste management systems is often termed “waste LCA” as it includes only the End-of-Life phase of a product. Waste LCAs are mostly of a comparative nature (e.g. assessing different treatment options for a material or a waste type) and thus, the previous life cycle stages of a material/product in question can be omitted. This is also called the “zero-burden assumption” (Ekval et al. 2007). In this respect, waste LCAs use different system boundaries assumptions than product LCAs.

Another particularity of waste LCAs is that waste treatment in many cases happens locally, close to the waste source. This fact facilitates the collection of site-specific data and thus increases the geographical resolution of the assessment.

35.1.1 Definition and Scope

A straightforward and descriptive definition of waste is as follows:

“Waste is a left-over, a redundant product or material of no or marginal value for the owner and which the owner wants to discard” (Christensen 2011).

In this chapter, only management of solid waste is addressed. Although, several definitions of solid waste exist, it is defined here as waste, which is neither water (wastewater) nor airborne (flue gases) (Christensen 2011). For application of LCA to wastewater management systems, see Chap. 34.

Towards their end-of-life, most goods and commodities eventually become discarded and typically enter solid waste management systems. The waste product thus goes through a number of activities, which can be divided in four main phases: (1) generation, (2) collection and transport, (3) treatment, and (4) recycling, utilisation or landfilling, illustrated in Fig. 35.1 (Christensen 2011).

Within the domain of waste management, the primary use of LCA is to inform about the environmentally preferable option when decision-making or policy-making communities evaluate different alternatives of solid waste management in a specific region. For instance when assessing the impact of integrating recycling in an existing municipal waste management system based on landfilling and incineration. The applications of LCA encompassed in this chapter are therefore service-oriented, focusing on assessments of processes, technologies and systems handling solid waste, and do not consider upstream activities prior to waste generation. The uses of specific types of waste as feedstock for manufacturing products are only discussed when describing the environmental offsets from

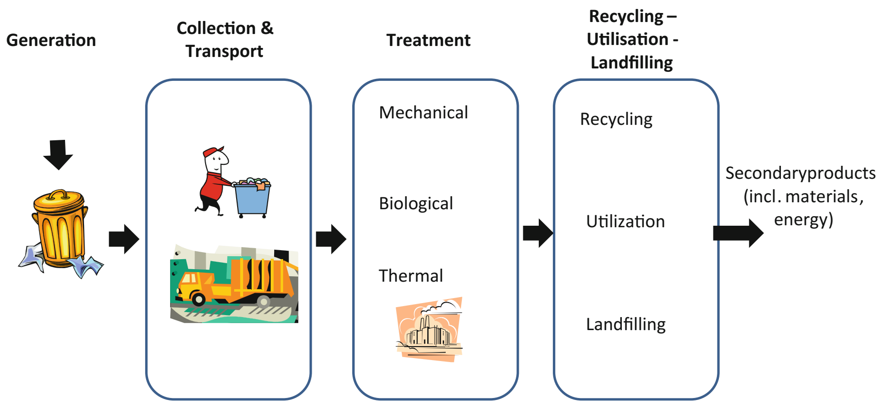

Fig. 35.1 The four phases of solid waste management systems (based on Christensen 2011)

material recycling and energy recovery, which can be credited to the assessed waste management systems (see Sect. 8.6.1).

35.1.2 Solid Waste Management Technologies and Practices

The technologies and practices involved in a solid waste management system can be arranged into distinct system stages.

The *collection and transport* stages refer to the collection of waste from its source of generation, which may include a large number of fractions (e.g. households) or fewer (e.g. industrial waste) depending on the waste type. Waste is then transported to central facilities for processing and/or treatment. The collection of waste may take place either as mixed waste or by targeting specific fractions that are separated at source (e.g. paper and cardboard destined to recycling). The type of collection system usually depends on the further treatment, e.g. for recycling waste is usually separated at the source in order to increase the homogeneity of the collected material.

The *treatment* stage refers to the processing of waste in order to modify its physical or chemical properties. Physical treatment may involve shredding and compacting of waste in order to reduce its volume. On the other hand, mechanical and biological treatment (MBT) facilities and thermal plants (such as incineration) mainly affect the chemical properties of waste, aiming at reducing its volume and environmental hazardousness.

The *Recycling-Utilisation-Landfilling* stage includes all final treatment options that follow the waste processing stage. The state and composition of waste determines the suitability of each of the alternative final options. Homogenous materials are suitable for recycling or utilisation (e.g. composting of organic waste), while

Fig. 35.2 Waste hierarchy indicating a scale of environmental preference for the five main treatment alternatives (EU-JRC 2011)

mixed waste usually ends up in landfills. This stage includes a large variety of technologies for recycling waste, composting (central composting or anaerobic digestion) and landfilling (engineered landfills, collection of landfill gas and leachate).

The selection of a treatment technology (but also the design of an integrated waste management system in general) has direct implications for the environmental impacts caused. Since 1980s many countries around the world have established a waste hierarchy to prevent or limit the impacts of waste management operations on the natural resources, ecosystems and human health. The hierarchy (see Fig. 35.2) has been included in the EU legislation as a legally binding framework for designing or improving a waste management system (see Directive 2008/98/EC or the EU Waste Framework Directive). The hierarchy is based on a "rule of thumb" regarding the environmental ranking of waste treatment options. Deviations from the hierarchy, according to the legislation are accepted if justified by means of appropriate tools such as LCA.

Waste prevention is mentioned as the first priority in the waste hierarchy. The assessment of prevention in LCA terms is fundamentally different compared to the other steps of the hierarchy as it involves upstream processes of a waste material, thus extending the system boundaries.

35.1.3 Main Environmental Concerns

The recent shift in the perception of waste as a resource is reflected in the waste hierarchy. Re-use and recycling are the highest ranking treatment options. The ambition of the legislators is to integrate waste management in a circular economy structure, where waste activities deliver recovered resources and close loops in material cycles. The reduction of the depletion of natural resources, such as fossil fuels, metals, as well as nitrogen and phosphorus is, therefore, a priority for waste management operations.

The main environmental concerns related to waste management, besides resource efficiency, are:

- Climate change and the related energy security issue. Greenhouse gases are emitted from various processes in waste management such as transport or landfilling. A major opportunity for climate change mitigation lies in the avoided emissions through waste materials recycling in a system expansion approach (see Sect. 8.6.1). Climate benefits also arise through waste incineration, where electricity and/or heat is produced locally, substituting other (usually fossil) sources of energy.
- Toxic emissions (to ecosystems and to humans) related to (1) processing waste (e.g. incineration) and (2) the eventual disposal of waste (e.g. in landfills). Toxic emissions also have a temporal aspect, since they may be released at a very slow rate (e.g. from landfills) and create problems at a much later time than when the waste deposition takes place.

Different impacts are related to different waste technologies:

- *Landfilling*: leachate created by water infiltrating the waste mass and not collected may pollute the surrounding soil and groundwater with organic and inorganic (metals) pollutants. Landfill gas created by the anaerobic degradation of organic matter contains methane, a strong greenhouse gas.
- *Incineration*: airborne emissions can affect local ecosystems. CO_2 is emitted from the incineration of carbon (e.g. fossil carbon in waste plastics). Bottom ash contains significant concentrations of toxic heavy metals that can potentially leach after its deposition. Benefits from incineration depend strongly on the local energy mix, substituted by the energy delivered by incineration.
- *Recycling*: recycling operations are linked mainly to energy use for processing the waste and chemicals used for recovery operations (e.g. de-inking of paper).

The complexity and variety of environmental issues arising from waste management calls for a comprehensive approach such as LCA that addresses all potential environmental impacts (e.g. JRC 2011).

35.2 LCA Applied to Solid Waste Management Systems (SWMS)

LCA is increasingly used to assess solid waste management systems. Two comprehensive review articles were published in 2014 on how LCA is applied on waste systems and which issues require special attention due to particularities in the field of waste LCA:

1. Laurent A, Bakas I, Clavreul J, Bernstad A, Niero M, Gentil E, Hauschild MZ, Christensen TH (2014) Review of LCA studies of solid waste management systems—Part I: Lessons learned and perspectives. Waste Management 34 (2014) 573–588

2. Laurent A, Clavreul J, Bernstad A, Bakas I, Niero M, Gentil E, Christensen TH, Hauschild MZ (2014) Review of LCA studies of solid waste management systems—Part II: Methodological guidance for a better practice. Waste Management 34 (2014) 589–606

The review and its results provide a useful background for describing the operational aspects of LCA applied to solid waste management systems. The authors analysed a wide range of peer-reviewed scientific articles and reports for their methodological approach to the LCA and contrasted it with the guidelines of the ILCD Handbook (JRC 2011). Key findings of the review are presented in this section, but the reader is referred to the original papers for a more in-depth analysis.

35.2.1 Review Process and Focus Areas

The selection of the studies was performed by choosing studies in English, peer-reviewed and referring to solid waste, excluding sewage sludge. The results of the review were summarised into a table, a version of which is presented in Table 35.3. The original version of the table included all elements of the review, namely:

1. References/sources
2. Type of LCA studies (public report, scientific article…)
3. Standard compliance (e.g. None, ISO, ILCD, …)
4. Goals (intended use/users of study)
5. Context situation (situation A, B, C1, C2)
6. Object(s) of study considered/compared
7. Type of waste (e.g. only organic waste included in study) (goal/scope)
8. Defined functional unit
9. System boundaries: Included/Excluded processes; included phases within the MSW based on intro definition (e.g. collection, incineration…).
10. Impact coverage (e.g. GW only)
11. Geographical coverage
12. Time scope (for validity of LCA results)
13. Date(s) of the collected primary (specific) data and secondary data (database) (to identify data representativeness in time, e.g. old/up-to-date)
14. Handling of multifunctional processes: approaches (e.g. allocation or syst. expansion) and type of data used to solve them (e.g. marginal/average data)
15. LCA software/Databases used for secondary data
16. LCIA method used
17. Use of normalisation and/or weighting (incl. method description for weighting if any)
18. Use of sensitivity analysis: what key parameters were identified and changed?

19. Main findings (e.g. significant impacts, comparative performances of 2 alternatives) ⇒ also in relation to goals is possible
20. Identified method shortcomings (*incl. "solutions" or "actions taken" for each identified problem*)
21. Identified modelling shortcomings (*incl. "solutions" or "actions taken" for each identified problem*)
22. Identified data uncertainties (e.g. which data are difficult to collect…) (*incl. "solutions" or "actions taken" for each identified problem*)

Table 35.3 in "Appendix" only includes some descriptive elements of the review, in order to inform about the external characteristics and variations of the reviewed studies. The more elaborate LCA elements of the review are included in Sects. 35.2.2–35.2.6 and 35.3. In these subsequent sections, the most important review findings are listed and methodological considerations are analysed in order to outline how a credible LCA should be applied on solid waste systems.

The majority of the studies reviewed (around 94%) were scientific articles published in peer-reviewed journals. Most of the studies claimed compliance with the ISO standards, namely that the methodology proposed by ISO was followed by the studies. In fact, many studies did not actually comply with the ISO provisions, despite their claim to do so. The review revealed that only about one out of five studies actually complied with the ISO standards. This is because of a number of elements (or combinations of elements) missing that are essential in the ISO standards provisions. In the following sections, these omissions that lead to deviations from the standards are described more in detail.

35.2.2 Goal

According to the ISO standards, the goal definition refers to the intended uses of the LCA case study and its potential users (ISO 2006). Moreover, the ILCD Handbook, launched by EU's Joint Research Centre, specifies the definition even further into six aspects, namely the intended applications, limitations in using the results, drivers for performing the study, target audience, disclosure to the public and the commissioner of the study (EC 2010a, b) (see also Chap. 7).

Since the majority of the studies reviewed come from scientific journals, they are rarely commissioned directly by an entity intending to use the results for decision support (some articles are based on larger reports that might be more complete and support decisions). This means that the goal definition is often out of focus for the study authors, which do not refer to potential users as the ISO standards require. Many of the studies only describe the intended use of the study, while many others do not have a specific purpose except for analysing methodological aspects of waste LCAs or tackling specific issues. Omitting the adequate description of the goal has a profound effect on the interpretation of the studies by the readers. The absence of context when considering the results might lead to overlooking the weaknesses of the study (such as the inclusion of only a small part of impact categories) or unjustified generalisations (e.g. generalising the environmental superiority of a treatment option over another when the results of the study refer to specific local conditions). These identified shortcomings might also apply to LCA studies from other technology fields published as scientific articles.

Another consolidated reference to the intended use of the study and the size of the consequences of the study's results is the decision context situation. The ILCD Handbook describes four cases of decision contexts: A (micro-level decision support), B (meso/macro-level decision support), C1 and C2 (accounting with no decision support) (see also Sect. 7.4). Most of the reviewed studies belong to situation B, followed by A. This was expected as normally the investigation of waste management systems happens on a larger scale (national, regional or municipal geographical units). Situation A refers to studies mainly assessing specific technologies or comparing them to others. However, although the classification of the study into a decision context situation helps put the results in perspective, none of the reviewed studies explicitly referred to a context situation.

35.2.3 Scope Definition

The *object* of the reviewed studies varies greatly among the studies. Different waste systems or parts of systems were assessed, while referring to various types of waste. Figure 35.3 shows the amount of studies investigating each distinct aspect of a solid waste management system. The traditional treatment options, as well as collection and transport feature as the most popular topics for investigation, while emerging technologies such as thermal and some forms of biological treatment are starting to gather attention. Due to the difficulty in framing LCAs on waste prevention in appropriate system boundaries or the lack of focus on prevention by decision-makers, only two studies were found that deal with this topic.

The *functional unit* in waste LCAs is expressed mainly according to four types: (1) unitary, (2) generation-based, (3) input-based and (4) output-based (see Box 35.1. with examples).

Box 35.1. Examples of Functional Units Used in the Reviewed Studies

1. Unitary: "management of 1 tonne of municipal solid waste"
2. Generation-based: "Management of the waste generated in Copenhagen municipality"
3. Input-based: "100 tonnes of waste entering a waste incineration plant"
4. Output-based: "Production of 500 kWh from a dedicated incineration plant for industrial waste"

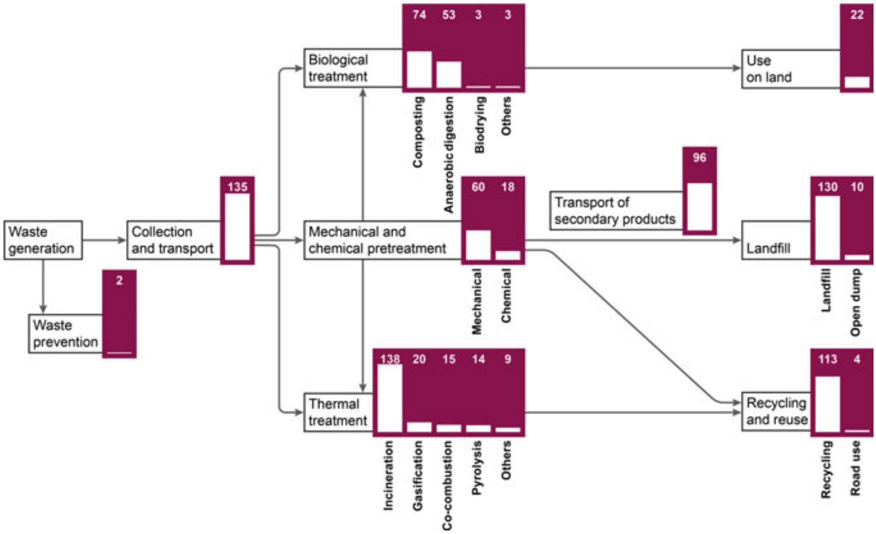

Fig. 35.3 Waste management technologies assessed in the studies. Many studies investigate more than one aspect of the system

Although, the definition of a functional unit is relatively straightforward, in many cases LCA practitioners neglect to specify an adequate functional unit, as shown in Fig. 35.4. It also seems that a unitary functional unit is by far preferred in the reviewed studies reflecting a more theoretical or methodological goal for the LCA or potentially a confusion of the functional unit with the reference flow of the system. The functional unit refers to a quantified description of the primary function of the system under study, while the reference flow refers to the physical flow required for the system to fulfil its function (see also Sect. 8.4). The use of a reference flow in the cases, where the functional unit is defined as unitary neglects the appropriate description of the functional unit in several aspects, such as the composition of the waste that is treated.

As already mentioned, the *system boundaries* in waste LCAs are set in order to include only the end-of-life stage of the products' life cycles. This is justified as waste LCAs are normally of comparative nature and it is therefore assumed that for the waste in question in each case, the previous life cycle stages are identical for the systems compared and therefore can be omitted.

Similar to all types of LCAs, a central issue in defining system boundaries is the inclusion of capital goods, i.e. the construction and use of infrastructure, plant facilities and equipment used in the assessed system. 62% of the studies reviewed did not mention the capital goods at all, 12% included them and 26% of the studies excluded them with justification.

Collection and transport processes are also occasionally excluded from the system boundaries, due to their minor contribution to the overall impact categories'

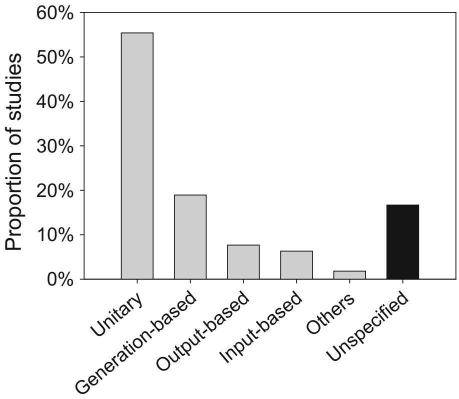

Fig. 35.4 Proportions of studies for each class of functional unit. A number of studies are classified into more than one category, including studies, for which the functional unit was only implicitly mentioned

results. 16% of studies chose to exclude such processes due to reasons such as their lack of relevance or identical contribution to all scenarios assessed.

Another set of processes that is often excluded from the system boundaries refers to secondary products (i.e. valuable outputs such as digestate from anaerobic digestion) and secondary waste stemming from waste treatment processes (e.g. air pollution control ashes from incineration). Secondary products and secondary waste are only included in 44 and 53% of the reviewed studies respectively.

Regardless of the impact of including/excluding such processes from the system boundaries, it is always recommended to address the issue transparently and in a case-by-case manner, as different systems with varying characteristics may justify opposite decisions regarding the definition of system boundaries.

The literature review also analysed LCA practitioners' preferences with respect to *included impact categories.* Figure 35.5 demonstrates their preference for already established, traditional impact categories. Almost all reviewed studies included, at least partially, non-toxic impact categories, while toxicity was considered by more than half of the studies. Resource impact categories such as land and water use were underrepresented, but as research in these fields advances, it is likely that they will become more central in future waste LCA evaluations. However, it should be underlined that incomplete assessments, as in the majority of the reviewed studies, may reduce credibility of the results: maybe the burden is shifted to one of the impact categories that is not assessed.

In order to better understand the characteristics of the reviewed studies, their distribution over space and time offers valuable insights. Figure 35.6 shows the geographical distribution of the studies with European countries and the US dominating the map. China, Australia and Japan follow in number of studies assessing waste produced in these countries. It is evident from the map that Africa and large parts of Asia are underrepresented in the waste LCA applications.

The time evolution of the studies as well as their distribution among the main scientific journals are shown in Fig. 35.7. As expected, the number of LCAs performed increases with time, alongside with the popularity of the tool and its

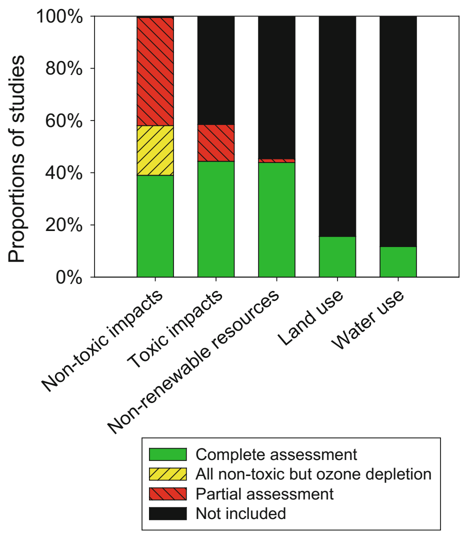

Fig. 35.5 Proportions of impacts covered in the assessments. Non-toxic impacts include climate change, stratospheric ozone depletion, acidification, photochemical ozone formation, eutrophication. Toxic impacts include aquatic and terrestrial ecotoxicity, human toxicity and impacts from particulate matters

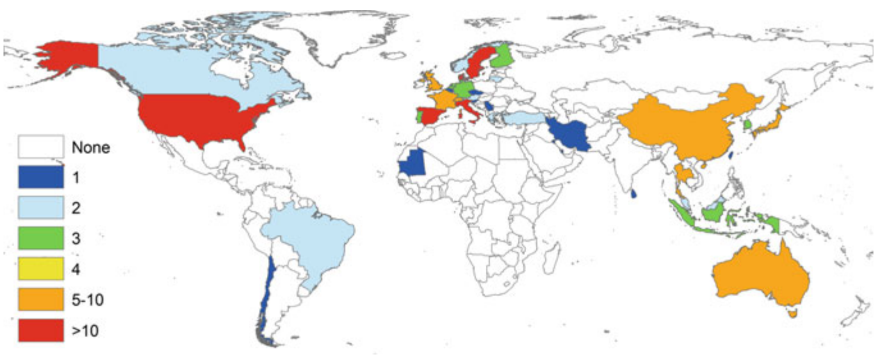

Fig. 35.6 Geographical distribution of case studies based on locations of waste management systems under study. Generic cases and European cases as well as technical reports were excluded from the figure

establishment as a mainstream evaluation method for waste management systems. The figure also shows the adoption of important European legislation to illustrate the influence of legislative measures on the intensity of the research on waste management's environmental impacts.

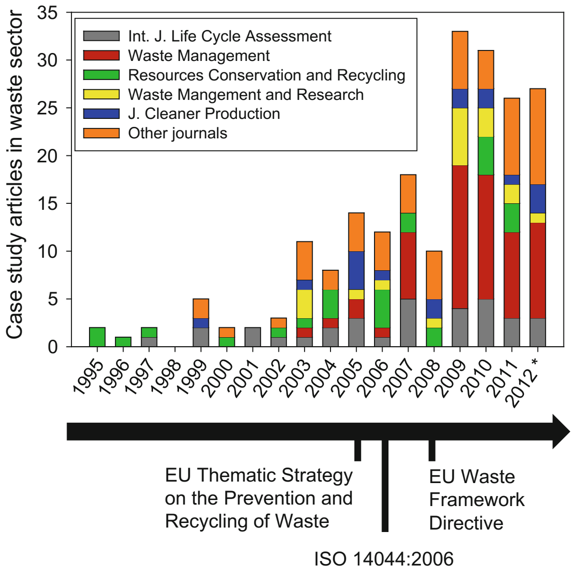

Fig. 35.7 Distribution of publications describing LCAs of solid WMS across peer-reviewed journals. For multiple articles describing the same case study, only the main article supporting the case was accounted for. Literature search was stopped mid-2012, hence 2012 is an incomplete year (indicated by *asterisk*)

35.2.4 Inventory Modelling

The inventory part of waste LCAs is given particular attention by practitioners due to its role in increasing the results' credibility. The accurate representation of the studied system with appropriate data is decided in the inventory preparations.

In the reviewed studies of LCA applied to solid waste management systems, the authors tried in general to use site-specific information and when not possible, search for data in literature and databases. Around 70% of the reviewed studies included at least partly primary data, as Fig. 35.8 shows, but in most of the studies, practitioners had to supplement their inventory analysis with literature information and/or generic data. Although, as mentioned before, waste LCAs typically refer to a specific geographical region, the quest for primary data is rarely fruitful. The reason is that data collection for LCIs is a difficult and time consuming process, leading many researchers to use generic data from widespread LCA databases, such as ecoinvent. These databases aim mainly at modelling the background system, but in the absence of relevant information they are often used as data sources for the foreground system as well. This solution also has the drawback that time representativeness is not followed. Databases are updated irregularly and usually after many years. Therefore, the use of generic database information in general reduces the relevance and representativeness of the study.

The use of LCA databases and the compilation of the inventory data are facilitated by the inclusion of LCA databases in LCA software. Both generic and waste-customised LCA tools are used, the latter ones enabling the specific modelling of different waste fractions through processes that can be parameterised (see

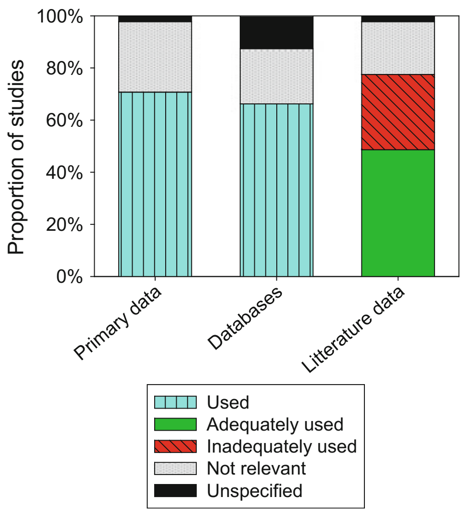

Fig. 35.8 Types of data sources used in studies. Primary data refers to site-specific data from, e.g. field investigations. Databases mainly refer to LCA software-embedded databases. Adequacy of literature data was based on a rough consistency check with the temporal and geographical scopes of the study

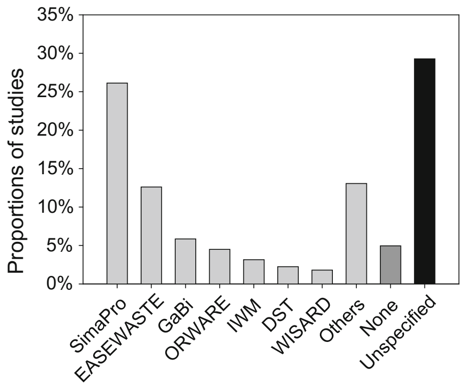

Fig. 35.9 LCA software used in studies. The category "Others" includes TEAM, UMBERTO, GEMIS, WRATE, LCAiT, JEMAI-LCA, EIME, WAMPS software

e.g. Clavreul et al 2014 for an example of such tools). The most popular LCA software among the reviewed studies was the generic LCA tool SimaPro (Fig. 35.9).

One important aspect in waste LCAs is the long-term emissions associated with waste landfilling. The issue around handling long-term emissions has been a subject of strong debate within the LCA community (Hischier et al. 2010). LCA in principle integrates emissions regardless of when they occur. This principle works well when considering relatively short time spans. But the time integration of emissions occurring in low concentrations over very long time spans (such as metal emissions leaching from landfills) leads to an estimation of very high and unrealistic impacts in toxic impact categories which are linked to toxic metal emissions when landfilling waste (Bakas et al. 2015). A suggestion has been to cut off all long-term emissions beyond the arbitrary threshold of 100 years from the waste deposition and either discard them (Hischier et al. 2010) or treat them in a separate impact category (Hauschild et al. 2008). These suggestions along with other proposals, all have inherent problems that do not allow them to become operational and widely accepted in the LCA community (Bakas et al. 2015). The lack of consensus and the absence of an adequate method to account for long-term emissions in LCA has led many practitioners in the reviewed studies to omit or assign less credibility to toxicity-related impact categories.

Within the LCI phase, reference needs to be made to the handling of multi-functional processes (see Sects. 8.5 and 9.2.2). This choice is particularly relevant as waste operations often lead to the production of secondary products such as secondary materials (recycling) and energy (incineration, landfill gas extraction). According to the ISO standards, system expansion is the preferable option for dealing with such processes and, as Fig. 35.10 shows, practitioners follow this recommendation to a great extent (around 75%), with a few cases of studies reported to resort to allocation. The allocation key varied among the studies with mass, heat value, waste volume, exergy and economic value all used by practitioners.

On the other hand, the choice between marginal and average data for crediting a waste system delivering secondary products is more evenly divided. In many cases, also, the choice is not sufficiently justified, which could be attributed to the difficulties of practitioners in identifying the proper approach and the lack of adequate framing of the goal and scope of their study. The choice between marginal and average data depends on the goal of the study and the context situation it belongs to (see Chap. 7).

System expansion is often very crucial for estimating the final results, as it strongly influences the benefits of one waste treatment option over another. Thus, the lack of transparency in how this is performed may substantially reduce the

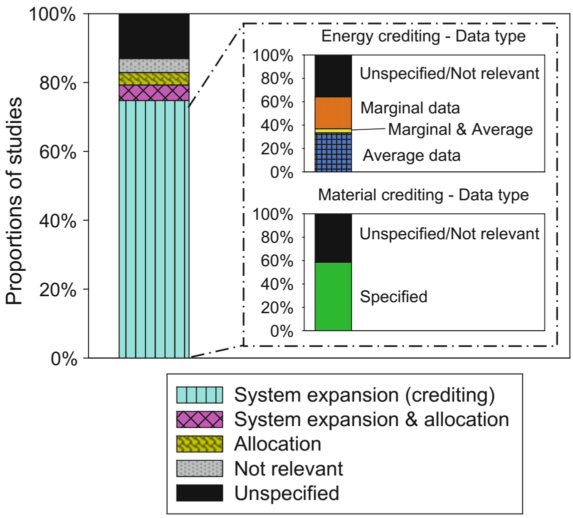

Fig. 35.10 Handling of multifunctional processes. Energy includes both heat and electricity. The differentiation between marginal and average data for material crediting is largely omitted in the studies, and is hence not reported in the figure

credibility of the final results and conclusions. A systematic framework for consistent modelling of recycling, co-production and energy recovery has recently been developed by Schrijvers et al. (2016), describing the relation between the LCA goals and the attributional/consequential approach. Most of the reviewed studies assume a 1:1 substitution ratio between primary and secondary material production and/or quality similar to the substituted product. However, an overestimated substitution ratio or grade of the recovered materials can significantly impact the benefits gained from recycling and alternative methods based on the average market consumption mixes of primary and secondary materials have been proposed for calculating the environmental credits of end-of-life material recovery in attributional LCA (Gala et al. 2015). One of the main challenges for LCA in the circular economy is to address the continuous loop of materials and account for the benefits from recycling in a consistent way (Niero et al. 2016).

35.2.5 Life Cycle Impact Assessment

The constant updating of existing and development of new impact assessment methods (see also Chaps. 10 and 40) makes it difficult to accurately map the popularity of specific LCIA methods among LCA practitioners in solid waste management. Figure 35.11 attempts to map the use of LCIA methods among the researchers and practitioners of the reviewed studies. CML is strongly preferred, followed by EDIP and Ecoindicator 99. Interestingly, around 20% of the studies failed to report on the LCIA method choice.

This mapping reveals information on the selection criteria applied by practitioners, and also the perception of credibility of LCIA methods by LCA practice. Additionally, the time of conducting the study is important as newly developed methods (such as ReCiPe; Goedkoop et al. 2009) are absent from Fig. 35.11 showing historical data, although they might be more widely used today. This information also needs to be put to perspective regarding the impact coverage

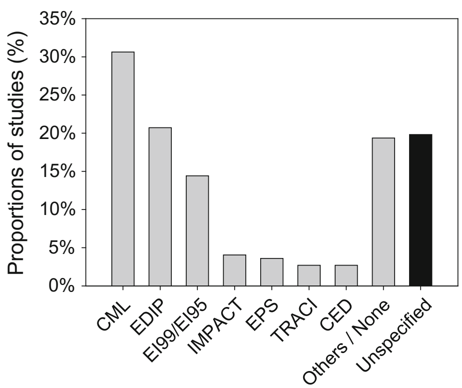

Fig. 35.11 LCIA methods used. Some studies used more than one LCIA method; all have been included here. Category "Others" includes the use of specific models, which are not considered as whole LCIA methods, e.g. IPCC (2007)

analysed in the previous chapter. The selection of a complete LCIA method does not guarantee its proper implementation as many cases demonstrate that some of the impact categories in the methods were omitted. This implies in most cases a reduced credibility of the LCA results (unless the omission is well justified and in line with the goal and scope of the study), despite the use of a well-established LCIA method.

Within the LCIA phase, *normalisation and weighting* steps are an option when appropriate. Performing these steps or not, is strongly associated with the choice of LCIA method and the normalisation and weighting frameworks these recommend. Most of the reviewed studies are concluded at the characterisation step, while 46% perform normalisation and 26% weighting. The majority of these cases perform weighting because of the choice of the Ecoindicator 99 LCIA method which is a damage-oriented method, offering its own weighting scheme (Goedkoop and Spriensma 2001).

With respect to weighting, a particular case arises when examining the impacts of long-term emissions from landfills. As mentioned before, this case poses particular challenges in an LCA framework when trying to characterise this type of emissions. Another aspect of this case is related to weighting, as some impacts from landfilling might occur in many millennia from waste deposition and might be weighted differently by some stakeholders. So far, there is no widespread weighting method for addressing time-differentiated impacts. Thus, this point was not addressed adequately by any of the reviewed studies.

In general, there are some specific *methodological considerations* during the execution of an LCIA on solid waste management systems that should be given particular attention when performing a waste LCA. The first consideration refers to the handling of the biogenic carbon contained in waste material and its contribution to global warming potential. Biogenic carbon can be considered either neutral or as contributing to climate change, depending on the approach, but this choice needs to be consistent throughout the study. Criteria for assigning global warming emission factors to biogenic carbon have been developed in the literature (Christensen et al. 2009).

Another particular consideration refers to the already mentioned issue of long-term emissions. The LCA community has not reached a consensus in the proposed impact assessment method (Bakas et al. 2015) and this causes significant confusion among practitioners. A new approach has recently been published that applies time differentiation on long-term emissions, estimating toxicity separately for distinct future time periods (Bakas et al. 2017).

35.2.6 Interpretation of Results/Conclusions

The interpretation phase of an LCA should present the results of the study in the context of the defined goal and scope, according to the ILCD Handbook (see also Chap. 12). Therefore, practitioners of waste LCAs should reflect on the goal and scope of the study and put their results in this perspective. The majority of the reviewed studies did not include an adequate interpretation section: instead the results were often presented out of context and only a fragmented commenting was included.

Many of the LCAs performed on solid waste management systems are comparative assertions on treatment technologies for a specific waste stream or material. The review of the LCA cases revealed some trends regarding the environmental superiority of some treatment options compared to other. Based on studies selected because of their higher quality, some generic statements of the superiority of different treatment options are presented in Fig. 35.12.

A central part of the interpretation is the *sensitivity analysis*, often accompanied by uncertainty analysis (see Chaps. 11 and 12). Sensitivity analysis is used for evaluating the dependence of the LCA results on input data, modelling choices and hypothesis made. Although, there are many methods for performing sensitivity analysis, in LCAs applied to solid waste systems, a scenario analysis is often used. Scenario analyses are based on constructing an alternative scenario to the main one, which includes a different assumption or data input. In the reviewed studies, many

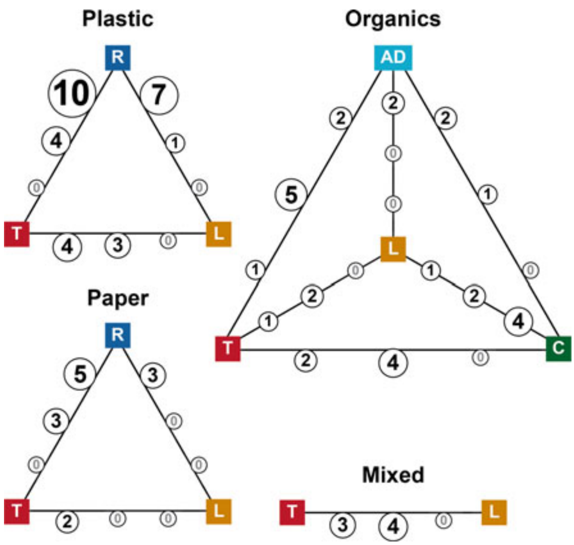

Fig. 35.12 Comparative analysis of key findings for selected waste treatment technologies applied to paper, plastic, organic and mixed waste fractions (total of 34 studies). The nodes "R" stand for recycling, "L" for landfilling, "T" for thermal treatment, "C" for composting, "AD" for anaerobic digestion. For each pair comparison, *three circled numbers* are indicated, representing the number of studies concluding on the better environmental performance (i.e. lower overall environmental impact) of one waste treatment technology over another (numbers closer to each of the two nodes), or reaching either inconclusive results or results with similar environmental burden (*numbers in the middle*). The size of the circles is proportional to the number of studies

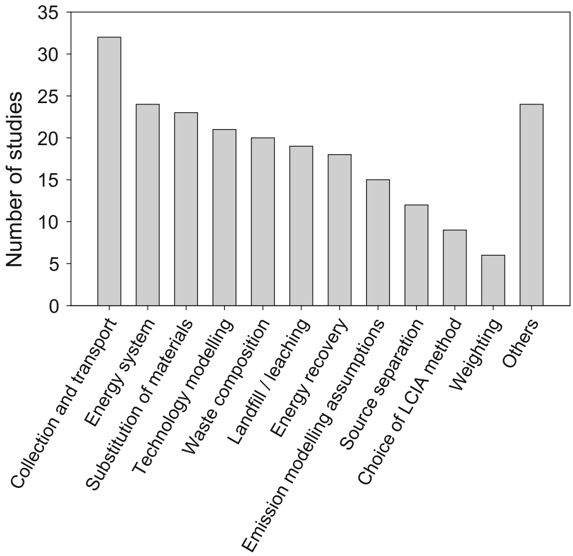

Fig. 35.13 Issues covered in sensitivity analysis (total of 101 studies). The category "Others" (25 studies) includes carbon accounting methods (6), inclusion of secondary materials (4), allocation rules (4), accounting of waste containers (3), time horizon in impact assessment (3), testing of other treatments (2), choice of databases (2) and normalisation (1)

different aspects of a waste system were processed in sensitivity analyses, as Fig. 35.13 shows. Preferred elements to include in sensitivity analyses are collection and transport.

35.3 Central Issues to Consider When Performing or Using Data from LCA Studies on Waste Management Systems

The analysis above provides the necessary background for identifying methodological issues of particular importance when conducting an LCA of waste management options. These issues are identified due to their importance in ensuring credibility of the LCA results and also the frequency by which researchers fail to address them properly. As a general recommendation, in Table 35.1 the main methodological issues are presented along with proposed solutions and recommendations.

The specific methodological challenges for waste LCAs comprise aspects like the differentiation in system boundaries, the zero-burden convention and specific capital goods. The particularities of waste LCAs also include the product system itself, which typically consists of more local installations and smaller geographical dispersion. Specific modelling issues also arise in waste LCAs: the inclusion of biogenic carbon in the modelling, which arises in many waste streams; also, the inclusion of long-term emissions when landfilling waste, which modifies the perception of temporal boundaries one needs to consider in the LCA.

Table 35.1 Key methodological issues and proposed solutions for application of LCA on solid waste management systems

	Methodological and consistency issues	Proposed solutions/recommendations
Goal	Absence of intended use, target audience and limitations of use	Follow ISO recommendations
	Consistency among goal elements	Check consistency among goal elements iteratively
Scope	Elements of functional unit definition missing	Define the functional unit comprehensively. Functional unit not to be confused with reference flow
	Lack of transparency in choices around the LCI	Ensure transparency and assess the choices in terms of uncertainty
	Fragmented description of system boundaries, especially in relation to capital goods and waste transportation	Document assumptions pertaining the definition of system boundaries
	Impact coverage lacking comprehensiveness and representativeness	Follow the selected LCIA method's recommendation for a comprehensive set of impact categories. If an impact category is excluded, justification should be provided
	Insufficient justification of modelling choices (e.g. allocation) and assumptions (e.g. data types used)	Key choices and assumptions, vital for the LCA results, should be transparently documented
	Consistency with the defined goal	Define scope elements within the context of the goal. Revise goal if necessary to ensure consistency
LCI (incl. modelling)	Lack of geographical and temporal data representativeness	Further data and information need to be collected to ensure a sufficient data representativeness
	Lack of data representing areas other than Europe and North America	More efforts for data collection from other parts of the world than Europe and North America
	Lack of documentation of data collection processes	Explain thoroughly how and why data sources are used (literature, databases, etc.)
	Distinction between fore- and background data sources missing and sources misused	Describe and assess the consequences of using background data for the foreground system if necessary
	Lack of data on long-term emissions	Consensus on how to deal with long-term emissions needed
	Use of non waste-specific LCA software	The use of waste-specific LCA software facilitates the more accurate waste system's modelling

(continued)

Table 35.1 (continued)

	Methodological and consistency issues	Proposed solutions/recommendations
LCIA	Missing impact categories (e.g. occupational)	The exclusion of the results in specific impact categories should be avoided or, if unavoidable, documented
	Modelling of impacts from long-term emissions missing	Assess the consequences of omitting the effects of long-term emissions
	Normalisation and weighting	Describe and justify where modelling stops (characterisation, normalisation, weighting)
Interpretation	Interpretation step often missing altogether	Interpretation of results is vital to putting results in context and should always be addressed
	Superficial analysis of impact potentials	Refer to contribution analyses at substance and process level, identify hotspots and recommend improvement potential
	Frequent absence of sensitivity analysis and sensitivity checks	Conduct sensitivity checks on most relevant processes and use the results in interpretation
	Negative impacts obtained from the disposal stage can mislead interpretations of LCA studies	Relate results to goal and system boundaries selection

35.4 Sources/Links to Access Information on LCA Applied to Solid Waste Management Systems

Table 35.2 presents a non-exhaustive list of sources for obtaining data, software tools and methodological guidance on LCA applied on solid waste management systems.

35.5 Concluding Remarks

This chapter attempts to provide guidance and recommendations in specific issues that differentiate waste LCAs from normal product LCAs. Due to these particularities, waste LCA has developed into its own sub-field encompassing its own sub-definitions of LCA elements, dedicated databases and software.

Legislators, through for example the official endorsement of the waste hierarchy in Europe, have acknowledged the importance of LCA in operating as a reliable tool for providing credible information to decision-makers. Waste generation is increasing globally, while new emerging waste streams appear for the first time (e.g. nanomaterials or composite plastics). The assessment of the environmental

Table 35.2 Key sources for information and tools addressing LCA applied on solid waste management systems

Sources	Short description	Used for
EU-JRC (2011)	Guidance document on application of LCA on SWMS	Guidance in conducting waste LCAs
Cleary (2009)	Review of methodological issues from applying LCA on SWMS	Better understanding of methodological challenges in LCA and waste management
Christensen (2011)	Description of technologies used in SWMS	Obtain knowledge on SWMS
http://www.wrate.co.uk/	Presentation of a waste LCA dedicated software	Modelling SWMS in an LCA context
https://www.epa.gov/warm	Presentation of the US EPA waste software, including a life cycle approach to greenhouse gas emission estimation	Modelling SWMS, combined with LCA elements
Gentil et al. (2010)	Review of nine software tools applying LCA on SMWS	Collecting information on dedicated waste LCA software
Doka (2009)	Information on the ecoinvent inventories for SWMS	Waste LCA inventories

implications of the management of new waste streams or of emerging treatment technologies, will remain an important topic in the future.

The new challenges bring also new methodological challenges to waste LCA practitioners with respect to environmentally sound treatment of new waste materials or new technologies. On the other hand, old debates still remain unresolved, such as the proper allocation procedure and the handling of long-term emissions. In any case, practitioners are encouraged to address all methodological challenges, present in waste LCAs, by following best practice examples and applying transparency.

Appendix: Reviewed Studies

See Table 35.3.

Table 35.3 Essential elements of reviewed studies of LCA applied on solid waste management systems

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Abduli et al. (2011)	L, C	MSW	GW, ODP, ET, O	IR	Eco-indicator 99
Abeliotis et al. (2012)	L	MSW	RD, GW, AC, EU, HT, PO	GR	CML 2
Al Maaded et al. (2012)	L, R	Mixed plastic waste	GW, AP, ADP, HTP	QA	NS
Al-Salem et al. (2009)	L, I, B	MSW	GW, AP, EU	KW	NS
Andersen et al. (2012)	C, I, L	Organic household waste	GW, PO, EU, AC, AET, TET, HT, O	DK	EDIP 1997
Arena et al. (2003)	I, L	Residual waste	GW, AC, EN, LW, WA	IT	NA
Arena et al. (2003)	L, I, R	PE/PET containers	GW, RD, LW, O	IT	NA
Assamoi et al. (2012)	L, I	Residual waste	GW, AC, EU, O	CA	NA
Assefa et al. (2005a)	I, B, T	Biodegradable waste	GW, EN	SE	NS
Assefa et al. (2005b)	T, I, L	Industrial waste	GW, AC, EU, EN, EI, PO	SE	NS
Aye and Widjaya (2006)	Int	Market waste	GW, AC, EU, PO	ID	NS
Banar et al. (2009)	Int	MSW	RD, GW, AC, EU, HT, PO, EI	TR	CML 2000
Beccali et al. (2001)	Int	MSW	GW, AC, EU, HT, TET, AET, EN, LW	IT	NA
Beigl and Salhofer (2004)	Int	MSW	GW, AC, EN	AT	NA
Bergsdal et al. (2005)	I	Municipal, commercial and special waste	GW, AC, EU, PO, TET, AET, EI, O	NO	CML 2
Bernstad et al. (2011)	I, C, B	OFMSW	GW, AP, EP, ODP, POP	SE	EDIP 1997
Bernstad et al. (2011)	R	MSW	GW, AP, EP, ODP, POP	SE	EDIP 1997
Bernstad et al. (2012)	COl	Food waste	GW, AC, EU, EN	SE	EDIP2003

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Bientinesi and Petarca (2009)	Int	WEEE	HT, GW, OD, ET, AC, O	NA	Ecoindicator 99, Impact 2002+
Bigum et al. (2012)	R	high-grade WEEE	GW, AC, NE, POF, HT, ET	NR	EDIP 1997
Birgisdottir et al. (2007)	L, R	MSWI bottom ash	GW, PO, EU, EC, HT, AET, TET, RD, O	DK	EDIP 1997
Bjorklund and Finnveden (2007)	Int	All waste	EN, GW, OD, PO, AC, EU, AET, TET, HT	SE	CML 2000
Björklund et al. (1999)	Int	Non-hazardous MSW, park and yard waste, sewage sludge and industrial biodegradable wastes	GW, AC, EU, PO, O	SE	NA
Blenghini et al. (2012)	Int	MSW	GW, EN, RD	IT	IPCC
Blenghini et al. (2012)	Int	Residual waste	GW, EN, RD	IT	IPCC
Blengini and Garbarino (2010)	R	C&DW	HT, IR, OD, PO, AET, TET, AC, EU, GW, EN, LU, O	IT	IMPACT 2002+, Ecoindicator 99
Blengini et al. (2008b)	B, C, L	OFMSW	GW, AC, NE, POF, EU	IT	NS
Blengini et al. (2008a)	C, L	OFMSW	GW, OD, AC, PO, EU, EN	IT	SEMC 2000, EcoIndicator 99
Boldrin et al. (2010)	L, C	Organic kitchen waste	GW, AC, EU, PO, AET, TET, HT, O	DK	EDIP 1997

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Boldrin et al. (2011)	I, C	Garden waste	GW, PO, EU, AC, AET, TET, HT	DK	EDIP 1997
Boughton et al. (2006)	L, I, R	Shredder residue	GW, AC, EU, PO, HT, AET, TET	US	CML
Bovea et al. (2010)	Int	NA	AC, EU, OD, GW, PO	ES	CML
Bovea and Powell (2006)	Int	MSW	GW, ADP, ODP, POF, AP, EP	ES	CML 2001
Brambilla-Pisoni et al. (2009)	Int	MSW	GW, OD, AC, EU, AET, TET, HT, PM, RD, LU	IT	Ecoindicator 99, CML2, EPS2000
Briffaerts et al. (2009)	R	Waste batteries	GW, AC, EU, AET, TET, HT, PM, RD, LU	BE	Ecoindicator 99
Buttol et al. (2007)	Int	MSW	GW, AC, EU, RD, TET, ET, AET, HT	IT	IPCC, CML, USES 2.0
Cabaraban et al. (2008)	C, L	MSW	GW, AC, EU, PO, AET, HT, EN	US	Ecoindicator 95, IPCC
Cadena et al. (2009)	C	OFMSW	GW, OD, AC, EU, PO, HT	ES	NA
Carballa et al. (2011)	B	Kitchen waste and sewage sludge	ADP, GW, EP, HTP, ETP	NR	NS
Carlsson-Reich (2005)	Int	MSW	GW, AC, EU, PO, EI, O	SE	NS
Chaya and Gheewala (2006)	I, L, B	MSW	GW, AC, EU, OD, PO, EN, O	TH	Ecoindicator 95
Chen et al. (2011a)	R, I	Plastics waste	GW, O	CN	IPCC (2006)

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Chen and Christensen (2010)	I	MSW	GW, AC, PO, EU, HT, AET, LW, O	CN	EDIP 1997
Chen et al. (2011b)	R	Iron and steel production wastes	GW, EU	CN	NS
Cherubini et al. (2008)	L, I, B	MSW	EN, GW, AC, EU, O	IT	NS
Cherubini et al. (2009)	L, B, I, R	MSW	EN, NR	IT	NA
Chevalier et al. (2003)	I	NA	GW, AC, HT, AET, RD, O	FR	IPCC 1995, CML 2000
Ciacci et al. (2010)	L, R, I	Automobile shredder residue (ASR)	GW, OD, AC, EU, AET, TET, HT, PM, RD, LU	IT	EcoIndicator 99
Ciroth et al. (2002a, b)	I	MSW	GW, AC, EU, PO, OD, HT, O	DE,CH,ES	EcoIndicator 95
Clauzade et al. (2010) and Lecouls et al. (2010)	I, R, L	Tyres	GW, AC, PO, EU, RD, WA, EN, LW	FR	NA
Coelho and de Brito (2012)	L, R	C&DW	GW, AC, O	PT	NA
Colón et al. (2012)	Int	OFMSW	GW, AC, PO, EU, HT, ADP, OD.	ES	CML 2001
Colon et al. (2010)	C	Left-overs of raw fruit and vegetables and pruning wastes	RD, AC, EU, GW, OD, PO, EN	ES	CML 2001
Consonni et al. (2005)	I	Residual MSW	GW, HT, AC, PO, EI, O	IT	CML 2001
Cook et al. (2012)	L, I	Unused pharmaceuticals (hazardous waste)	GW, OD, AC, EU, PO, HT, AET, TET, PM	US	TRACI
Corti and Lombardi (2004)	Int	Tyres	GW, OD, AC, EU, PO, EN, O	IT	Ecoindicator 95

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Craighill and Powell (1996)	R, L	Household waste	GW, AC, O	UK	IPCC, NA
Dahlbo et al. (2007)	R, L, T, I	Discarded newspaper	GW, OD, AC, EU, AET, TET, HT, PM, RD, LU, WA, EI, O	FI	DAIA, Ecoindicator 99, EPS2000
Damgaard et al. (2011)	L	Household waste	GW, PO, OD, AC, EU, HT, TET, AET, O	DK	EDIP 1997
Damgaard et al. (2010)	I	MSW	GW, PO, AC, EU, HT, TET, AET	EU	NA
de Feo and Malvano (2009)	Int	MSW	EN, GW, AC, EU, O	IT	NA
DEFRA (2006)	Int	Portable batteries	GW, AC, EU, OD, HT, AET, TET, RD	NA	CML 2001
Del Borghi et al. (2007)	L	Urban waste	GW, OD, AC, EU, PO, RD, LU, WA, LW	IT	NA
Delgado et al. (2007)	R, I	Plastics	GW, EN	EU	NA
Di Maria and Fantozzi (2004)	L, T	MSW	GW, ETP, AP, EP, LU, ODP, O	IT	Ecoindicator 95
Diggelman and Ham (2003)	C, I, L	Food waste	GW, O	US	NA
Dodbiba et al. (2008)	I, R	Plastic wastes from discarded TV	GW, RD, AC, PO, EU, HT	JP	Guinée 2002
Eggels et al. (2001)	Int	plastic packaging	GW, OD, AC, EU, RD, EN, HT, AET, PO, LW, O	EU	CML
Emery et al. (2007)	L, R, C	MSW	GW, OD, AC, EU, EN	UK	CML, WMO, IPCC
Eriksson et al. (2005)	I, L, B, R	MSW	GW, AP, EU, PO, O	SE	NS

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Fallaha et al. (2009)	Int	NA	GW, OD, AET, TET, LU, AC, EU, EN, O	NA	IPCC, IMPACT2002 +
Finnveden et al. (2000)	I, L, R, B, C	Food waste, newspaper, corrugated board, mixed cardboard, PP, PE, PS, PET, PVC	EN, NEN, RD, LW, GW, OD, PO, HT, AET, TET, AC, EU, O	SE	EDIP, USES-LCA
Fruergaard and Astrup (2011)	I, T, B	SRF and organic waste	GW, AC, EU, PO, HT, AET, TET	DK	EDIP 1997
Fruergaard et al. (2010)	L, T	APC	GW, AC, NE, POF, HT, ET	DK	EDIP 1997
Gamberini et al. (2010)	Col	WEEE	GW, OD, AC, PO, HT, ET, IR, PM, RD, LU	IT	Ecoindicator 99
Gentil et al. (2010)	P	Food waste, unsolicited mail, beverage packaging (MSW)	GW, AC, AET, HT, EU, PO	EU	EDIP 1997
Giugliano et al. (2011)	Int	MSW	GM, AC, HT, PO	IT	CML 2001
Grant et al. (2005)	R	C&DW	GW, EN, RD, PO, EU, HT, LU, WA	AU	NA
Grant et al. (2001)	L, R	All commonly recycled materials (newspaper + packaging)	GW, PO, EN, WA, O	AU	IPCC 2000
Grant et al. (2003)	Int	MSW	GW, RD, HT, AET, TET, PO, EU	AU	NA
Guereca et al. (2006)	L, C	Biowaste	GW, OD, AC, EU, PO, HT, ET, LU, WD, RD	ES	NA
Gunamantha et al. (2012)	L, I, B, T	MSW	GW, AC, EU, PO	ID	NA

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Güereca et al. (2007)	C, B, I, L	Biowaste	GW, OD, AC, PO, EU, AET, TET, HT, RD, WA, LU	ES	TRACI
Hanandeh and El-Zein (2010)	Int	MSW	GW, AC, O	AU	NA
Hassan et al. (1999)	L, I, C	Urban waste	GW, EI, LW	MY	IPCC
Hellweg et al. (2005)	L, I, T	MSW	O	CH	CML2001, Ecoindicator 99, Ecological Scarcity
Hischier et al. (2005)	Int	WEEE	ADP, GW, EP, HTP, ETP, AP	CH	CML
Hong and Li (2012)	R	Paper waste	Midpoint: OD, AET, TET, AC, EU, GW, EN, O. Endpoint: Human health, ecosystems quality, climate change, and abiotic resources	CN	IMPACT 2002+
Hong et al. (2010)	L, I, C	MSW	Midpoint: OD, AET, TET, AC, EU, GW, EN, O. Endpoint: Human health, ecosystems quality, climate change, and abiotic resources	CN	IMPACT 2002+
Hong et al. (2006)	C, L, I	MSW	GW, AC, EU	CN	NA
Hunt (1995)	L, I, C	Paper and plastic wastes	GW, O	NA	NA
Iriarte et al. (2009)	Col	Organic, glass, paper, packaging and rest	RD, GW, OD, HT, AET, TET, PO, AC, EU, EN	ES	CML 2000

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Jenseit et al. (2003)	R	Plastic parts of end-of-life vehicles	EN, RD, GW, AC, PO, EI, O	EU	Jensen 1996, IPCC, UBA, own method
Johansson and Björklund (2009)	R, I	NA	GW, ADP	SE	CML 2001
Kaplan et al. (2008)	Int	MSW	GW, EU, O	US	NS
Khoo et al. (2009)	B, C, I	Food waste	GW, AC, EU, PO, EN	SG	EDIP 2003
Khoo (2009)	T	MSW, wood, organic waste, scrap tyres	GW, AC, EU, PO	SG	EDIP 2003
Khoo and Tan (2010)	C, I, L	Plastic bags	GW, AC, PO	SG	EDIP 2003
Kiatkittipong et al. (2009)	L, B, I	Bagasse waste	GW, AC, EU, PO	TH	EDIP, UMIP 97
Kim et al. (2009)	R	Waste home appliances	GW, RD, OD, PO, AC, EU, EC, HT, EI	KR	Ecoindicator 95
Kirkeby et al. (2006)	B, I	Household waste	GW, AC, PO, EU, HT, AET, TET, OD	DK	EDIP 1997
Klang et al. (2008)	L, C, I, B	MSW	GW, AP, EP	SE	NA
Koci and Trecakova (2011)	Int	Mixed municipal waste	RD, AC, EU, AET, GW, HT, OD, PO, TET	CZ	CML 2001

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Koneczny and Pennington (2007)	L, R, I, C, B	Wet biodegradable wastes, paper and cardboard, plastic, glass, iron and steel, aluminium, other	Midpoint: AC, AET, TET, EU, GW, HT, EN, OD, PO, O. Endpoint: Ecosystem impacts, human well-being, economic production	PL	IMPACT 2002+, EDIP2003
Koroneos and Nanaki (2012)	L, R, B	MSW	GW, RD, EN, O	GR	Ecoindicator 99
Kreißig et al. (2003)	R, I, L	Cable waste (PVC)	GW, EN, AC, EI, O	EU	CML
Larsen et al. (2010)	R	Household waste	GW, AC, PO, EU, HT, RD, O	DK	EDIP 1997
Larsen et al. (2009)	Int	Residual household waste, paper, glass, bulky waste	GW, AC, PO, EU	DK	EDIP 1997
Le Borgne and Feillard (2001)	L, R	Bumper skin (car equipment)	EN, GW, RD, AC, EU, OD	NA	CML, EPS, critical volumes
Lee et al. (2007)	L, C, B	Food waste	GW, HT, AC, EU, ET	KR	CML 2002
Lelah et al. (2011)	Col	Waste glass packaging	GW, EN, ADP, O	FR	NS
Li et al. (2010)	R, T	Tyres	GW, O	CN	Ecoindicator 99
Liamsanguan and Gheewala (2007)	I	MSW	GW, PO, AC, EU	TH	IPCC, EDIP 1997
Liamsanguan and Gheewala (2007)	L, I	MSW	GW, EU	TH	NS

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Lundie and Peters (2005)	C, L	Household food waste	EN, GW, WA, HT, AET, TET, AC, EU	AU	Heijungs et al., 1992
Manfredi and Christensen (2009a)	L	Household waste	GW, EU, OD, AC, PO, HT, O	NA	NA
Manfredi et al. (2009b)	L	Household, industrial, healthcare, public administration, education, trade and commercial	GW, EU, OD, AC, PO, HT, O	FI	NA
Manfredi et al. (2010)	L	Mixed waste	GW, OD, AC, EU, PO, AET, TET, HT, O	NA	EDIP 1997
Manfredi et al. (2011)	L, I, R	Organics, recyclable paper, recyclable plastic, aluminium and glass	GW, OD, AC, EU, PO, HT, AET, TET	DK	NA
Marinkovic et al. (2010)	R	Concrete wastes	GW, AC, EU, PO, EN, RD, O	RS	CML 2001
Martínez-Blanco et al. (2010)	C	OFMSW	RD, AC, EU, GW, OD, PO, EN	ES	CML 2001
Menard et al. (2004)	L	MSW	GW, OD, AC, EU, PO, HT, AET, TET, RD, LW	NA	EDIP 1997
Mendes et al. (2003)	L, C, B	MSW	GW, AC, EU	BR	EDIP 1997
Mendes et al. (2004)	L, I	MSW	GW, AC, EU	BR	EDIP 1997
Mercante et al. (2012)	Int	C&DW	GW, OD, PO, AC, EU	ES	CML
Merrild et al. (2012)	I, R	Household glass, plastics, paper, cardboard, steel and aluminium	GW, AC, EU, PO	DK	EDIP 1997
Miliute and Staniskis (2009)	Int	MSW	GW, AC, EU, PO	LT	NA
Molgaard (1995)	R, T, I, L	Plastic fraction in MSW	GW, OD, AC, EU, PO, LW	DK	NA

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Morris (2005)	R, L	MSW	GW, AC, EU, HT, ET	US	TRACI
Morris (2005)	R, L	MSW	GW, AC, EU, HT, ET	US	TRACI
Morselli et al. (2005)	I	MSW	AC, EU, GW, RD, AET, TET, HT,, PO, OD, O	IT	NA
Morselli et al. (2008)	Int	MSW	GW, AP, EP, HTP, OD, PO	IT	Ecoindicator 95
Morselli et al. (2007)	I	MSW	GW, OD, AC, PO, HT, ET, IR, PM, RD, LU	IT	EcoIndicator 99
Muller (2011)	B, C	biogas digestate	GW, AC, EN	DE	CML
Munoz et al. (2004)	Int	Household, industrial-commercial waste	GW, AC, OD, HT, EU, PO, RD, WA, EN, LW	ES	NR
Munoz and Navia (2011)	R, L	Industrial waste	GW, AC, EU, PO, TET, AET, HT, LU, RD, PM	CL	Ecoindicator 99, CML 2000
Møller et al. (2011)	I	MSW	AC, ET	DK	EDIP 1997
Nakatani et al. (2010)	R	PET bottles	GW, O	JP/CN	NA
Navia et al. (2006)	R	Contaminated volcalic soil	GW, ODP, ET, AP, EP, LU, O	ES	NS
Nishijima et al. (2012)	R	Plastic wastes	GW, O	JP	NS
Niskanen et al. (2009)	L	All waste	GW, AC, EU, PO, OD, HT, TET, AET, O	FI	EDIP 1997
Noon et al. (2011)	L, I, R	Computer monitors	GW, EN, O	US	NA
Ortiz et al. (2010)	L, R, I	Construction waste	GW, AC, EU, AET, TET, HT, EN, WA, O	ES	CML 2001

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Passarini et al. (2012)	Int	Automotive shredder residue	HT, GW, ET, AC, EU, LU, RD	IT	Ecoindicator 99
Perugini et al. (2005)	R, I	Plastic packaging	GW, WA, O	IT	NS
Pires et al. (2011)	Int	MSW	GW, AC, RD, EU, HT, PO	PT	CML 2000
Pires and Martinho (2012)	Int	Waste lubricant oil (WLO)	GW, AD, AP, EP, HT, ET, ET, POP	PT	NA
Pisoni (2009)	Int	MSW	GW, OD, ET, AC, EU, ET, O	IT	Ecoindicator 99
Riber et al. (2008)	I	MSW	GW, AC, EU, PO, OD, HT, AET	DK	EDIP
Rieradevall et al. (1997)	L	Household waste	GW, AC, EU, HT, RD	ES	NS
Rigamonti et al. (2009a)	R, I	MSW	GW, HT, AC, PO	IT	CED, CML
Rigamonti et al. (2010)	Int	Packaging waste, municipal biowaste and MSW	CED, GW, HT, AC, PO	IT	CED, CML 2001
Rigamonti et al. (2009b)	Int	MSW	GW, HT, AC, PO	IT	CED, CML
Rivela et al. (2006)	R, I	Wood waste	GW, HT, RO, RI, ODP, ET, EU, AC, LU, O	ES	NS
Rives et al. (2010)	Int	MSW	GW, AC, EU, OD, PO, HT, TET, EN, O	ES	CML
Rodríguez-Iglesias et al. (2003)	Int	Residual MSW	GW, AC, EU, O	ES	IPCC, Ecoindicador 95
Ross and Evans (2003)	R	Plastics	GW, PO, RD	AU	NA

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Saft (2007)	T	Paint waste	RD, GW, OD, PO, AET, TET, HT, AC, EU, O	NL	CML
Salhofer et al. (2007)	L, I, R	Refrigerators, PE films, EPS, paper	GW, OD, AC, EU, PO, HT, EN	AT	CML
Santos Vieira and Horvath (2008)	R	Concrete wastes	GW, EN	US	NS
Scharnhorst et al. (2006)	I, L, R	Antenna rack	TET, AET, OD, PO, NEN, GW, O	EU	IMPACT 2002+
Scipioni et al. (2009)	I	MSW	GW, OD, AC, PO, HT, ET, IR, PM, RD, LU	IT	Ecoindicator 99
Shen et al. (2010)	R	PET	GW, AC, EU, PO, HT, AET, TET, RD, EN	EU	CML, IPCC
Sonesson et al. (1997)	C, L	Organic	GW, AC, EU, PO,OD, EN	SE	CML
Sonesson et al. (2000)	Int	Organic	GW, AC, EU, PO, RD, EN, EI	SE	NA
Stichnote and Schuchardt (2010)	C, B	Empty fruit bunches (EFB) and palm oil mill effluent (POME)	RD, AC, EU, AET, GW, HT, OD, PO, TET	ID	CML 2001
Tabata et al. (2010)	Col	MSW	GW, AC, O	JP	IPCC, NEDO
Tan et al. (2006)	Int	MSW	GW, AC, ET, RD	SG	NA
Tarantini et al. (2009)	Int	MSW	GW, AP, EP, ET, HT, POP, EN	IT	NA
Toller et al. (2009)	R, L	Wood ash, MSWI bottom ash	NR	SE	NR
Tonini et al. (2012)	I, R, T, B	Residual MSW	GW, AC, EU, AET, HT	DK	EDIP 1997
Tukker (1999)	I, T	Hazardous waste	HT, GW, OD, PO, AC, EU, LW, EN, O	NL	CML
Tunesi (2011)	I, T	MSW	GW, AC, AD	UK	NA

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Turconi et al. (2011)	I	Residual MSW	GW, AC, EU, PO, ET, HT	IT/DK	EDIP 1997
Van-Haaren et al. (2010)	C	Yard wastes	GW, AC, EU, O	US	Ecoindicator 99
Welsh Assembly Gvt (2003)	Int	C&D, industrial, commercial, municipal waste	GW, OD, AC, EU, HT, RD	UK	CML, IPCC, WMO
Wenisch et al. (2004)	I	Household waste	GW, AC, HT, RD, WA, LW	FR	NA
Werner et al. (2007)	R, I	Creosote-treated beech-wood railway sleeper	GW, AC, OD, PO, EU, HT, TET, AET, RD	CH	CML
Winkler et al. (2007)	L, I, R	Household waste	GW, HT, AC	DE	CML
Wollny et al. (2002)	I, R, T	Mixed plastic waste packaging	GW, AC, EN, EI	DE	NA
WRAP (2008)	L, I, R	Mixed waste plastic	GW, OD, AC, EU, PO, HT, RD, LW, EN	UK	CML 2002
Wäger et al. (2011)	R, I, L	WEEE	GW, AC, EU, PO, OD, ARD, ET, HT	CH	CML 2002, Ecoindicator 99
Yi et al. (2011)	L, R, I, B	MSW	Midpoint: GW, OD, RD, HT, AC, EU, PO, O Endpoint: human health, social assets, biodiversity and primary production	KR	NA
Zaman (2010)	I, L, T	MSW	GW, AP, EP, ABD, ODP, HT, ET, POP	SE	CML

(continued)

Table 35.3 (continued)

References/sources (short; details to be provided in spreadsheet 'LCA studies list')	Technology assessed	Type of waste (e.g. only organic waste included in study)	Impact coverage (e.g. GW only) (*use glossary in first spreadsheet*)	Geographical coverage	LCIA method used
Zhang et al. (1999)	I, R	PCB and plastics contained in dismantled non-nuclear components	GW, AC, OD, EU, PO, HT, AET, TET, EI, O	US	EDIP 1997
Zhao et al. (2009a)	Int	MSW	GW, AC, EU, PO, OD	CN	EDIP 1997
Zhao et al. (2012)	Int	MSW	GW, AC, EU, PO, OD	CN	EDIP 1997
Zhao et al. (2009b)	I	Medical waste	RD, GW, OD, HT, AET, TET, PO, AC, EU	NA	CML 1999
Özeler et al. (2006)	Int	MSW	GW, AP, EP, HTP, CED	TR	NS

The studies on sewage sludges are excluded from the table as the focus is on solid waste management systems

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Author Biographies

Ioannis Bakas LCA expert focusing on environmental impacts from solid waste management systems. Developed method for accounting long-term emissions from landfilling. Interested in LCA modelling of soil emissions, integrated waste systems' evaluation and policy assessments.

Alexis Laurent working with LCA since 2010 with a strong LCIA focus, particularly on normalisation aspects. Main LCA interests include development of LCIA methods, LCA applications and footprinting of large-scale systems for policy-making (e.g. nations, sectors), and LCA applied to various technology domains, including energy systems.

Julie Clavreul LCA expert since the early 2010s. Her background is with a focus on the modelling and life cycle assessment of waste management systems and the analysis of uncertainties. Interest in the EU environmental footprint methodology.

Anna Bernstad Saraiva has been working with environmental engineering since 2008. Has done Post-doctoral studies on LCA of biorefinery processes and biomaterials. Research focus is on solid waste management, co-treatment of household waste flows, sustainable materials and chemicals and sustainable urban development.

Monia Niero background as chemical engineer, LCA expert since late 2000s. Involved in several LCA industrial projects. Main areas of expertise are LCI modelling and LCM in waste management, packaging and agri-food sectors. Interested in developing decision support tools for circular economy implementation at product and organization levels.

Emmanuel Gentil has been working in life cycle thinking, related to waste management systems since 1999, where he was involved in the development of a life cycle assessment software.

Research focus and consultancy services on life cycle assessment for waste management policy for the European Commission. Teaching LCA for American undergraduates studying abroad in Denmark.

Michael Z. Hauschild involved in development of LCIA methodology since the early 1990s. Has led several SETAC and UNEP/SETAC working groups and participated in the development of the ISO standards and the ILCD methodological guidelines. Main LCA interests are chemical impacts, spatial differentiation and science-based boundaries in LCIA.