Chapter 6
Incorporation of Life Cycle Thinking in Development of Integrated Solid Waste Management Systems

V. R. Sankar Cheela and Brajesh K. Dubey

1 Life Cycle Thinking: A Brief History

Scottish economist and biologist Patrick Geddes coined the concepts of life cycle thinking during 1880, with an aim to develop an inventory for coal with a focus on energy supply. During the late 1960s and early 1970s, industries started performing LCA studies with an emphasis on resource consumption, energy analysis and emissions for the product systems. This process is termed as Resource and Environmental Profile Analysis (REPA) by the Midwest Research Institute located in the United States. This process was termed as inventory studies without impact assessment; in present scenario they are known as Life Cycle Inventory Studies. The impact assessment is not a part of the study during the period 1970–1980. Due to the lack of knowledge sharing platforms for LCA, a standardized procedure was not in practice for performing the LCA studies. Hence, the outcome of the analysis conducted for the same objective and product are contrasting and contradicting.

After one decade, the terms “life cycle analysis” and “life cycle assessment” are coined in Europe and North America with an increase in environmental consciousness. In the year 1984, Switzerland has drafted a report “Environmental report on Packaging”. In the year 1990, during a workshop conducted by SETAC on “A Technical Framework for Life Cycle Assessment”, the committee introduced the concept of LCA triangle. Inventory, impact analysis, and improvement analysis are the components of the LCA triangle (Fig. 6.1a). Between the period 1990 and 1993, SETAC and SETAC Europe made new developments for further standardization of the LCA process. SETAC revised the LCA triangle during the workshop held at Sesimbra, Portugal in the year 1993. The team introduced a new component termed “Goal Definition and Scoping”. This component is located in the middle of the LCA

V. R. S. Cheela · B. K. Dubey (✉)
Environmental Engineering and Management Division, Civil Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India
e-mail: bkdubey@civil.iitkgp.ac.in

D. Sengupta et al. (eds.), *Treatment and Disposal of Solid and Hazardous Wastes*,
https://doi.org/10.1007/978-3-030-29643-8_6

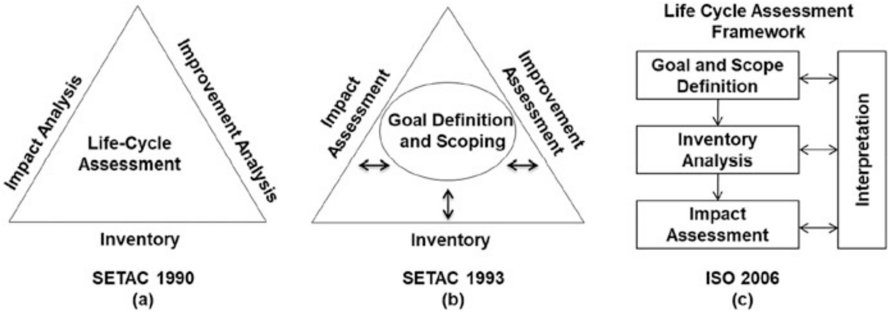


Fig. 6.1 Formulation and developments in LCA framework

triangle with interconnections to the other three elements (Fig. 6.1b). In the year 1996–1997, ISO revised the framework for the LCA (ISO 14040:2006a) and developed a flow chart representing step-by-step procedure in place of the LCA triangle (Fig. 6.1c). This framework included the direct applications, indicating that the study has to consider the intended use of results obtained. Figure 6.1 represents the formulation and developments of the LCA framework (Klopffer and Grahl 2014).

2 Life Cycle Assessment

2.1 *Definition and Limitations*

As per the International Standard Organization, definition of LCA is “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” and definition of life cycle is “consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal” (ISO (International Standard Organization) 1997). LCA is a systematic and scientific approach to compute, analyse, and evaluate the environmental impacts of a product based on the product itself or function provided at all stages of the product lifecycle. In a broader sense, the product includes physical goods, services and systems. The product life is a combination of the unit process involving the development, utilization, management, and disposal of the product. The unit process includes extraction of resources, raw material, production, utilization, management, and disposal of the product. The assessment of the environmental burdens includes all the impacts associated with extraction process, types of land use, raw materials, energy and emissions. The end results of the LCA approach are quantitative in character; however if a quantitative output is not possible qualitative aspects are taken into consideration for developing an overall picture in terms of environmental impacts. The final application and utilization of the product play a pivotal role in the economic growth. Cradle-to-grave approach is applied in the development of a holistic approach to determine the overall impacts from all the unit process involved in development of the product. Further this approach reduces the shifting of the impacts between the stages of product development. This is applied in strategic planning, government policies and business approaches. This includes design, development, analysis, and comparison of an existing or new product, process or a service. For example, in solid waste management, LCA study can be performed for the existing waste management system in an urban local body (ULB) (or) during the decision making process for implementing a new treatment technology (or) to compare different types of biological treatment systems (or) comparison of the waste management systems being implemented in different ULBs (Sankar and Dubey 2019).

Any approach has both sides of the coin; for LCA, its holistic nature is major strength and limitation. LCA framework will not address the localized impacts to the full extent, certain technical assumptions and choices are to be developed as transparent as possible to achieve the required results. The environmental impacts are assessed based on an arbitrarily defined functional unit and not based on spatial and temporal components. Life cycle inventory databases that are used as datasets for assessment of the potential impacts should be revised and updated over a period of time based on the advancements in technology, variations in energy production and other temporally varying factors. The format of database has to be standardized globally for performing comparative studies. The databases are developed based in the given time frame and over a period of time they become obsolete. Furthermore, development of database is time and cost extensive process. The design of the LCA model is based on the linear modelling and will not address the economic and social factors. Finally, LCA is not a decision making process by itself; it provides the information in support of decision, equipping the decision makers for better and effective planning of systems.

Risk assessment and substance flow analysis along with LCA studies provide a better understanding of the local impacts due to the core processes of individual substances. Economic studies can be conducted using Life Cycle Costing (LCC) approach and cost-benefit analysis. Social impact assessment studies for social factors can be included to develop an integrated toolbox for the overall and holistic solution. Figure 6.2 represents the ISO standardized LCA framework. The LCA study includes four stages.

Stage one is the **definition phase**. In this goal and scope are described: need, necessity and nature of the work to be performed during the study. The aim and objective of the LCA study predominantly depend on the goal. Based on the purpose of the study, subject and intended application, the scope of the LCA is determined. During this stage, system boundary, functional unit, and reference flow are determined. For comparative study, different scenarios are developed based on the combination of possible and feasible alternatives.

Stage two is known as the **inventory analysis phase**; this is the heart and core of the LCA study. In this stage, to achieve the required goal, the input and output data is acquired based on the spatial, temporal and technical constraints for each unit process. Data compilation is carried out by data collection from both primary and

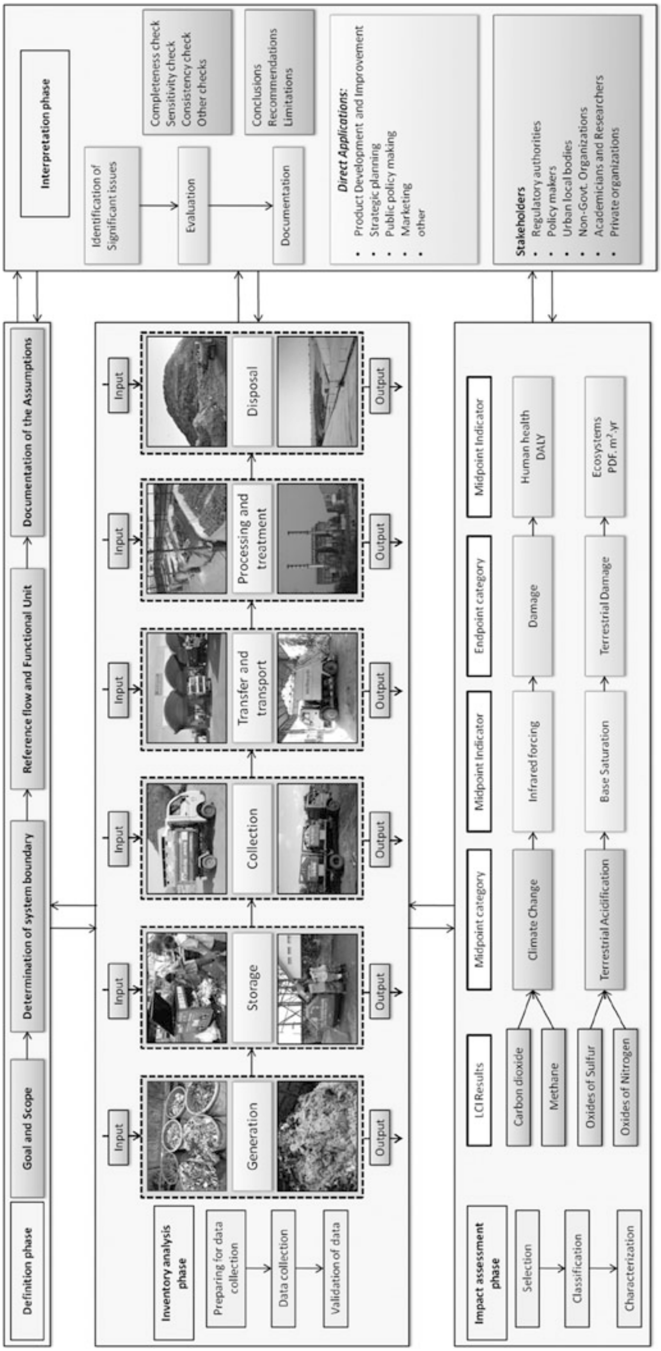


Fig. 6.2 ISO standardized LCA framework

secondary sources to develop an inventory database. This stage is also known as the Life Cycle Inventory Analysis.

Stage three is known as the **impact assessment phase**; in this stage, the assessment of environmental impacts is performed. Based on the inventory database compiled, analysis and investigations are conducted to quantify the magnitude of the environmental burdens of the product or service within the system boundary defined in stage one. This knowledge provides the basis for the designing and planning of environmentally sound systems. This stage is also known as the Life Cycle Impact Assessment (LCIA).

Stage four is known as the **interpretation phase**; this phase is a documentation phase in which the results obtained from steps two and three are discussed and summarized. Based on this, necessary conclusions and recommendations are developed as a part decision making by the goal and scope.

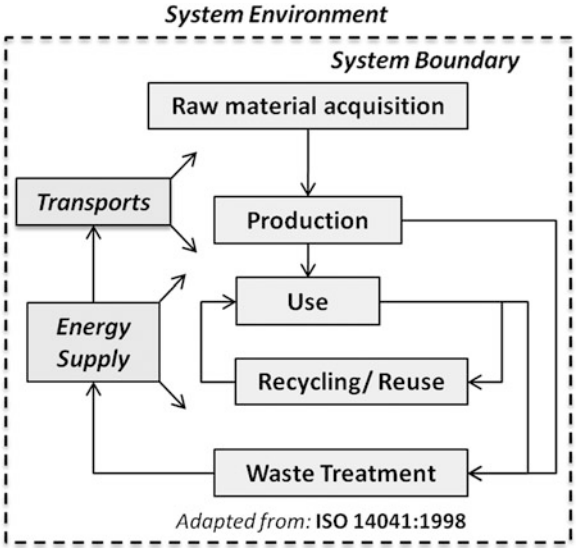
2.2 Goal and Scope Definition

In the LCA, the goal and scope is the primary component. Fundamentally, we have to identify the aim, objective and the need for performing LCA in our study. As per ISO 14040:2006a "The goal and scope of an LCA should be stated clearly by the practitioner, and it should be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study". The stakeholder(s) commissioning or performing the LCA, defines the goal with a detailed explanation on the objective of the study (range of applications), need for the survey (interest of realization), target group(s), and accessibility to the public in the form of publication or other modes (if comparative assertions are intended). During the study, the domain knowledge gained and database created provide a better understanding of the system. At this stage, the scope can be modified by the concerned authorities based on the revised requirements. The framework standardized by ISO represents that the LCA study is iterative (double arrows). Documentation has to be done periodically to record and track the modifications in goal or scope made throughout the study.

2.2.1 Product System

Product system plays a vital role in the LCA studies. It is a grouping of unit processes, intermediate products, elementary and product flows across and within the system boundaries performing one of the more defined services. The product system is defined based on the function of the product and not by the end products. Figure 6.3 represents the product system for life cycle inventory analysis.

Fig. 6.3 Product systems for life cycle inventory analysis



2.2.2 System Boundary

As per ISO-14040:2006a, a system boundary is defined as "interface between a product system and the environment or other product systems". System boundary is determined based on the goal of the study. The criteria for establishing the system boundary should be justified in the scope. It describes the unit processes that are included in the LCA study. Data category, intended application, cut-off criteria, assumptions, cost, and the intended audience are the factors to determine the system boundary. The system boundary should include all the life cycle stages, processes and inputs or outputs in the development of the product. The deletion of any component from the system boundary should be substantiated with proper justification and documented. Figure 6.4 presents the types of system boundaries for LCA studies on integrated solid waste management.

The LCA study is classified based on the technical components included in the system boundary. The following sections present the description of the system boundary:

1. *Cradle-to-grave:* The system comprises the extraction of resources, manufacturing, utilization, and disposal of the product. In an SWM study, generation, collection, transfer and transport, processing, treatment and disposal of the waste are part of the system boundary. Figure 6.4 represents the system boundary for cradle-to-grave analysis.

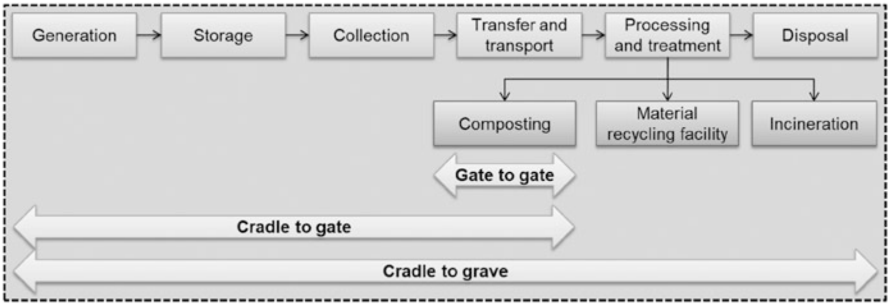


Fig. 6.4 Types of system boundaries for LCA studies on integrated solid waste management

2. *Cradle-to-gate:* The system includes extraction for resources, manufacturing, and other process involved before the product leaves the factory gate. In an SWM study, generation, collection, transfer and transport, processing, treatment and disposal of the waste are part of the system boundary. Figure 6.4 represents the system boundary for cradle-to-gate analysis.
3. *Gate-to-gate:* The system includes the manufacturing process of the product within a factory or a project site. In an SWM, if composting, bio-methanation, incineration, or material recycling facility are studied exclusively as part of this system. For example, in the composting unit for LCA studies waste entering the unit gate to the preparation of compost will be considered as the system boundary. Figure 6.4 represents the system boundary for gate-to-gate analysis.

2.2.3 Functional Unit and Reference Flow

As per ISO-14040:2006a, a functional unit is defined as "quantified performance of a product system for use as a reference unit in a life cycle assessment study". The functional unit provides scope for normalization of the input and output data. Solid waste management is one of the essential functions of an urban local body. The primary elements of the SWM system include storage, collection, transfer and transport, processing, treatment and disposal of waste. Based on the resources availability, economy and characteristics of the waste, ULBs are implementing different methods and approaches. The ULBs implement individual or combination of material recovery, composting, bio-methanation, incineration process for the treatment of the waste in the ULB. Hence, for performing a full scale LCA study or comparative LCA study, the function and the functional unit must be defined initially. In the SWM-LCA studies, management of the waste is the function. The functional unit can be one ton of garbage or the total amount of waste generated in a year. Once the functional unit is defined, it provides a basis for the determination of the input(s) and output(s) for the unit operations specified in the reference flow.

2.3 Life Cycle Inventory Analysis

As per ISO 14041:1998, life cycle inventory analysis is defined as “phase of life cycle assessment involving the compilation and quantification of inputs and outputs, for a given product system throughout its life cycle”. Life cycle inventory analysis is a systematic process for developing an inventory database from the input and output flows associated with the unit process. Inventory development process involves three stages of planning, collection, and validation of the data. Figure 6.5 represents the flow chart for the life cycle inventory analysis.

In the planning stage, based on the goal and scope of the LCA study, data to be collected for the foreground and background systems is determined. Foreground data is data associated with the unit process involved in the system boundary. Raw materials, energy, water and emissions into the air, water and soil are examples for foreground data. This dataset has a direct influence on the results obtained from the impact assessment study. Background data is data associated with the process that is allied with the unit process involved in the system boundary, for example, manufacturing of storage bins, diesel production (collection) and manufacturing of trucks (transport), etc. This dataset has indirect, direct or zero influence on the impact assessment study. In a full-scale LCA study, the background data can be considered based on the goal and scope definition. While in the comparative LCA study this data is neglected as this data is listed under the common dataset for different system boundaries under consideration.

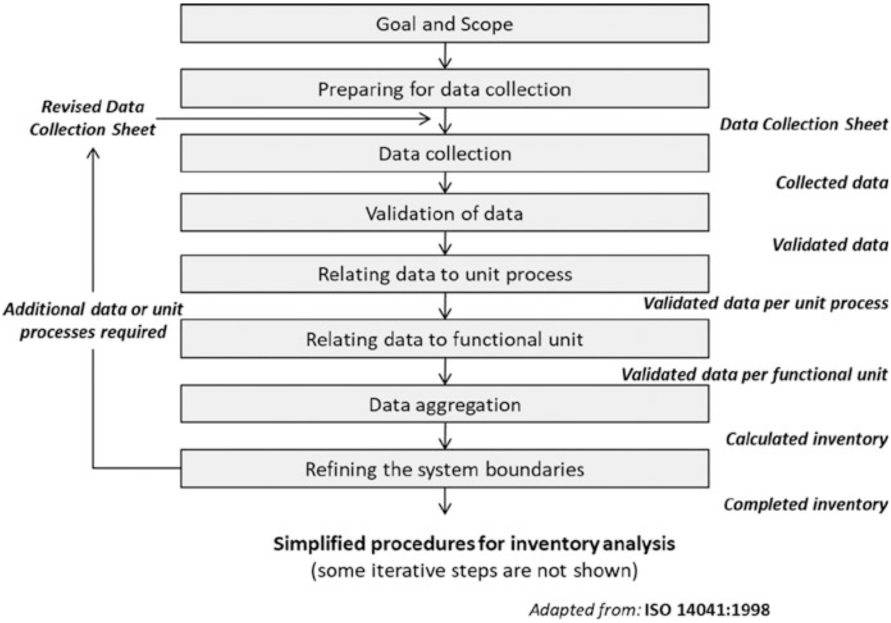


Fig. 6.5 Flow chart for the life cycle inventory analysis

In the collection stage, measurement, calculation and estimation of data related to the unit process are performed using two approaches. In the first approach, data collections performed internal audits at the waste management units. This type of data is known as primary data. Availability of data, finance and time are the significant constraints for this approach. In the second approach, information is collected from the reports and published references available from the previous studies. This type of data is known as secondary data. Data availability and accuracy are the constraints for this approach. Missing data and irregularities is a common problem associated with both the procedures. Data collection based on reports and literature, calculations form the known sources, estimating the value based on experience or accepting and documenting the data gaps are in practise to fulfill the missing data. Quantitative and qualitative characterization of the data is essential to understand the quality of the collected data. The vital factors determining the quality of the data are the geographical coverage (location), temporal coverage (age), and technology coverage. Precision, completeness and representativeness are the additional data requirements to be considered for the data collected from a specific site.

In the validation stage, the data collected is verified by the competent technical people from academic and field to ensure the quality of the data. During the validation, the relation between the data collected, goal and scope, functional unit or reference flow and unit process has to be verified. The calculation procedures implemented should substantiate to confirm the consistency throughout the system boundary.

2.4 Life Cycle Impact Assessment

As per ISO 14042:2000a, life cycle impact assessment is defined as “phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system”. The objective of the impact assessment is to examine the product system using impact categories and category indicators from an environmental perspective and further provide information for the interpretation phase. In this stage, data is converted into pre-defined impact categories for effective communication to the stakeholders. The framework of LCAI includes mandatory and optional elements. The necessary components include the selection of impact categories, assignment of LCI results to impact types (classification) and calculation of impact category indicator results (characterization). The optional elements include normalization, weighting, grouping, and data quality analysis.

The LCA framework (ISO 14044:2006b) does not provide or recommend any impact categories and indicators list. However, the categories, indicators and characterization models intended to be studied should be accepted internationally or authorized by an international board. The persons performing the LCA study determine these selections of components. These are defined during goal and

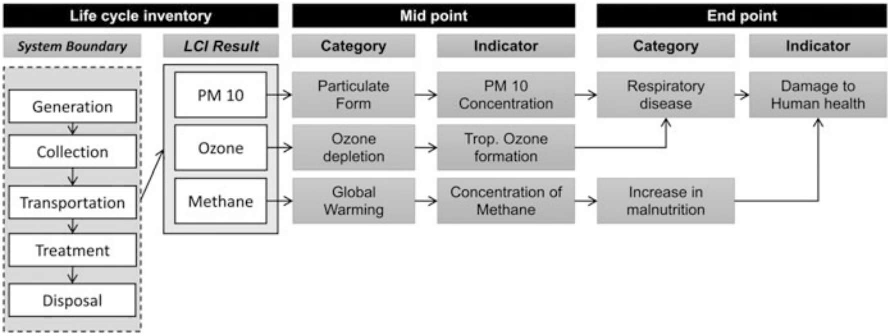


Fig. 6.6 Model of impact assessment structure used in ReCiPe 2016

scope, enabling the user to procure specific data, to fulfill the requirements of the impact assessment.

Classification is a systematic scientific approach in which the input and output data collected during the inventory phase are identified and assigned to the impact categories (environmental impacts). During the process of mapping, the data can be categorized under multiple impact categories. The quantification of the effects associated is acceptable only if the results are independent; else measures are to be taken to avoid the duplication. The classification of the impact categories is based on the spatial and temporal variations. Spatially they are classified as global, continental, national, regional and local levels. The temporal classification plays a pivotal role since some impact categories will have long-term impacts (example global warming). Figure 6.6 shows model of impact assessment structure used in ReCiPe 2016.

Characterization is a systematic quantification of the impacts associated with each category using scientific analyses and models. In this process, the potential effects of the input and output results are determined. They are converted to a common indicator (unit) based on the classification; for example, under global warming indicators all the results are converted to carbon dioxide equivalents. The translated results are summed up to determine the total indicator value.

2.5 *Life Cycle Interpretation*

As per ISO 14043:2000b, life cycle interpretation is defined as "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistently with the defined goal and scope to reach conclusions and recommendations". In the interpretation phase, significant issues related to the results obtained from the inventory analysis and impact assessment phase are identified. Further, evaluation is performed in a systematic approach through completeness, sensitivity and consistency checks. Finally, the conclusions,

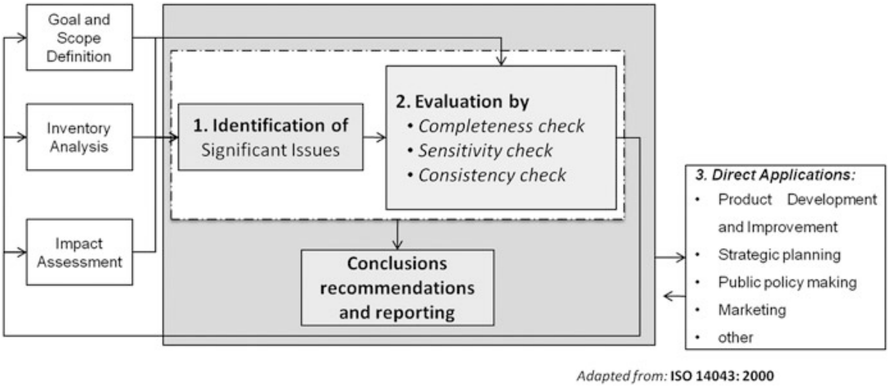


Fig. 6.7 The flow components of the life cycle interpretation stage

recommendations and limitations are documented in a complete, consistent, understandable and transparent manner. Figure 6.7 represents the flow components of the life cycle interpretation stage.

3 Case Studies

3.1 Kerbside Organics Disposal and Treatment, Auckland Council

This case study illustrates the life cycle assessment performed by Auckland Council to assess the environmental impacts from landfill of kerbside organics (KSO) compared to composting, anaerobic digestion (AD), and the combination of AD and composting. The primary emphasis of this case study is to illustrate that the LCA can be performed using the mathematical calculations in the absence of the software. This type of analysis can form a basis for decision making during the preliminary assessment stages (Dubey and Singhal 2014).

The organic component of the kerbside collection refuses stream constitutes 40% food waste (FW) and 10% garden waste (GW). To achieve this, following four scenarios are compared: Landfilling of KSO material assuming 90% gas recovery efficiency; Aerobic composting of KSO and application of a product to land; Anaerobic digestion of KSO with energy recovery and application of digestate to land; and Anaerobic digestion of KSO followed by aerobic composting of digestate before application to soil. The life cycle inventory database was collected from secondary sources (i.e., literature and previous studies). The research is focused on performing mass balances for carbon, nutrients (nitrogen), and global warming potential (GWP). Figure 6.8 illustrates the scenarios considered for performing the life cycle assessment.

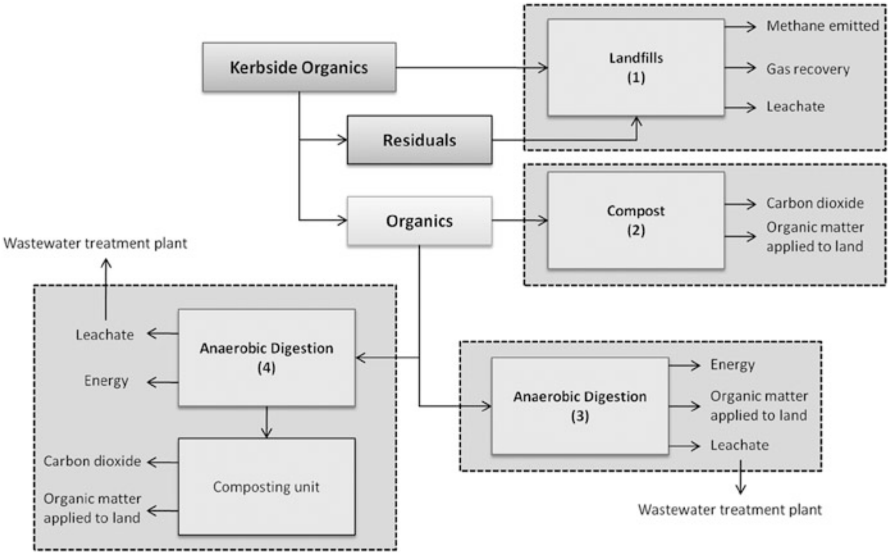


Fig. 6.8 Scenarios for disposal and treatment of kerbside organics

The major assumptions that are made during this study are:

1. In the council 248,590 tons of KSO are produced each year and 40% of KSO is FW and 10% is GW.
2. In the landfill scenario (1), 90% of gas produced is captured; 76 kg of CH_4 and 180 kg of CO_2 are produced per each ton of FW, and 99 kg of CH_4 and 232 kg of CO_2 are produced per each ton of GW; 1% of total carbon is lost in leachate.
3. In the Composting Scenario (2), 1 Kg of CH_4 and 115 Kg of CO_2 Are Produced per each Ton of FW and 3 Kg of CH_4 and 194 Kg of CO_2 Are Produced per each Ton of GW; 350 Kg/Ton-FW and 200 Kg/Ton-GW of Carbon Are Retained in Compost

   - In the anaerobic digestion scenario (3), 70 kg of CH_4 and 50 kg of CO_2 are produced per each ton of FW and 50 kg of CH_4 and 30 kg of CO_2 are produced per each ton of GW; 0.6 ton of digestate is produced per each ton of organic waste.
   - In the anaerobic digestion followed by composting of digestate scenario (4), 52 g of CH_4 is assumed to be produced per ton of digestate.

A sample mass balance calculations for the carbon mass balance in the landfill scenario is presented in Table 6.1.

The carbon mass balance study was performed for the four scenarios using the mathematical calculations in an excel spreadsheet. Table 6.2 presents the mass carbon balance for all the scenarios under consideration. For the landfill scenario, 46,219 tons/year of carbon (78% of carbon in food and garden waste deposited in landfills) is lost via retention in the landfill. In comparison, composting, anaerobic

Table 6.1 Mass balance calculations for the carbon mass balance in the landfill scenario

		Wet waste				Carbon			
Qualifier	Parameter	Basis	Unit	Amount	Unit	Basis	Unit	Amount	Unit
Input	KSO			248,590	Tons/year				
Input	*Food waste (FW)*	40	% of KSO	99,436	Tons/year	48	%	47,729	Tons-C/year
Output	CH_4 produced	76,622	g/ton	7619	Tons/year	0.75	g-C/g-CH_4	5714	Tons-C/year
Output	CH_4 released	10	% biogas produced	762	Tons/year	0.75	g-C/g-CH_4	571	Tons-C/year
Output	CH_4 captured	90	% biogas produced	6857	Tons/year	0.75	g-C/g-CH_4	5143	Tons-C/year
Output	CO_2 released	180,183	g/ton	17,917	Tons/year	0.27	g-C/g-CO_2	4886	Tons-C/year
Input	*Garden waste (GW)*	10	% of KSO	24,859	Tons/year	47.8	%	11,883	Tons-C/year
Output	CH_4 produced	98,514	g/ton	2449	Tons/year	0.75	g-C/g-CH_4	1837	Tons-C/year
Output	CH_4 released	10	% biogas produced	245	Tons/year	0.75	g-C/g-CH_4	184	Tons-C/year
Output	CH_4 captured	90	% biogas produced	2204	Tons/year	0.75	g-C/g-CH_4	1653	Tons-C/year
Output	CO_2 released	231,664	g/ton	5759	Tons/year	0.27	g-C/g-CO_2	1571	Tons-C/year
MB							Total C released (g)	14,008	Tons-C/year
Output	Leachate C released	1%					Total C loss	140	Tons-C/year
C lost via retention in landfill + emissions							78%	46,219	Tons-C/year

C lost via retention in landfill + emissions = [Input Food waste + CH_4 released (FW) + Input Garden Waste + CH_4 released (GW)] – [Total C released + Total C loss]

% C lost via retention in landfill + emissions = C lost via retention in landfill + emissions/[Input (FW + GW)]

Table 6.2 Carbon mass balance results for the scenarios under consideration

Scenario	Mass (Tons-C/year)	Fraction of input (%)
Landfill	46,219	78%
Compost	4108	8%
Anaerobic digestion (AD)	2594	5%
AD with composting of digestate	2597	5%

digestion, and anaerobic digestion followed by compositing result in 4108 tons/year (8%), 2594 tons/year (5%), and 2597 tons/year (5%) of carbon lost from the system.

3.2 Comparison of Organic Processing Odour Control Technologies

A comparative LCA of odour control technologies used in organic processing units was performed by Bindra (2015), and his team was illustrated in this case study. Three odour control technologies packed-bed wet scrubber (PBWS), organic bio-filter system (OBFS) with wood chips media and inorganic bio-filter system (IBFS) with synthetic media were compared. The study is aimed to assess the potential environmental burdens of the odour control technologies in organic processing systems. The assessment was performed over a period of 15 years based on the life expectancy of the inorganic media used in these technologies. In the system boundary, raw materials for construction, transportation, energy utilization, water consumption, and chemical usage, recycling, and disposal phases were considered. Figure 6.9 illustrates the system boundary and the process considerations for the three technologies.

The life cycle inventory database was developed by performing field surveys at the organic processing plants to understand the technologies and collect the preliminary data. The data for OBFS with wood chip media was obtained from a composting plant located in Guelph; the processing capacity of the plant is 30,000 tons of organic waste a year. The data for the IBFS with synthetic media was collected from a centralized composting facility located in Hamilton; the processing capacity of the plant is 70,000 tons of organic waste a year. The inventory database for the PBWS system was developed from the secondary sources (i.e., literature and previous studies). For the analysis and comparison of the technologies, 1000 t of organic waste per year was selected as functional unit. Life cycle inventory database was developed by conducting the field visits at both the compost units. For all the three technologies, the components contributing in significant quantity were considered (chemicals, equipment, etc.), while small parts (screws, bolts, wires, etc.) with negligible effect were excluded. The data gaps were quantified and scaled to the functional unit based on the reasonable assumptions from the background of the system, field data, and common knowledge. SimaPro® V.8.0 software and Ecoinvent v3.0 databases were used to perform impact analysis. Twelve environmental impacts

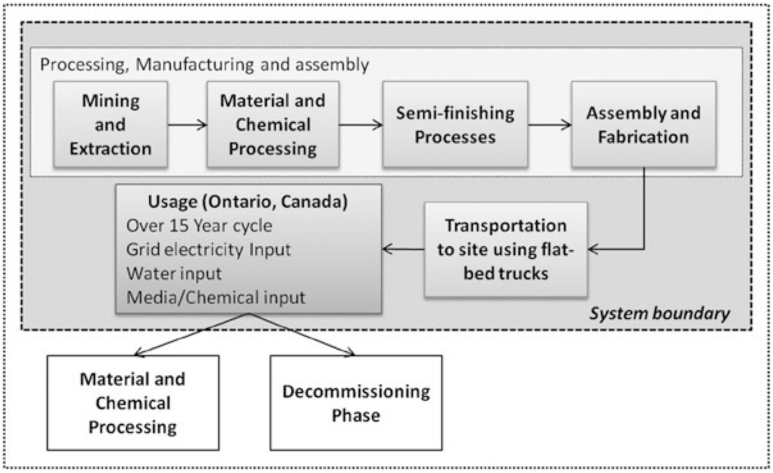


Fig. 6.9 System boundaries for the odour control technology

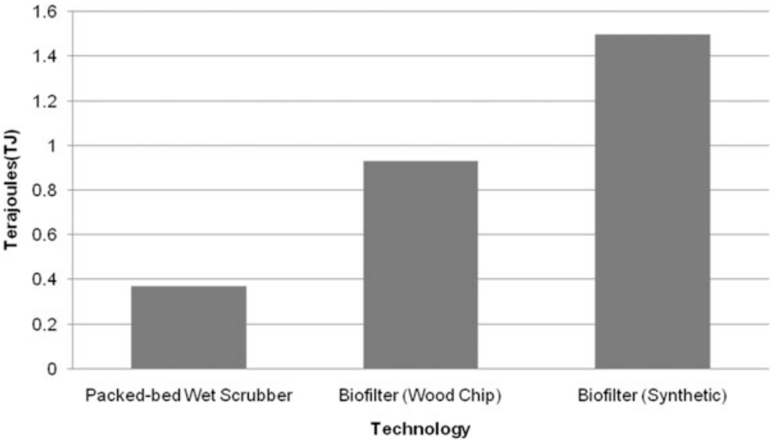


Fig. 6.10 Cumulative energy demand for each technology. (Adopted from Bindra et al. 2015)

categories were considered as a part of this study. The categories include non-toxic impact categories include cumulative energy demand (CED), climate change, freshwater, and marine eutrophication; Toxic impact categories include human, terrestrial, freshwater, and marine eco-toxicity, photochemical oxidant formation, terrestrial acidification; Resources include metal depletion, fossil depletion. The source mix of the Ontario city electricity generation for the year 2014 was considered to determine the CED. The sources of the electricity generation include nuclear (62%), hydro (24%), gas/oil (10%) and wind (4%). Figure 6.10 represents the CED for each odour control technology.

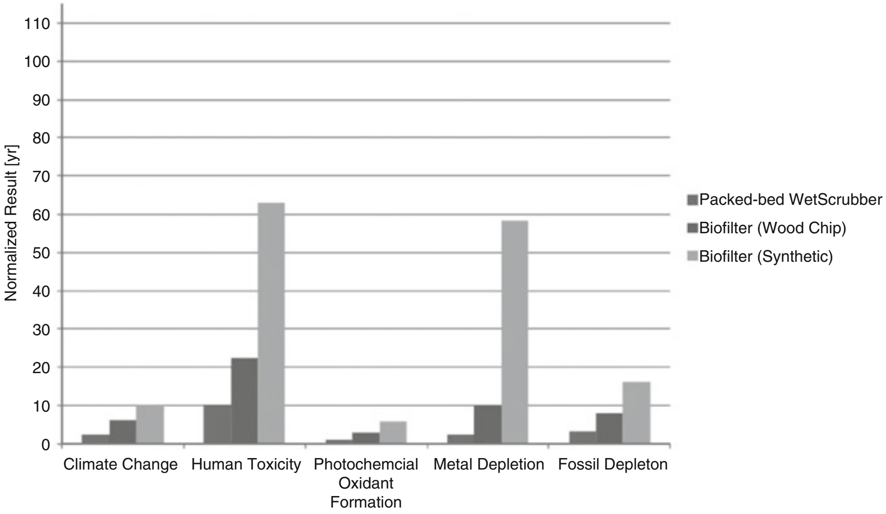


Fig. 6.11 Comparative normalized results of selected impact categories for odour control technologies. (Adopted from Bindra et al. 2015)

For the PBWS the total demand of CED is 0.37 TJ; for the OBFS with wood chip media the total demand of CED is 0.93 TJ, and for the IBFS with synthetic media CED is 1.5 TJ. The normalized impact assessment results for the non-toxic impact categories (climate change), toxic impact categories (human toxicity, photochemical oxidant formation), and resources (metal and fossil depletion) are presented in Fig. 6.11. Based on the LCA study, impact associated with the PBWS is the lowest for all the impact categories followed by the OBFS with wood chip media. The environmental impacts are highest for the IBFS with synthetic media.

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