CHAPTER 3
METHODOLOGY

3.1 Overview of the Methodology

There is still no consensus regarding which aspects should be included for optimization of waste management technologies and move towards sustainable systems. From a pragmatic perspective, sustainable development should consider three sustain areas (environmental, economic and social) of MSW technologies which are designed for a particular local authority (Singh et al., 2009). Formation of quantifiable indicators for sustainability assessment is essential for the conception of long-term municipal policies concerning the three pillars of sustainability. LCA methodology was used as the "tool" to develop sustainability indicators since it facilitates to identify life cycle inputs/outputs a particular system related to environmental, economic and social aspects and all the phases of life. The basic framework of the methodology for developing indicators and assessing sustainability via life cycle thinking is shown in Figure 3.1.

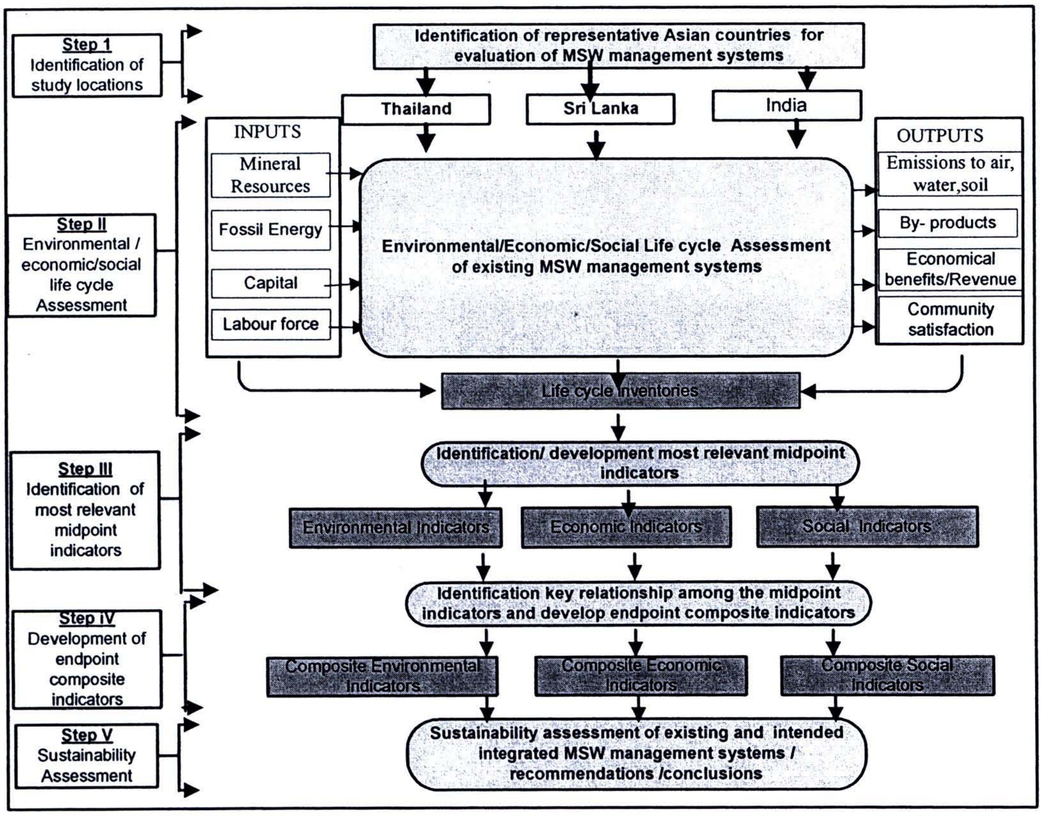


Figure 3.1: Basic framework of the research methodology

The methodology basically consists of five major steps, such as identifying study locations, life cycle inventory analysis of exiting MSW management systems for recognizing the priority issues, identifying most relevant midpoint indicators through the inventory analysis results, developing endpoint composite indicators to measure the ultimate damage/effects and sustainability assessment of existing and intended integrated systems by using developed indicators.

3.1.1 Selection of the study locations

Identification of life cycle inputs/outputs related to various MSW management systems would be the key aspect in developing sustainability indicators. However, there are a lot of deviations may expect in life cycle inputs/outputs of MSW management from one country to another due to variation of waste composition, waste generation rate, capacity of waste management methods, economic development level, population density and so forth. Three representative Asian countries were selected in order to understand the life cycle of various MSW management systems. The basic criteria for the selection of countries were the country's development levels and accessibility to more reliable and recent data on different MSW management technologies.

Considering all those aspects, three Asian countries were selected for the evaluation process, namely: Thailand, Sri Lanka and India. These selected countries have different levels of development, waste generation rate and treatment technologies. It is noteworthy to mention that magnitude of life cycle inputs/outputs or its impacts of the same technology that have been applied in different nations cannot be compared since the magnitude is highly depended on the country's waste composition and characteristics. But situation analysis of MSW management methods in the selected three countries may perhaps reflect the situation of most of the other developing countries in the Asian region. General background of MSW management of the selected three Asia countries is described below.

3.1.1.1 General background and situation of MSW management in Thailand

Thailand is situated in the Southeast Asian mainland and the area is composed of 99.6% of land and 0.4% of marine territory, and is approximately 513,000 sq km. The climate of Thailand is tropical, with an average low temperature of 23.6 ^{0}C and a high temperature of around 39-40 ^{0}C during summer. With a well-developed infrastructure, a free-enterprise economy, and generally pro-investment policies, Thailand was one of East Asia's best performers from 2002-2004, averaging more than 6% annual real GDP growth. The economic growth rate was 2.6% in 2008 and the per capita GDP-PPP (GDP-Purchasing Power Parity) was 8400 US$ (CIA, 2008).

In 2009, the volume of garbage in Thailand reached about 15.11 million tonnes, or approximately 41,410 tonnes per day. In which only approximately 3.32 million tons, or approximately 22 percent were separated and sent to recycling centers, which was a very small amount compared to the amount of garbage produced. More than 20% of the country's MSW generation is collected and disposed from Bangkok Metropolitan Area (BMA), the capital of Thailand (Nithikul et al., 2010). In the year 2009, the amount of collected solid waste only in the BMA was 8,834 tonnes. There is a potential of an annual increment of 0.2 million tonnes of MSW generation in Thailand (PCD, 2009b). This increasing amount of solid waste might come from the population growth, expansion of communities, and economic stimulus by the governmental sector, tourism promotion and development.

Before the 1990's, most of the waste collected from urban areas in Thailand was dumped in open areas but during the past decades, there has been a gradual improvement in waste disposal practice from open dumping to sanitary landfilling (Chiemchaisri et al., 2007). The fraction of collected waste being disposed by sanitary landfills and open dumpsites was found to be 47% and 53%, respectively (PCD, 2009b). According to the survey done by Pollution Control Department (PCD) in the year 2009, 107 sanitary landfill sites, three incineration plants and four integrated systems in Thailand has been identified (Table 3.1).

Table 3.1 MSW disposal facilities in Thailand in 2009 (Source: PCD, 2009b)

Sanitary Landfill	**Incineration**	**Integrated MSW systems**
In operation - 93 sites	Phuket – 250 tonnes /day	Wieng Fang (Chiang Mai) – 150 tonnes/day
Never run - 8 sites	Sumai Island – 150 tonnes/day	Rayong Municipality – 180 tonnes/day
Stop operating – 6 sites	Lamphun – 10 tonnes/day	Mae Sai – 60 tonnes/day
		Chonburi Provincial Administration* – 70 tonnes/day (* stop operation)
Total – 107 sites	Total -3 sites	Total – 4 sites

3.1.1.2 General background and situation of MSW management in Sri Lanka

Sri Lanka is an island located in the Indian Ocean, separated from India by the Palk Strait. It is located between 6° and 10° North latitude and 80° and 82° Eastern longitude. Sri Lanka has a tropical climate with little seasonal variation. It consists of three major climatic zones: wet zone, intermediate zone and dry zone. Sri Lanka has eight provinces with a total area of 65,525 km^2 and a population of 20 million people. According to a study by the Central Bank (2008), Sri Lanka has a Gross Domestic product (GDP) of US$ 4400 and an economic growth rate of 6.8%.

For administrative purpose Sri Lanka is divided into 25 districts and 9 provinces. There are 18 municipal councils, 37 urban councils, and 256 Pradeshiya Sabhas. Average per capita MSW generation was 0.89 kg/cap/day in 1999, and it has been predicted that per capita waste generation in 2025 will be 1.0 kg/cap/day (Vidanaarachchi et al., 2006). In 1999, the approximate MSW generation in Sri Lanka was estimated to be around 6400 tonnes/day (UNEP, 2001) thus at the rate of 1.2%, total MSW generation in 2009 would be approximately 7045 tonnes per day. While the Western Province, the biggest waste generator, accounts for 35% of the country's waste, the Southern Province accounts only for about 9%. House-to house solid-waste collection is being utilized by most of the municipal councils. In addition, community collection and curbside collection are also being practiced in some municipal council areas (Asian Productivity Organization, 2007). More than 85 % of the MSW is open dumped and only 5% of organic waste is being composted by windrow method. As of now there are no MSW incineration plants, though some Local Authorities (LAs) burn the waste in enclosures and technical incineration remains vague to some local bodies. There are few dry anaerobic biogas units operational on MSW feed materials and due to maintenance difficulties, the success rate of the system is reducing. Engineered landfill facilities are being considered by the LAs in Sri Lanka in recent times to overcome the problem of MSW disposal with the insight of promoting energy production and reducing global warming.

Open dumping is still practiced in Sri Lanka as the main disposal method of solid waste, leading to many environmental as well as health problems. Thus, present MSW method is a critical environmental, economic and social concern in Sri Lanka and most of the local authorities are urgently seeking a sustainable solution.

3.1.1.3 General background and situation of MSW management in India

India, the sixth largest country in the world, extends over 3.28 million square kilometers and the estimated population in the year 2009 is 1.17 billion. India has achieved 7.3% of economic growth rate in 2008 and per capita GDP is 2800 US$ (CIA, 2008). Annually, Asia alone generates 4.4 billion tonnes of solid wastes and MSW comprise 790 million tonnes (MT) of which 48 MT (6%) are generated in India (Pappu et al., 2007). Per capita waste generation rate in India is 0.3-0.6 kg/cap/day (Shekdar, 2008).

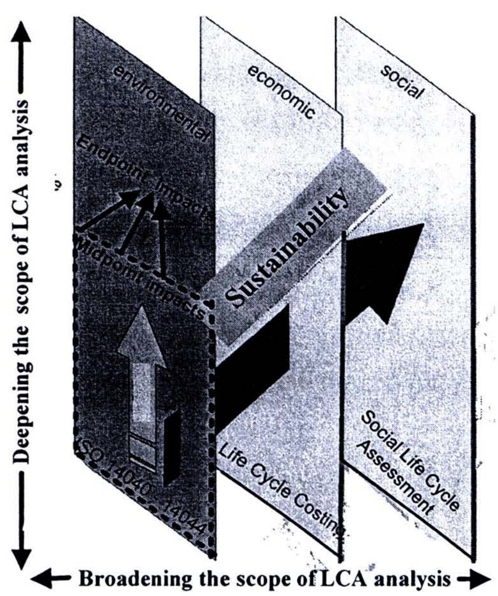
For MSW management, generally local governments are responsible, but most administrations fail to provide the service for a large section of the population. The main reason for this situation is the rapid growth of population coupled with the expansion of cities together with the diminishing financial resources (Ojha, 2010). In India, municipal bodies carry out the job by employing their own staff, equipment and other resources. Only in a few cases are parts of the activities, such as transportation, entrusted to private agencies on a contract basis. These labour-oriented systems are usually executed as a part of public health schemes by the municipal bodies. More than 90% of the MSW generated in India is directly disposed on land in an unsatisfactory manner, thereby causing a number of health, environmental and aesthetic hazards.

3.1.2 LCA methodology developed for the study in developing indicators and assessing the sustainability

This study follows the life cycle methodology to develop the sustainability indicators on environmental, economic and social perspectives and to evaluate the existing and more sophisticated potential MSW management systems for three-dimensional sustainability. Therefore, a comprehensive LCA was conducted in relation to the three pillars of sustainability, from “Cradle to Grave” including all the phases of life cycle such as auxiliary material production, collection and transportation, treatment and final disposal. Life cycle inventory analysis is the most important step that involves data collection and calculation procedures to quantify life cycle inputs (energy and material, costs, labour force) and the life cycle outputs (emissions, products, by-products, revenues, benefits to the community). The next stage of life cycle is impact assessment, which analyzes the environmental, economic and social effects/burdens associated with the material and energy flows, finance, stakeholder involvement etc that was determined in the inventory analysis phase. Therefore, based on the life cycle inventory analysis results of MSW management systems, most relevant impact indicators were identified to assess the three dimensional sustainability. LCA methodology development for the study is described in the section below.

3.1.2.1 "Broadening" and "deepening" of the scope of LCA

The goal of the study was, the incorporation of life cycle thinking approach to develop sustainability indicators on environmental, economical and social points of view for evaluating sustainability of existing and intended MSW management systems for selected Asian countries. In this regards, broadened and deepened the scope of "traditional environmental LCA assessment" to the full scale life cycle sustainability assessment. "Broadening" the LCA scope was done by better incorporating of three pillars of sustainability into a common LCA framework. "Deepening" the LCA scope was done by adding more mechanisms and/or more sophistication to measure the ultimate damages/effects instead of traditionally practice midpoint impact assessment. These modifications to the scope of LCA concept, would improves its applicability and increase its reliability and usability in three-dimensional sustainability assessment. The schematic diagram for "broadening" and "deepening" of scope of LCA is shown in Figure 3.2.



----- Scope of traditional environmental LCA assessme...

Figure 3.2: Schematic diagram for "broadening" and "deepening" of the scope of traditional LCA

3.1.2.2 Functional unit

Definition of the functional unit is a part of the goal and scope phase of the LCA methodology. The primary purpose of the functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). In addition, comparison of different MSW technologies can be done on the basis of the same functional unit. Therefore, functional unit should be defined for MSW management systems based on the origin of waste generated, composition and amount of waste generation.

Different MSW treatment facilities have diverse capacities from large to small at the treatment and final disposal phases. However, these different scale MSW management methods should be compared using the functional unit. Therefore, in this study, functional unit is refined as the "one tonne of generated MSW treatment". Once the estimation is done for a functional unit (one tonne of MSW), the environmental, economic and social impacts can be easily calculated for different plants with diverse capacities.

3.1.2.3 Defining the system boundary/LCA framework

In order to perform a "Life Cycle Sustainability Assessment", the traditional LCA system boundary was broadened to an appropriate LCA framework. It included all the phases of life cycle from "Cradle to Grave" of MSW management, including auxiliary material production (energy and raw materials), MSW collection and transportation, treatment and final disposal. In addition, LCA framework is highlighted the major life cycle inputs arrive to the system and the major life cycle outputs leave from the system with respect to the environmental, economic and social aspects. These life cycle inputs/outputs categories have to be accounted in the next phase to perform the sustainability assessment. As described below, identification of priority issues of MSW management is important to account the major life cycle inputs/outputs which are associated with the key aspects.

- Collection and transportation

It is a well known fact that MSW collection and transportation need a huge amount of energy and produce emissions to the environment. According to the mode of collection and transportation, efficiency of collection vehicles, severity of environmental impacts can vary significantly in different nations in Asia. Energy requirement for different MSW management methods cause abiotic resource depletion and various other environmental effects due to greenhouse gas emissions. Therefore, collection and transformation method of MSW in selected nations was considered in the evaluating process. Material flow analysis and energy balances were done via the LCA approach. The basic data on mode of transportation, transportation distances, type of vehicle used and their fuel efficiencies, frequency of waste collection etc was collected from the representative municipal councils in selected nations.

- *Fuel production for transportation*

Besides the direct emissions from fuel burning during the transportation, indirect emissions/resource consumption caused from the fuel production chain was taken into account. Collection and transportation of MSW require a considerable amount of fuel. Therefore, diesel production process chain of selected Asian countries was studied within the system boundary, since diesel is used as the main fossil fuel for waste transportation as well as for operation of different type of machineries at the processing and final disposal phases. The types and amount of energy sources necessary for fuel production and emissions released from the diesel production process chain (emissions from crude oil extraction in Middle East, crude oil transportation to particular Asian countries by ships, crude oil refining at the local refineries, and diesel production) was considered within the system boundary.

- *Collection vehicle manufacturing*

Materials and energy requirements for collection vehicle manufacturing process was not taken into account since it was realized that the effects of vehicle manufacturing process was not significant when the emissions and resource consumptions were accounted for a functional unit. Collection vehicles like tipper trucks and compactor trucks are used only for 6-10 years for waste collection services and during this period 14,000 -24,000 tonnes of waste can be transported (Nonthaburi Municipality, 2009). Thus, negligible environmental damage results are found from the vehicle manufacturing process when it is calculated for a functional unit. The same concept is valid for the machineries, which are used for waste handling and processing for a period of 8-10 years. Thus, energy and material consumption and emissions from manufacturing of those machineries was not taken into account.

- Electricity production

Electricity is required as a major input for the operation of equipment and machinery, in the waste processing stage by utilizing improved technologies. For instance, recycling process requires a significant amount of electricity during various operational activities. Therefore, grid electricity production process of selected nations was studied, and fossil resource consumption and emissions from grid electricity production was accounted for. In contrast, by applying "waste to energy" technologies like landfill gas to energy, anaerobic digestion, incineration etc significant amount of energy can be recuperated as electricity. Thus electricity production process can be credited in LCA perspective, for avoidance of conventional electricity production process. Therefore, all the potential credited processes that are interacting with MSW management system can be included for evaluation through the system expansion approach. The resource consumption and emissions from conventional grid electricity production of selected countries is summarized in Table 3.2.

Table 3.2: Resource consumption and emissions from grid electricity production in selected Asian countries

Country	**Thailand ***	**Sri Lanka ****	**India*****
Contribution of energy resources for grid electricity production	Natural gas – 73.4% Coal/lignite – 20.2% Fuel oil & diesel -0.70% Hydro and renewable energy – 5.40%	Hydro power -40% Thermal power (fuel oil based) -60%	Coal – 53.3% Natural gas – 10.5% Oil – 0.90% Hydro – 24.7% Nuclear – 2.90% Renewable sources -7.7%
Fossil fuel consumption to produce 1 MWh	Lignite – 197 kg Fuel oil & diesel – 2.03L Natural gas – 173 m^3	Fuel oil -117 kg	Coal – 305 kg Natural gas – 24.3 m^3 Oil - 2.18 kg
Emissions (from 1 MWh electricity production)	CO_2 – 566 kg CO – 0.461 kg NO_x – 1.77 kg CH_4 - 0.0475 kg SO_2 – 2.39 kg PM_{10} – 0.542 kg	CO_2 – 362 kg CO – Negligible NO_x – 1.62 kg CH_4 - Negligible SO_2 – 3.61 kg PM_{10} – Negligible	CO_2 – 648kg CO – 0.147 kg NO_x – 1.64 kg CH_4 - 0.0525 kg SO_2 – 4.18 kg PM_{10} – 0.00578kg

(Sources: * DEDE, 2008; EGAT, 2008 ** Ceylon electricity board, 2007; *** Ministry of Power, 2009; Chakraborty, 2008; Kannan, 2005)

- Thermal energy production

Thermal energy is needed as a major input during the processing phase of waste management technologies like recycling. Therefore, different types of fossil energy consumption, amount of fossil resources requirement, furnace efficiencies, emissions from combustion, etc were accounted for within the system boundary for functional unit of waste treatment. Whenever online databases were used (eg: eco-invent) to find the thermal energy requirement for a unit process of MSW, it was adjusted to the local situation (databases values represent the situation of Europe) based on the potential energy sources available for supplement of same amount of thermal energy. Also, emissions from combustion of local fuel sources were taken into account in the inventory analysis. This kind of adjustment would be useful for avoiding uncertainties of the analysis work.

- Defining the LCA framework for existing and intended sustainable MSW management systems

Considering all the above aspects, LCA framework was defined for the existing MSW management systems in selected three Asian countries as the base scenario. As the next step, sanitary landfill with landfill gas collection system was assessed since it would be the initial step towards the sustainable development. Therefore, the LCA framework was defined for sanitary landfill with landfill gas collection systems for the sustainability assessment.

Then, the potential sustainable integrated approaches had to be identified for three countries based on waste characteristics, local climatic situation, and development stage, the countries specific policies and regulations and so forth. Therefore, LCA frameworks were defined for the intended sustainable integrated approaches by combining appropriate technologies to treat different fractions of waste. Potential material and energy recovery processes were also included within the framework via system expansion process. As an example, the LCA frameworks for an existing MSW management system (open dumping), sanitary landfill with landfill gas recovery system and a potential integrated approach have been shown in Figures 3.3 to 3.5.

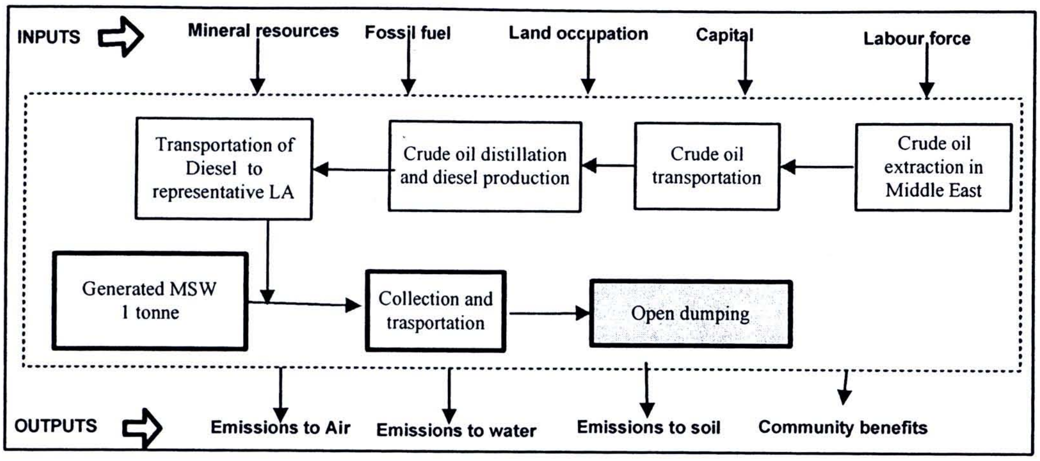


Figure 3.3: LCA framework for the existing MSW management system

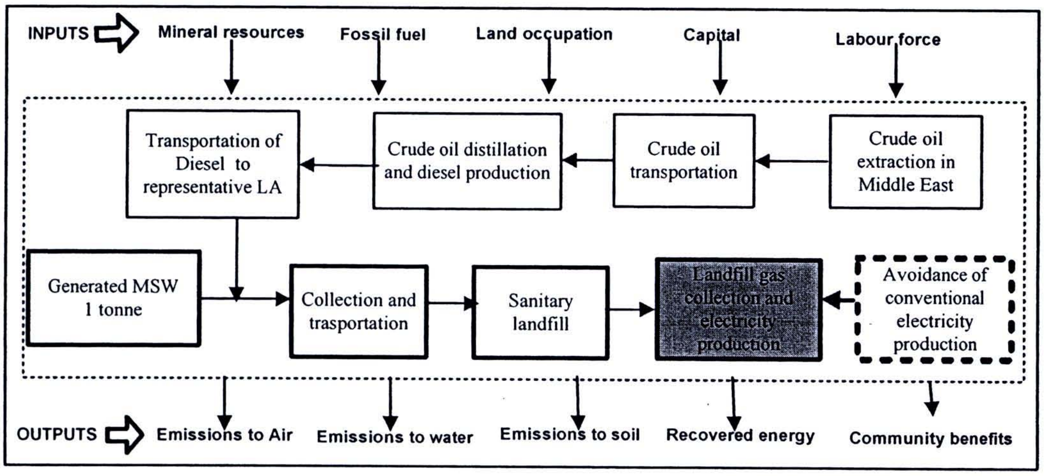


Figure 3.4: LCA framework of sanitary landfill with landfill gas recovery

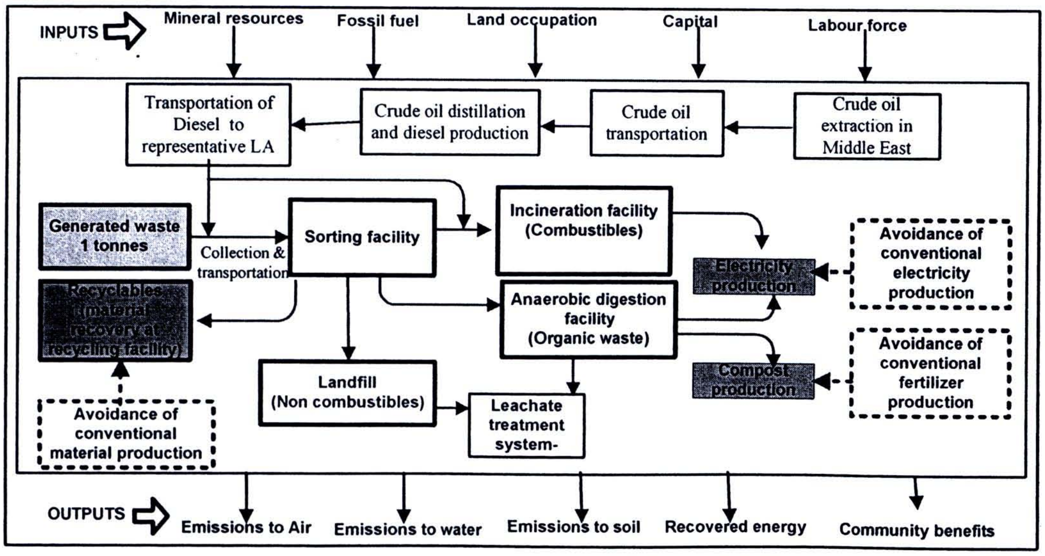


Figure 3.5: LCA framework of the intended integrated MSW management system

3.1.2.4 Life cycle inventory analysis

In this phase, the inventory analysis was carried out to gather all the required data related to environmental, economic and social aspects while following the complete chain of the life cycle. Thus, compiling of all the inputs and outputs, such as raw material, energy consumption, environmental emissions to the air, water, and soil under the different phases of life cycle was done within the defined LCA framework for identifying the most relevant environmental indicators and then assessing the environmental sustainability. In addition, all the costs and revenues involved in different phases of the life cycle were gathered in relation to various MSW management technologies to perform the financial sustainability assessment. Major social issues that are associated with MSW management, like direct and indirect income generation methods for the community from the particular MSW management methods, creation of employment opportunities, potential health hazards, etc were accounted for throughout the life cycle for the purpose of social life cycle assessment. In this phase, various data sources such as onsite data, electronic databases, literature data, plant records, and estimations/calculations were used to find the required massive amount of life cycle data. Types of data required for the assessment and the sources of data collection are summarized in Table 3.3.

Most of the data that has been used for assessment of MSW management systems in Thailand is onsite data. For instance, specific onsite data was collected by visiting MSW management facilities in Thailand such as, sorting facilities (Nonthaburi), Wonpanit group (recyclables collecting companity), sanitary landfill (Nonthaburi), various recycling facilities (paper, plastic, aluminium, metal and glass), incineration plant (Phuket) and anaerobic digestion facility (Rayong). If onsite data were not available, electronic databases were also used, especially to find out the potential life cycle emissions from improved technologies like recycling. In the case of primary data was not available, secondary data from published journals and technical reports had to be used, after a careful revision. Some reasonable assumptions/estimations were also made in some instances since required information was not available.

Unlike in Thailand, there are no existing appropriate MSW management technologies in Sri Lanka and India. Therefore, a lot of assumptions had to be made, and most of the time, the real data which are obtained from Thailand were adjusted to the situation of Sri Lanka and India. However, questionnaires were made and information gathered pertaining to each country's specific economic, social and transportation conditions.

Table 3.3: Types of data required for life cycle inventory analysis

Sustainability assessment	Phases of the life cycle	Data required	Data sources
Environmental life cycle assessment	MSW collection and transportation	-Emissions from fuel production chain (crude oil extraction, transportation, refining, diesel production, diesel transport to representative local authority) -Emissions from burning of fuel in collection vehicles -Vehicle specifications (capacity of vehicle, fuel consumption, transportation distances)	-LCA data bases (SimaPro) -Report from international organization (LIPASTO traffic emissions) -Literature review data -Catalog of collection vehicle manufacturing companies - Local authority's reports
	MSW treatment	-Waste generation rate of the particular local authority, composition of waste, physical and chemical characteristics of waste -Types of technologies use for different fraction of MSW treatment -Mass balances and energy balances of each treatment technology - Resources/ materials consumption and emissions from different treatment methods -Energy consumption data (electricity and thermal) for processing and its emissions -Auxiliary material requirement for processing and its emissions	-Site specific data from representative local authorities -Literature review data -Site specific data from representative local authorities -Plant specific data on waste processing plant -Calculation based on primary data collection, -Electronic databases (ecoinvent, SimaPro) -Country specific technical reports from responsible organizations -Literature review
	Final disposal	- Emissions from various machinaries, and from final disposal itself	-Site specific data from representative local authorities - Literature sources
Economic Life Cycle Assessment	MSW collection & transportation	-Market price of vehicles -Durability/life time of collection vehicles, capacity of vehicles	-Vehicle manufacturing company reports/catalog of vehicle model
	MSW treatment	-Annual capital expenditure for waste treatments, (land cost, equipments cost) -Total operational and maintenance cost (cost of labour, fuel, electricity, water, auxiliary materials and any other utilities), insurance, tax -Cost of environmental emissions/resource consumption (Monetization values)	-Plant specific data from plant reports -Plant specific data from plant reports, questionnaire survey, interview with top management, -Electronic databases, literature papers
	Final disposal	-Capital cost for final disposal facility (land cost, machinery cost etc) Operational cost (cost of fuel, labour, utilities, maintenance of machineries),	-Site specific data from representative local authorities -Site specific data from representative local authorities or privet companies

Social Life Cycle Assessment	MSW collection & transportation	-Labour power requirement for collection and transportation activities -Health issues arises with collection and transportation activities	-Interview with representative local authorities, companies -Databases, models to quantify the emissions based health effects
	MSW treatment	-Direct and indirect income generation potential to the community -Skilled and unskilled employment opportunities creation -Working hours, employees benefits -Health issues arises with particular treatment methods	-Interview with representative LAs, privet companies - Interview with representative local authorities, companies -Plant specific annual reports /sustainability report -Databases, models to quantify the emissions
	Final disposal	-Indirect income generation potential to the workers/labours -Skilled and unskilled employment opportunities creation Health issues arises with particular treatment methods	-Interview with workers who are working at sites -Interview with representative local authorities, companies, -Databases, models to quantify the emissions-based health effects

3.1.2.5 Impact assessment - Identification of the most relevant midpoint indicators via life cycle inventories

Environmental sustainability can be summarized as rational resource consumption and reduction of environmental pollution. Priority issues of environmental assessment might vary from one nation to another based on MSW management rules, regulations and standards. However, to measure the major environmental burdens which are associated with the emissions and resource consumption, a set of indicators was identified via life cycle inventories as the most relevant midpoint indicators. Then, calculations were made to see the magnitude of the environmental impacts potentials considering the effects of different type of emissions on the same impact category. In mathematical expression, the sums of the impact potentials for the emissions occurring throughout the life cycle can be estimated by using the following mathematical expression (Wenzel et al., 1997).

$$\sum EP(j)_i = Q_i \times EF(j)_i$$

Where: $EP(j)_i$, is the i's potential contribution to the environmental impact category j, Q_i is the magnitude of the emission of substances i, $EF(j)$ is the substance's equivalency factor (EF) for the environmental impact category j.

This type of indicator combines the effect of a number of components. Thus, these aggregated indicators can be re-named as midpoint indicators in life cycle perspective and are useful for scientific decision making (Pennington et al., 2004; Rebitzer et al., 2004). The next section has summarized the effects of the basic emissions and resource consumption from MSW management on different types of environmental burdens. To measure the severity of the burdens the most relevant mid point indicators were identified and the usefulness of each indicator in sustainability assessment is described below.

Global warming potential (GWP)

Global warming potential is the main environmental indicator since MSW management methods contribute to a major share of anthropogenic greenhouse gases (GHG) production. In fact, the waste sector contributes approximately 5% of the global greenhouse budget (IPCC, 2006). This 5% consists of methane (CH_4) emission from anaerobic decomposition of solid waste (IPCC, 2006). The effect of methane is 25 times worse than the CO_2 in terms of global warming potential. GHG emissions potential from MSW management methods are becoming increasingly important for assessing sustainability. According to the LCA study that was done by Banar et al, (2008), non-engineered landfill situation can create GWP of 6,990 kg of CO_2 equivalent from one tonne of disposed MSW especially due to the CH_4 emissions. When compared to incineration and anaerobic digestion like improved MSW management technologies, the GWP is considerably lower than non engineered landfill (Chaya and Gheewala, 2007). However, net GWP from improved technologies can be further reduced through materials and/or energy recovering processes and those processes can be credited. Apart from MSW treatment, GHG emissions (CO_2, CO) from transportation and handling of machineries are also significant. Thus, estimation of GWP from proposes MSW management system would be an appropriate indicator for decision making process prior to implementation.

Abiotic resource depletion potential (ADP)

Fossil energy and mineral resources are essential for the development of a country and those resources are finite and lack sustainability. In fact, due to high consumption rate, the world's oil reserves are estimated to be depleted by 2050 (Saxena et al., 2009). Management of MSW is associated with fossil energy consumption, especially for collection, transportation operations and maintenance. In contrast, there is a possibility of reducing abiotic resources depletion by selecting appropriate solid waste management technologies such as recycling, waste to energy, composting etc., and those processes can be credited for avoiding virgin production process. For instance, in Sri Lanka, there is a potential for providing 2.5% of total energy requirement (maximum per capita energy consumption in Sri Lanka is 5000kWh) which is sufficient to provide 42% of electricity requirement for the communities by applying waste to energy concepts (Menikpura and Basnayake, 2009). Therefore, recuperation of energy from MSW would be a good solution to replace fossil fuel consumption so as to reduce abiotic resource depletion. Estimation of abiotic resource depletion potential from any MSW management system would be an appropriate indicator for decision-making process.

Photo-oxidant formation potential (POFP)

Formation of tropospheric ozone has been recognized as one of the most important environmental threats on a regional scale due to its influence on human health, degradation of materials, and induced crop yield reduction. Emissions of CO, NO_x and VOCs from different MSW treatment technologies can contribute to photo-oxidants formation and it is usually measured relative to the ethylene and is expressed as C_2H_4 equivalents (Guinée et al., 2001). Many communities in the developing world, burn MSW at dumpsites to reduce the volume of waste which contributes to significant emissions of VOCs, CO and NO_x (Lemieux et al., 2004). Incineration and composting of MSW also contribute to such emissions. Other activities of MSW management systems such as transportation, electricity consumption and auxiliary material production also contribute to VOC, CO and NO_x emissions and should not be neglected. Therefore, estimation of overall photo- oxidant formation potential of proposed MSW management system for entire life cycle would be an important indicator for assessing environmental sustainability on decision making.

Acidification Potential (AP)

The major acidifying substances which can be released from MSW management methods are NH_3, SO_x, H_2S, NO_x and HCl compounds. Acidifying pollutants reach the atmosphere and react with water vapor to form acids. This can influence as a regional environmental effect and can have a severe influence on biotic compounds (Guinée et al., 2001). Acidification potential for each acidifying emission is expressed as kg SO_2 eq. According to the MSW elemental composition (Tchobanoglous et al., 1993), food waste and garden waste have the higher nitrogen percentages among the biodegradable components which is amounted to 2.6%, 3.4% of dry weight respectively. Sulfur content of biodegradable waste is around 0.2-0.4% of dry weight. Based on Nielsen and Hauschild (1998) landfill model, 50% of total nitrogen and 50% of total sulfur can be released to the atmosphere as NH_3 and

H_2S during the degradation process which can be the major acidifying substances under open dumping and non engineered landfilling situation. Moreover, incineration can emit higher NO_x and SO_x concentrations and can cause higher acidification potential (Liamsanguan, 2005) since leather, textile like high energy waste components consists of the highest percentages of nitrogen and sulfur (Tchobanoglous et al., 1993). Furthermore, significant amounts of NOx and SOx can be emitted from fuel production, and waste transportation. Thus, quantification of potential acidifying substances emissions and acidification potential would be an appropriate decision supportive indicator.

Eutrophication potential (EP)

Eutrophication covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an increase in the aquatic plant growth and/or shift in species composition in both aquatic and terrestrial ecosystems. Eutrophication potential for each eutrophying emission to air, water and soil is generally measured in PO_4^{3-} eq./kg or NO_3^- eq/kg emission (Guinée et al., 2001).

The high fraction of food waste, garden waste, etc. in MSW can release significant amounts of eutrophying substances to the environment. Open dumps and landfills would be the major sources where 50% of total nitrogen can be emitted as leachate NH_4^+/NO_3^- (Nielsen and Hauschild, 1998) which can highly influence the eutrophication potential at the regional level. Incineration, composting and anaerobic digestion have the potential of releasing significant amount of NO_3^- and PO_4^-substances to the environment. In addition to the main treatment technology, potential emissions from N and P compounds transportation, energy consumption, raw material extraction, lime production (for incineration), energy and fertilizer production from conventional methods and energy and material saving from recycling, waste to energy concept (to calculate avoided emissions), etc. should be taken into account via the life cycle approach of different MSW management technologies in order to calculate the overall impact.

Human toxicity potential (HTP)

Human toxicity can be caused by a number of different aspects such as acute toxicity, irritation/corrosive effects, allergenic effects, irreversible damage, genotoxicity, carcinogenic effects, toxicity to reproductive system/teratogenic effects, and neurotoxicity. Emission of VOCs, NO_x, SO_x, NH_3 and PM_{10} compounds from MSW management systems can make its influence on human toxicity. The human toxicity potential (HTP) for each emission of a toxic substance to air, water and soil is often measured relative to 1,4 dichlorobenzene and is expressed as kg 1,4 DB eq (Guinée et al., 2001). It should be noticed that human toxicity potential (HTP) is also originated from acidifying emissions. Most of the health damagers from MSW management systems can be caused due to human toxicity potential and it can be measured as "damage to human health" considering the ultimate damage.

Land Occupation (Ecological footprint)

Land occupation (LO)/ecological footprint (EF) measures the demands that humans place on nature and it serves to sharpen the focus on the ecological requirements for sustaining human settlements (Rapport, 2000). It provides a quantitative assessment of the biologically productive area required to produce the necessary resources (food, energy, and materials) and to absorb the wastes of a given population (Wilson et al., 2007). Present poor solid waste management practices occupy a considerable fraction of productive land area for MSW management technologies as well as for releasing huge load of emissions (Ngoc and Schnitzer, 2009). As a result, it has created pressure on human living standards due to unavailability of adequate productive land for dwellings and it may have its influence as a critical social issue (Den Boer et al., 2007). Moreover, land occupation and land conversion for a waste management facility would have its influence on ecosystem quality and ultimate damage.

In order to derive the direct land consumption (transportation, treatment facilities, final disposal, etc.), the following formulas are used, based on the concept explained by Huijbregts et al, (2008).

$$LO_{Direct(Local)} = \sum_{a} A_a \times t_a$$

Where, LO_{Direct} is direct land occupation (m^2 yr), A_a is the occupation of area by local land use type *a* (*a* – direct land use for disposal, treatment facility etc) (m^2), t_a-occupation time (years).

Indirect land occupation for CO_2 emissions from fossil energy consumption and from the treatment process in local scale can be found using the following formula. Even though, this kind of assessment is not suitable for all cases, this concept can be helpful for applying Clean Development Mechanism (CDM) under Certified Emissions Reductions (CER) for avoidance of CO_2 emissions.

Thus, indirect land occupation for CO_2 absorption can be calculated as follows (all the greenhouse gas emissions can be converted to CO_2 equivalent).

$$EF_{CO_2(Local)} = M_{CO_2} \frac{1 - F_{CO_2}}{S_{CO_2}}$$

where EF_{CO2} is the ecological footprint of indirect land occupation (local) by related CO_2 emissions (emissions from treatment, emissions from fossil energy consumption, etc.) (m^2.yr), M_{CO2} is the product-specific emission of CO_2 (kg CO_2), F_{CO2} is the fraction of CO_2 absorbed by oceans (one-third of anthropogenic emissions absorbed by the oceans from the total anthropogenic emissions (IPCC, 2006)), S_{CO2} is the sequestration rate of CO_2 by biomass (kg CO_2 $m^{-2}yr^{-1}$).

Total local land occupation can be found by adding all those direct and indirect local land occupation, Furthermore, the net land occupation in local level can be derived by incorporating credited land occupation from valuable by-products production.

3.2 Development of Endpoint Composite Indicators for Assisting Three-Dimensional Sustainability

So far, a set of appropriate midpoint environmental indicators were identified as a probing tool for scientific decision making process on sustainability. Furthermore, mathematical formulae were developed to quantify the environmental indicators in a methodical approach considering all the phases of life cycle. Moreover, to assess the sustainability in a tangible way, a set of endpoint composite indicators were developed as the major research findings of this study. Therefore, development of sustainability indicators is presented in a separate chapter (Chapter 4) in the results and discussion.