ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF ORGANIC FRACTION OF MUNICIPAL SOLID WASTE TREATMENT BY COMPOSTING AND ANAEROBIC DIGESTION: A CASE STUDY IN SRI LANKA

BY

MS. WELIGAMA THUPPAHIGE RASANGIKA THATHSARANEE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING AND TECHNOLOGY)

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Thesis Title	ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF ORGANIC FRACTION OF MUNICIPAL SOLID WASTE TREATMENT BY COMPOSTING AND ANAEROBIC DIGESTION: A CASE STUDY IN SRI LANKA
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ABSTRACT

The management of solid waste has continued to be a significant issue in Sri Lanka. Since a large amount of organic waste is produced, thus it is important to find an appropriate option for treating the organic fraction of municipal solid waste (OFMSW). Composting or anaerobic digestion systems are widely adopted in managing OFMSW. The present study focuses to assess the environmental impacts of both anaerobic digestion and composting systems using life cycle assessment (LCA). The study was carried out in the anaerobic digestion and composting plants located in Kaduwela, Sri Lanka. The inventory data were collected from direct interviews and field measurements. The ReCiPe 2016 available in the SimaPro 9.1.0.11 was used as the impact assessment methodology. The collected inventory data were related to 1 tonne of OFMSW. Based on the inventory data, the composting plant consumes 3.12 kWh electricity, 29.1 L water, and 1.59 L diesel for the treatment of 1 tonne of OFMSW and produces 97.1 kg/tonne OFMSW of compost. The anaerobic digestion plant consumes only 0.0948 electricity and 28.8 L of water for the treatment of 1 tonne of

OFMSW and results in 3.73 kWh net electricity production. Based on the field measurements, 4 kg of methane (CH_4), 3.17 kg of ammonia (NH_3), and 0.3 kg of nitrous oxide (N_2O) per tonne of OFMSW are emitted from the composting plant, while $1.47\times10^{-6}\pm0.99$ kg NH_3 and 6.82 ± 0.02 kg CH_4 per tonne OFMSW are emitted from the anaerobic digestion plant. The impact assessment results indicated that global warming human health and terrestrial ecosystem impact categories are highly influenced by both composting and anaerobic digestion systems, whereas fine particulate matter formation and terrestrial acidification are highly influenced by the composting system. Finally, a total environmental load of 3.95 points for the anaerobic digestion plant and 12.46 points for the composting was calculated. Therefore, the total environmental load is three times higher in the composting system than the anaerobic digestion system thus the anaerobic digestion process makes the most viable option for treating OFMSW in Sri Lanka.

Keywords: Anaerobic digestion, Composting, Environmental impacts, Impact assessment, Inventory analysis, Life cycle assessment, Organic fraction of municipal solid waste

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Ms. Weligama Thuppahige Rasangika Thathsaranee

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LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	Terms
CHP	Combined heat and power
DALY	Disability-adjusted life year
FID	Flame ionization detector
GHGs	Greenhouse gases
GDP	Gross domestic production
ISO	International organization for Standardization
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
MSW	Municipal solid waste
OFMSW	Organic fraction of municipal solid waste
POP	Persistent organic pollutants
TCD	Thermal conductivity detector
TS	Total solids
VOC	Volatile organic compounds
VS	Volatile solids
USD	U.S. dollar

CHAPTER 1
INTRODUCTION

1.1 Background

The rising amount of solid waste due to the increasing population, industrialization, rapid urbanization, growing economy, and increasing resource consumption has continued to be a global issue around the world (Cadena, Colón, Artola, Sánchez & Font, 2009b; Laurent et al. 2014). The annual production of solid waste in the world is 17 billion tonnes (Laurent et al. 2014). Among this, 1.3 billion tonnes are known as municipal solid waste (MSW) which causes harmful effects (Elwan, Arief, Adzis & Muhamad, 2015; Laurent et al. 2014). Recently, the importance of adequate waste management has been emphasized over the world to ensure environmental protection and human health.

Although, the objective of waste treatments is to reduce the environmental impacts, there are still unavoidable impacts associated with these treatment options. Therefore, using multiple techniques and approaches such as EASEWASTE, ORWARE, and WASTED, evaluations of such treatments have been carried out worldwide (Cadena, Colón, Artola, Sánchez & Font, 2009b). However, there has been a major shift towards the life cycle assessment (LCA) which is known as an important tool for environmental assessment that aims to predict the total environmental impacts by gathering all inventories, compiling impact assessment, and interpretation (Liamsanguan & Gheewala, 2008a; Wittmaier, Langer & Sawilla, 2009).

Due to the lack of financial support, expertise, and experience, Sri Lanka also faces severe waste management issues. The overall production of MSW was 7,250 tonnes/day in 2009 (Menikpura, Gheewala & Bonet, 2012), and it was found that the generation of MSW per capita was projected to increase to 1 kg/capita/day by 2025 (Maheshi, Steven & Karel, 2015). Although Sri Lankan local authorities are responsible for the waste management in their jurisdictions, they have failed to provide adequate services (Dissanayaka & Vasanthapriyan, 2019; Liyanage, Gurusinghe, Herat & Tateda, 2015). Only half of the generated waste (3500 tonnes/day) is collected and transferred to disposal sites by local authorities (Dissanayaka & Vasanthapriyan, 2019).

Anaerobic digestion and composting have been used for the biological treatment of organic waste in a few local authorities.

Furthermore, composting is known as the process of aerobic conversion of organic matter into compost, which is used as organic fertilizers (Cadena, Colón, Artola, Sánchez & Font, 2009b; Narayana, 2009; Sharholy, Ahmad, Mahmood & Trivedi, 2008).

The anaerobic digestion process essentially relies on the activities of microorganisms that transform organic matters under anaerobic conditions into biogas (Adekunle & Okolie, 2015; Sharholy, Ahmad, Mahmood & Trivedi, 2008). The biogas is mainly used for heat and electricity production and the produced liquid slurry is recovered as a fertilizer or low-quality soil conditioner.

1.2 Problem statement

MSW management in Sri Lanka remains a significant challenge due to the higher organic content (Vidanaarachchi, Yuen & Pilapitiya, 2006) which contributes to harmful environmental impacts if not properly managed. Therefore, sustainable solid waste treatments are much needed to mitigate the associated impacts of organic fraction of municipal solid waste (OFMSW). Chemical and physical characteristics, including high organic fraction, high moisture content, and low calorific values of solid waste make it more suitable for biological conversion technologies such as anaerobic digestion and composting. Environmental impact assessment of these technologies can help in selecting the most appropriate treatment for handling organic waste.

As far as environmental impact assessments are concerned, few impact assessments using LCA were conducted in Sri Lanka on open dumping (Maheshi, Steven, & Karel, 2015; Menikpura, Gheewala, & Bonet, 2012). However, no studies were conducted on composting or anaerobic digestion either. Thus, it becomes essential to conduct LCA on composting and anaerobic digestion.

1.3 Objectives

1. To assess the environmental impacts of OFMSW treatment by anaerobic digestion and composting using LCA.
2. To compare the environmental impacts of two treatment methods and identifying the most suitable option.

1.4 Scope of the study

The present study was conducted in the full-scale composting and anaerobic digestion plants located in Kaduwela, Sri Lanka. The primary data were obtained from direct interviews and field measurements. The necessary secondary data were gathered from specific databases, literature, and reports. In this study, the definition of goal and scope, inventory analysis, impact assessment, and interpretation, were considered for the LCA. SimaPro 9.1.0.11 was used for setting up the LCA models.

CHAPTER 2
REVIEW OF LITERATURE

2.1 Overview of solid waste

Waste is known as any garbage, sludge, refuse, and other rejected materials that are discarded from municipal, industrial, commercial, and agricultural activities (Basu, 2009). Based on its physical status, source of origin, and degree of environmental effect, waste is classified into various categories (Figure 2.1). Based on that, household, industrial, agricultural, commercial, demolition and construction, and mining are categorized as the main sources of waste.

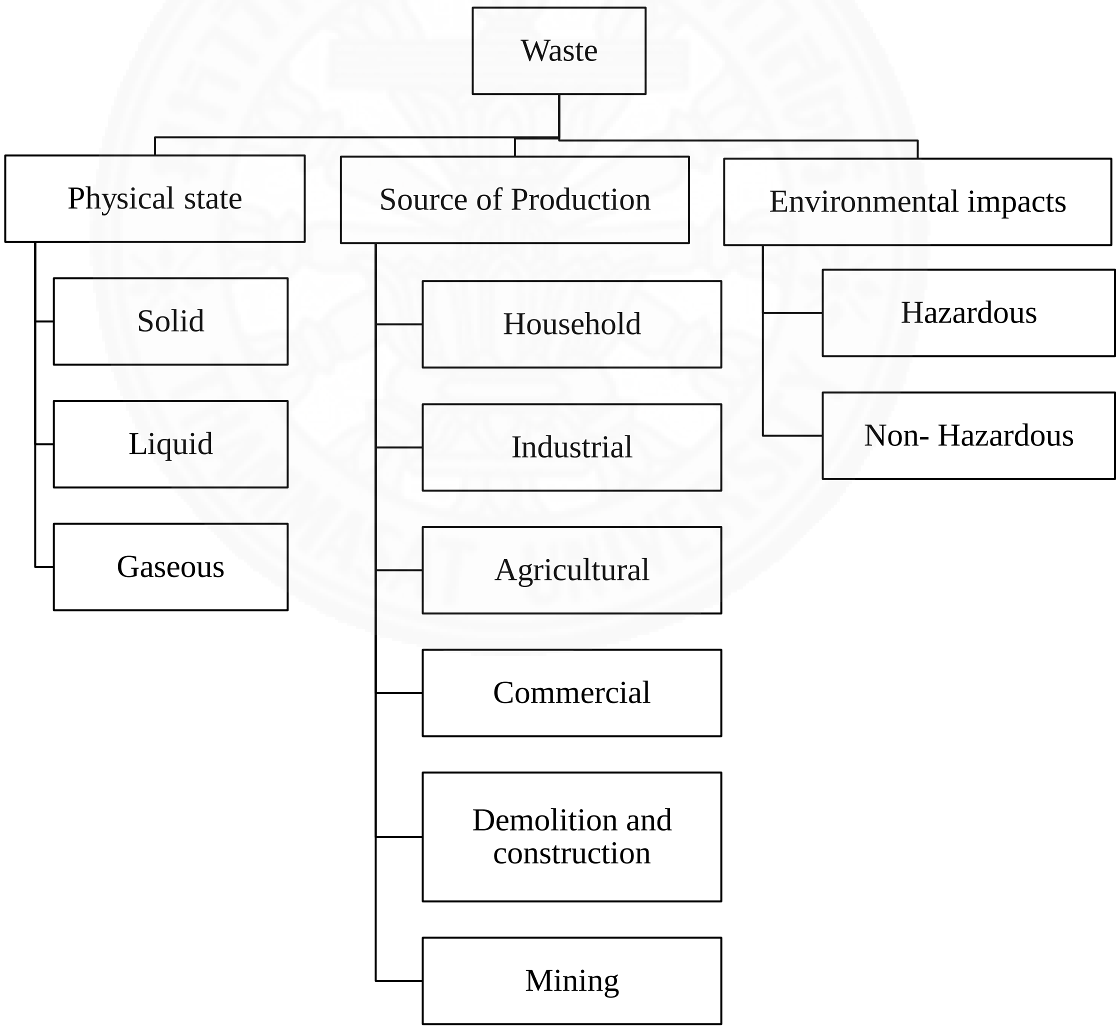

Figure 2.1 The most common waste classifications (Amasuomo & Baird, 2016).

2.2 Municipal solid waste

MSW is known as undesirable materials or waste mostly generated from households and municipal services (Suma et al. 2019). Residential, business, institutional premises, and municipal services are considered as the main sources of MSW (Table 2.1). Among them, the highest contribution to MSW generation is from the residential sector (Chanhthamixay, Vassanadumrongdee & Kittipongvises, 2017).

Table 2.1 Sources of MSW (Amasuomo & Baird, 2016).

Sources	Typical waste generators	Solid waste types
Residential	Single and multifamily households	Organic waste: garden and food waste, cardboard, paper, plastics, glass, textiles, metals, other waste: electronics waste, hazardous waste
Business	Shopping centers, restaurants, hotels, office buildings, markets	Food residues, cardboard, paper, plastics, wood, glass, metal parts, bulky waste, hazardous waste
Institutional	Schools, hospitals, prisons, government centers,	Organic waste: food and garden waste, cardboard, paper, wood residues, plastics, metals, glass, hazardous waste
Municipal activities	Roadsides, park areas, recreational areas	Street sweepings, tree trimmings, waste from the park, beaches, and recreational areas

2.2.1 Municipal solid waste generation

Increasing population growth, industrialization, rapid urbanization, higher resource consumption, and economic development have been identified as major influences for rising solid waste generation (Cadena, Colón, Artola, Sánchez & Font, 2009b; Elwan, Arief, Adzis & Muhamad, 2015). The world’s estimated annual waste generation is 17 billion tonnes, and 27 billion tonnes are predicted to be produced by 2050 (Laurent et al. 2014). Among them, 1.3 billion tonnes have been identified as MSW and it is projected to approach 2.2 billion tonnes by 2025 (Elwan, Arief, Adzis & Muhamad, 2015; Laurent et al. 2014). However, estimated per capita waste generation can be seen as 1.2 kg/capita/day (Elwan, Arief, Adzis & Muhamad, 2015; Pansuk, Junpen & Garivait, 2018; Stan, Collaguazo, Streche, Apostol & Cocarta, 2018) and it is expected to rise to 1.42 kg/capita/day by 2025 (Elwan, Arief, Adzis & Muhamad, 2015).

Based on the proportion of waste generation by region (Figure 2.2), Kaza, Yao, Bhada-Tata and Woerden (2018) indicated that the largest share of waste generation (23%) have found in East Asia and the Pacific region followed by Europe and Central Asia (20%), South Asia (17%), North America (14%), Latin America and the Caribbean (11%), Sub-Saharan Africa (9%), and the Middle East and Africa (6%).

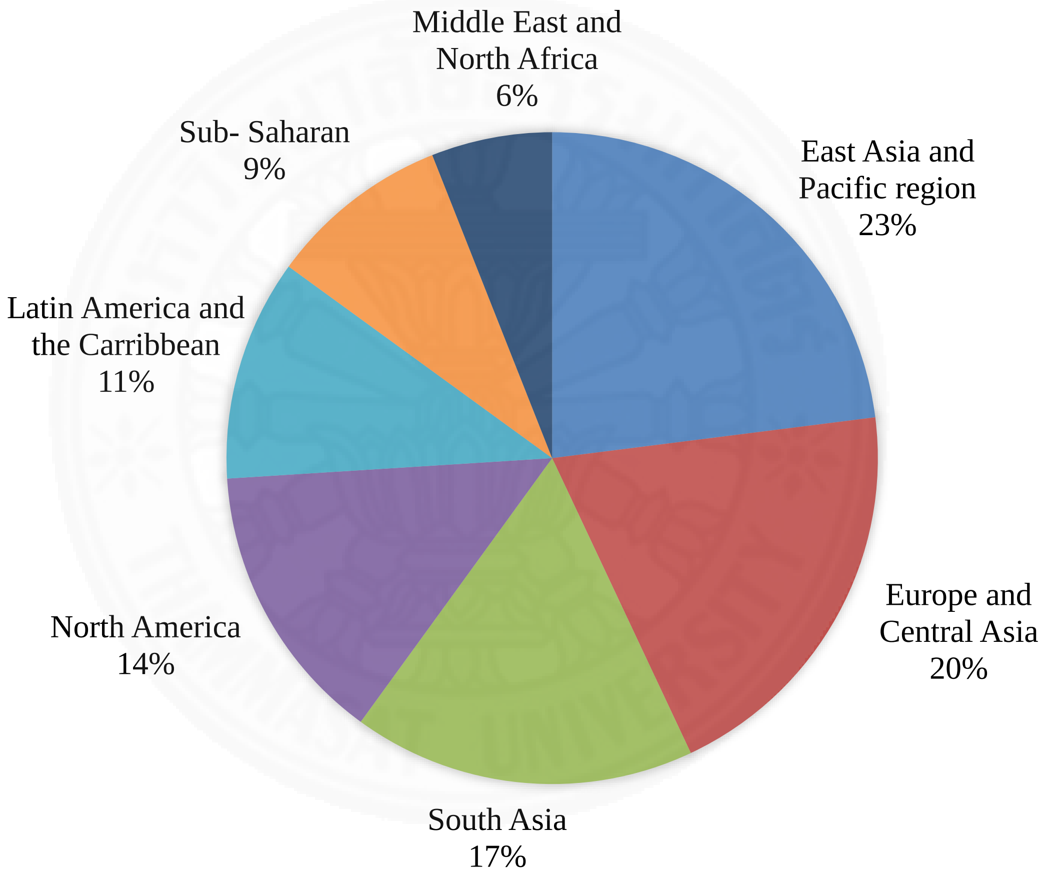

Figure 2.2 Waste generation, by region (%) (Kaza, Yao, Bhada-Tata & Woerden, 2018).

Based on the amount of waste generation (Figure 2.3), being the world's largest waste producer, East Asia, and the Pacific region generates 468 million tonnes of waste. Moreover, the Middle East and North Africa documented 129 million tonnes of waste while becoming the least waste producer (Kaza, Yao, Bhada-Tata & Woerden, 2018).

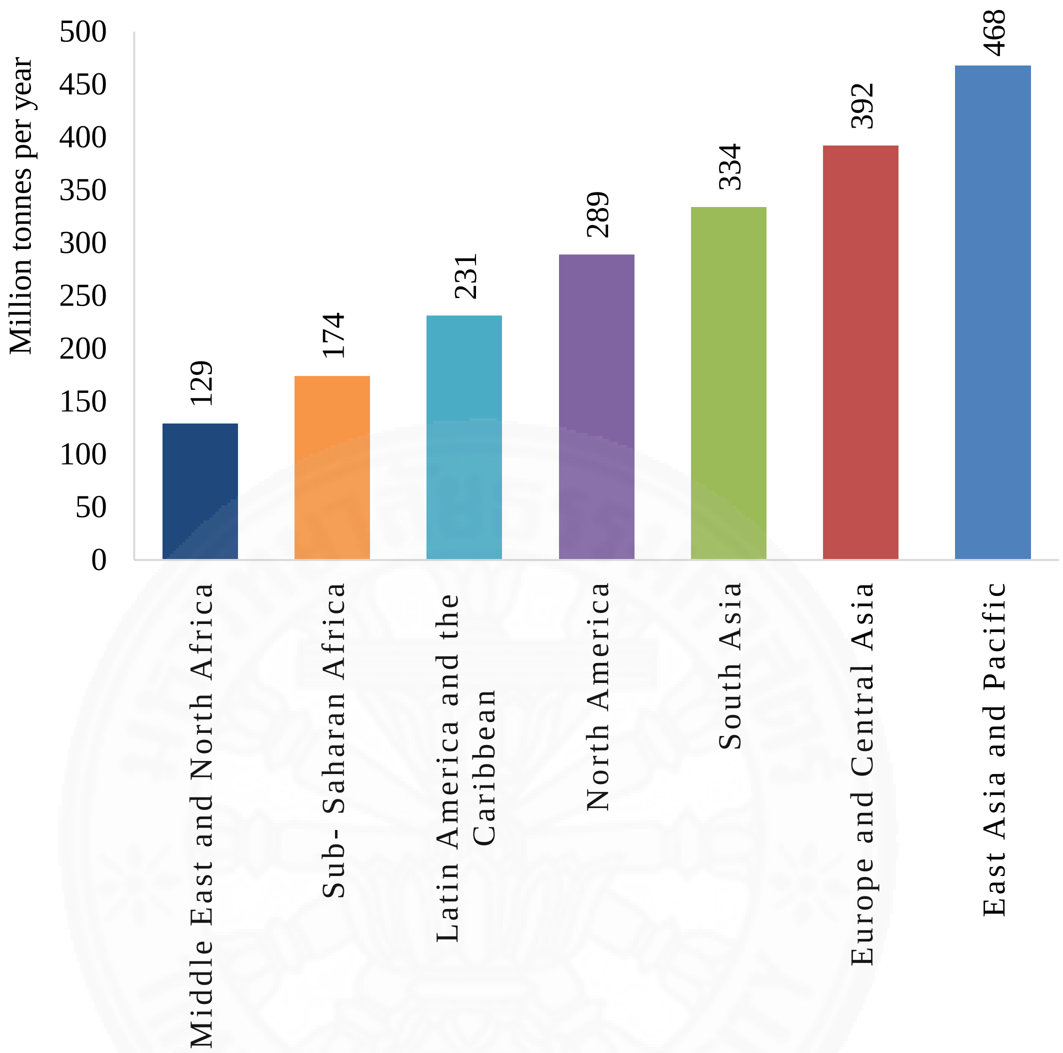

Figure 2.3 Amount of waste generation, by region (Kaza, Yao, Bhada-Tata & Woerden, 2018).

2.2.2 Municipal solid waste composition

The classification of waste materials in the MSW according to the percentages is referred to as the waste composition (Karak, Bhagat & Bhattacharyya, 2012). The physical composition would be an important parameter to be used as a criterion to classify and characterize MSW. The study conducted by Karak, Bhagat and Bhattacharyya (2012) found that the typical categories of MSW are organic matter, paper and cardboard, plastics, glass, metals, and other substances including rubber, leather, wood, textile, ash, and electronic (Table 2.2).

Table 2.2 Types of waste and their source (Karak, Bhagat & Bhattacharyya, 2012; Kaza, Yao, Bhada-Tata & Woerden, 2018).

Types	Sources
Organic	Food waste, garden waste, wood residues
Paper	Paper scraps, wrapper, cardboard, packaging paper, shredded papers, paper cups
Plastic	Plastic bags, bottles, packaging materials, containers, cups
Glass	Glass bottles, broken glass, pottery items, earthen pots
Metals	Cables, foils, ferrous and non-ferrous materials, cans, empty tins, appliances, railings, bicycle parts
Other	Textiles, rubber, leather, electric waste, ash

According to Kaza, Yao, Bhada-Tata and Woerden (2018), the global waste composition is shown in Table 2.3. The biggest share of 44% is provided by organic waste followed by 17% of paper and cardboard, 14% of other materials, 12% of plastic, 5% of glass, 4% of metal, 2% of rubber and leather, and 2% of wood. However, the waste composition always depends on the country or the region, cultural background, economic development, climate, and energy sources.

Table 2.3 Global waste composition (Kaza, Yao, Bhada-Tata & Woerden, 2018).

Composition	Amount (%)
Organic matter	44
Paper and cardboard	17
Other	14
Plastic	12
Glass	5
Metal	4
Rubber and leather	2
wood	2

2.3 Municipal solid waste management

The escalating amount of MSW creates adverse environmental issues and severe effects on the quality of life. Most developing countries have been suffered a lot from accelerated MSW and its inappropriate management (Karak, Bhagat & Bhattacharyya, 2012). Air pollution from uncontrolled gaseous emissions, odor generation, water pollution from leachate, soil contamination from direct leachate and waste interaction, and diseases are some major consequences of inappropriate MSW management (Karak, Bhagat & Bhattacharyya, 2012). Therefore, appropriate MSW management is much needed to ensure the protection of the environment and quality of life.

MSW management is recognized as a strategic framework for managing waste generation, waste transportation, waste processing, and disposal (Baba, Aydın & Imneisi, 2018; Joshi & Ahmed, 2016; Purity, Ifeoma & Yusuf, 2016). Therefore, the main goals of effective MSW management are to facilitate and enhance the quality of the urban environment, create job opportunities, ensure environmental protection, and uplift human health either by eliminating or reducing air, water, and soil contaminants (Igbinomwanhia, 2011; Ogwueleka, 2009). Therefore, waste generation, storage, collection, transportation, waste processing, and disposal are primarily included in the MSW management system.

2.3.1 Waste generation

Management of MSW starts with the generation of waste at the sources followed by the collection, storage, transportation, processing, and disposal.

2.3.2 Waste collection and transportation

The door to door collection system is the most popular and commonly used waste collection method over the world (Sharholy, Ahmad, Mahmood & Trivedi, 2008). Plastic bins, rattan baskets, plastic, and polythene bags are often being used for waste collection.

Once the waste materials are collected, they are transported either to the treatment or disposal sites using vehicles such as trucks, small vehicles, handcrafts, donkeys, bullock carts, tractor-trailers, tricycles, motor vehicles, lorries, and modern hydraulic vehicles (Sharholy, Ahmad, Mahmood & Trivedi, 2008). Modern hydraulic vehicles are usually used for the waste collection and transportation phases in developed nations.

2.3.3 Waste treatment

Three main MSW treatment categories are physical, biological, and thermal treatments. Among the three, physical and biological treatments comprise recycle, composting, and anaerobic digestion while, the thermal treatment method includes incineration, pyrolysis, gasification, and plasma arc.

2.3.3.1 Reduce, Reuse, and Recycle (3R approach)

When it comes to the 3Rs method, the most important entity is waste reduction at the sources by reducing consumption, utilization of reusable, and long-lasting products. The second priority is given to reuse, implying the use of objects, devices, or substances again without any alterations to original materials. Use refillable containers, durable products, reusable packaging are some of the suggestions for reuse of waste. Then recycling refers to the approach that produces a new product using discarded materials.

2.3.3.2 Biological treatment

Currently, biological treatments are widely used for the management of MSW, due to its higher organic fraction. Therefore, the most popular biological treatments include aerobic composting, anaerobic digestion, and vermicomposting. The detailed explanations of composting and anaerobic digestion are given in the next section. These biological treatments involve the conversion of unstable organic compounds to stable inorganic compounds with the support of microorganisms (Sharholy, Ahmad, Mahmood & Trivedi, 2008). Aerobic composting is considered as the aerobic biological conversion of OFMSW into compost (Joshi & Ahmed, 2016; Narayana, 2009; Sharholy, Ahmad, Mahmood & Trivedi, 2008). The anaerobic digestion is known as the degradation of OFMSW on the activities of microorganisms that transform organic matters under anaerobic conditions into biogas (Adekunle & Okolie, 2015). Vermicomposting is also a biological treatment method that is used for the treatment of OFMSW. It is known as the stabilization of OFMSW accomplish by the types of earthworms and microorganisms (Joshi & Ahmed, 2016; Sharholy, Ahmad, Mahmood & Trivedi, 2008).

2.3.3.3 Thermal treatment

Thermal treatments are widely applicable to both solid and hazardous waste. In general, breaking down the waste materials at high temperatures either combustion or pyrolysis in a controlled environment is known as the thermal treatment (Joshi & Ahmed, 2016). Incineration, pyrolysis, gasification, and plasma arc are the renowned major thermal treatment techniques.

Incineration defines as the process of control and complete combustion for burning solid waste at a high temperature, approximately 1000 ℃ using incinerators in the presence of excess air. It is considered the most commonly used thermal waste treatment method (Alam & Ahmade, 2013; Zaman, 2010).

Gasification defines as the process in which partial combustion of MSW in the presence of less amount of oxygen than the complete combustion in 400-600 ℃ (Sharholy, Ahmad, Mahmood & Trivedi, 2008; Zaman, 2013).

The waste combustion in the complete absence of oxygen at 600-650 ℃ is known as pyrolysis (Zaman, 2010).

And the process of mineralization of waste under isothermal plasma obtained by inert gas passing through an electric arc is known as plasma arc (Zaman, 2013).

2.3.4 Waste disposal

The least preferred treatment strategy has been pointed out as waste disposal. Because, inappropriate waste disposal causes severe environmental effects on the atmosphere, water, and soil. Landfilling is being used as a widely available disposal technique over the world (Baba, Aydın, & Imneisi, 2018; Karak, Bhagat, & Bhattacharyya, 2012). Three types of landfills, namely open landfill/open dump, semi-controlled/operated landfill, and sanitary landfill are used for waste disposal. Among them, sanitary landfills and semi-controlled landfills are quite popular among developed nations. However, open dumping is widely used by developing countries resulting in adverse environmental and health issues (Karak, Bhagat & Bhattacharyya, 2012; Narayana, 2009).

2.4 Biological treatments of OFMSW

2.4.1 Composting

Composting is considered a widely accepted environmentally friendly waste management strategy over the world thus it is an inexpensive and simple treatment method (Atalia, Buha, Bhavsar & Shah, 2015). Currently, composting is employed to treat organic matter including MSW, sewage, agricultural waste, and agro-industrial waste.

Three stages of the composting process are mesophilic, thermophilic, and maturation. In the mesophilic phase, the microbial activity tends to increase rapidly resulting in high temperature. Here, microbes produce organic acids by consuming soluble carbon sources, starch, monosaccharides, and lipids (Atalia, Buha, Bhavsar & Shah, 2015). Then the rising temperature inhibits the reaction of mesophilic microbes and it influences the startup of thermophilic microbes. Thermophilic microbes begin to degrade the proteins of organic waste until the temperature falls and starts the curing phase. During the curing phase, fungi and actinomycetes begin to colonies and decompose the resistant materials (Atalia, Buha, Bhavsar & Shah, 2015). Windrow composting, enclosed composting, and static pile composting methods are the widely used composting methods in the world (Kumar, 2011; Lim et al. 2017).

2.4.2 Anaerobic digestion

Anaerobic digestion is also a very important and common biological treatment method well-known as waste to energy technology (Adekunle & Okolie, 2015). It is gaining attraction over the world because of its potential to reduce greenhouse gases (GHGs).

Anaerobic digestion is a complex process that includes four different processes performed by microorganisms including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. As revealed by Adekunle and Okolie (2015) and Meester et al. (2012), the transformation of insoluble organic materials into soluble organics is known as hydrolysis. In here, lipids, proteins, polysaccharides, and nucleic acids are converted into monosaccharides, amino acids, and other simple organics. Then, simple organic compounds produced from hydrolysis are converted into organic acids and alcohols in acidogenesis phase. Acetogenesis is the conversion of substrate into methanogenic substrates. Finally, methanogenesis is the generation of methane and carbon dioxide under strictly anaerobic conditions by the methanogenic bacteria. Batch reactors and continuous reactors including one-stage, two-stage, and multi-stage are widely used for the anaerobic digestion systems (Khalid, Arshad, Anjum, Mahmood & Dawson, 2011).

2.5 Environmental impacts of MSW management techniques

Although the waste treatments are used for the minimization of environmental and health impacts, those waste treatments create numerous impacts to the surrounding environment near to the operation and far way (Giusti, 2009).

Table 2.4 illustrates the summarized potential sources, emissions, and impacts of different waste management techniques including anaerobic digestion and composting. Therefore, climate, air quality, soil and geology, ground and surface water, flora and fauna, human health, landscape, and noise are impacted by the MSW management practices.

Among them, climatic impacts are mainly produced by the GHGs such as nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO) during the construction, maintenance, and operational phases.

Air quality impacts are mainly caused by dust emission, decomposition gases (CO_2, CH_4), volatile organic compounds (VOC), bioaerosols, odor compounds, and other gaseous compounds such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), and hydrogen sulfide (H_2S).

Heavy metals, microorganisms, synthetic organic compounds, and other inorganic compounds have the potential to create impacts on the soil and geology.

Also, heavy metals, salts compounds, and persistent organic pollutants (POPs) from leachate are considered the main pollutants of ground and surface water.

Table 2.4 Sources, emissions, and environmental impacts of MSW management techniques (DEFRA, 2004; Giusti, 2009).

Sources	Emissions	Potential environmental effects
Landfill	Dust, microorganisms, litter, odor and landfill gas (CH_4, CO_2), gases from landfill gas combustion (CO_2, CO, SO_2, NO_x, other trace components)	Acidification of soil, vegetation damages, increases in soil metals due to the deposition of acid gases
	Leachate: heavy metals, salts, biodegradables, POPs to sewer, surface, groundwater	Contamination of ground and surface water, bioaccumulation of toxic metals
	Metal compounds and organic compounds	Soil contamination and bioaccumulation
Thermal Treatments (Incineration, gasification, and pyrolysis)	Emission of SO_2, NO_x, VOC, CO_2, CO, dioxins and furans, metals, dust, odor, and microorganisms Decomposition of combustion gases: sulfuric acid, carbonic acid, nitric acid, particulate matter	Soil acidification, vegetation damages, and increases in soil metals and dioxins due to acid gases
Composting	CH_4, CO_2, dust, odor, and microorganisms: bacteria and fungi	Global warming due to GHGs
	Trace contaminants: metals and organic compounds	Soil contamination
Anaerobic digestion	CH_4, CO_2, and N_2O from biogas generation; CO, SO_2, NO_x, and VOC from biogas combustion; Decomposition gases from digestate: NH_3, N_2O, hydrocarbons, and odor compounds	Global warming due to GHGs
	Digestate: NH_3, heavy metals, and microorganisms	Contamination of ground and surface water
Collection and transportation	CO, CO_2, NO_x, particulate matter, metal, dust, VOC, diesel and petrol, VOC from cleaning	Exposure to exhaust fumes, ground and surface water contamination
Material recycling	Dust and odor during waste handling, storage, and sorting	Visual impacts
	Organic compound from cleaning	Contamination of surface and groundwater Soil contamination

2.6 Environmental impact assessment of waste management techniques in a life cycle perspective

Recently, numerous methods and tools were used to assess the sustainability aspects of solid waste management such as environmental technology assessment, material flow analysis, environmental impact assessment, risk assessment, cost-benefit analysis, and life cycle costing. Among those, the LCA methodology has been used widely over the world to assess the environmental impacts in the field of waste management (Kulczycka, Lelek, Lewandowska & Zarebska, 2015). LCA is a method for evaluating the environmental impacts associated with inputs and outputs of a product or service (Liamsanguan & Gheewala, 2008a; Wittmaier, Langer, & Sawilla, 2009).

2.6.1 Life cycle assessment methodology

The definition of ISO 14040-14044 (International Organization for Standardization) specified that LCA methodology comprised of four different stages: (i) goal and scope definition (ii) inventory analysis (iii) impact assessment (iv) interpretation (Figure 2.4).

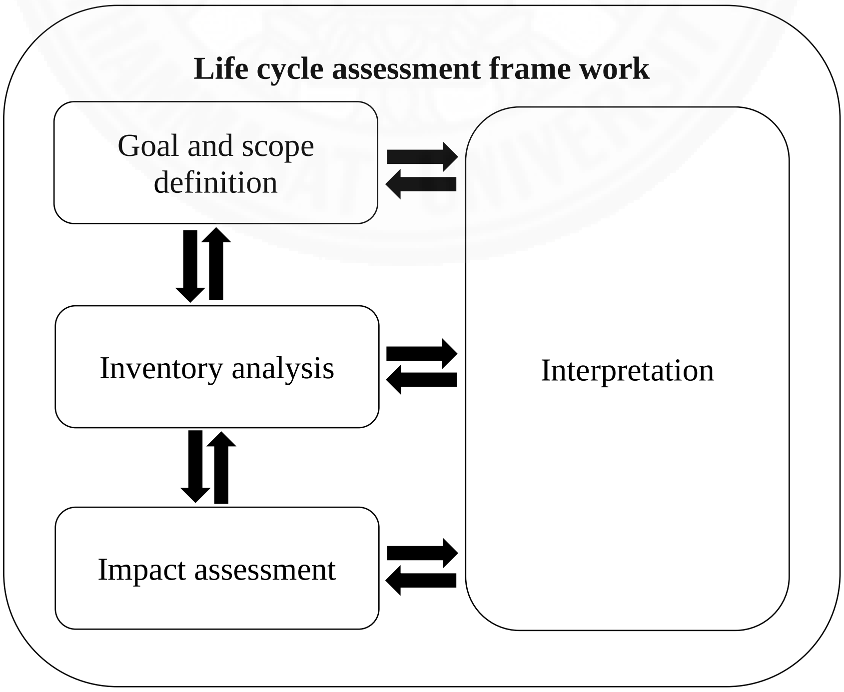

Figure 2.4 Phases of LCA (ISO, 1997; ISO, 2006).

2.6.1.1 Definition of goal and scope

Definition of goal and scope is the initial phase of any LCA, which defines the product or service, life cycle, functions, the reason for executing the LCA, functional unit, system boundaries, assumptions, limitations, and intended audience (ISO, 2006). The purpose, target audience, and way of outcomes used are carefully described under the goal. The scope includes definitions of functions, functional unit, system boundaries, allocation process, impact assessment methodology, assumptions, limitations, data requirements, and data quality.

2.6.1.2 Inventory analysis

The collection of all inputs and outputs associated with the system boundary and the calculation of associated emissions are contained within the inventory analysis. Therefore, it can be defined as a procedure of identification and quantification of inputs of raw materials, resources, energy, transport, and outputs as emissions to air, water, and soil, waste, and other releases (ISO, 2006). The primary data from the product, system, or services and secondary data available in databases, are used in this phase.

2.6.1.3 Impact assessment

The impact assessment is known as the transformation of life cycle inventory results into impacts. Five subsequent steps are included in this step as (a) selection of impact categories (b) classification (c) characterization (d) normalization (e) weighting. The mandatory elements are selection, classification, and characterization whereas normalization and weighting are classified as optional elements.

(a) Selection of impact categories

The first mandatory step is the determination of relevant impact categories, category indicators, and characterization models. Global warming, acidification, eutrophication, stratospheric ozone depletion, ozone formation, ecotoxicity, resource scarcity, land use, and water consumption, are identified as the main impact categories. However, the selection of impact categories depends largely on the author of the study relating to the goal. In general, the existing life cycle impact assessment method available at the LCA software is used for the characterization model.

(b) Classification

Classification is the process of assigning life cycle inventory results to impact categories. The assignment of GHGs into the climate change impact category and acid-forming gases into the acidification impact category are two examples for the classification. After completion of the selection of categories, input and output data from life cycle inventory is assigned to these categorized environment impact and convert them into indicators are the basis of this process (ISO, 2006).

(c) Characterization

Simply, the calculation of category indicator results is considered as the characterization. This conversion uses the results of the inventory and characterization factors. In this step, the category indicators are obtained by multiplying the inventory results and characterization factors.

(d) Normalization

Normalization is an optional step of LCA which is used to simplify the interpretation results. Normalization is explained as the computation of the magnitude of the category indicator relative to a reference system. Therefore, normalized values are obtained by dividing the characterization values of impact categories by normalization reference.

(e) Weighting

Weighting is also considered as the optional step of the LCA which is known as assigning weights to the impact category. Weighted values are calculated by multiplying normalized values of each impact category by the related weighted factors that appeared in the impact assessment methodology. Therefore, weighted results allow to find the relative importance of each impact category and calculate the total impact by adding together all weighted values.

2.6.1.4 Interpretation

The interpretation phase is mainly used for the analysis of significant issues by complying with completeness, sensitivity, consistency, and other checks. (ISO, 1997).

2.6.2 Applications of life cycle assessment on solid waste

Most of the studies have been evaluated specific waste management systems such as home composting (Colón et al. 2010), landfilling and compost (Blengini, 2008), landfilling (Rieradevall, Domenech & Fullana, 1997), pyrolysis-gasification (Zaman, 2013), incineration and anaerobic digestion (Chaya & Gheewala, 2007), home and full scale composting (Martínez-Blanco et al. 2010), tunnel and confined windrow composting (Cadena, Colón, Artola, Sánchez & Font, 2009b), landfill gas to energy (Wanichpongpan & Gheewala, 2007), and recycling (Menikpura, Gheewala, Bonnet & Chiemchaisri, 2013). Also, some of the assessments have been addressed on the MSW management systems of various cities and regions such as Phuket (Liamsanguan & Gheewala, 2008a), Sri Lanka (Menikpura, Gheewala, & Bonet, 2012), Eskisehir, Turkey (Banar, Cokaygil & Ozkan, 2008), Sub-Saharan African region (Komakech, Sundberg, Jönsson & Vinnerås, 2015), Malaysia (Saheri et al. 2012) and Tricity India (Rana, Ganguly & Kumar, 2019). Focusing on the biological treatments, most of the authors have been evaluated the environmental impacts of composting in different composting techniques such as tunnel, turned windrow, confined windrow, and home composting. However, few authors have been focused on the full-scale anaerobic digestion plants. The applications of LCA on composting and anaerobic digestion are presented in Table 2.5.

A study performed by Cadena, Colón, Artola, Sánchez and Font (2009b) compared the environmental impacts of the tunnel and confined windrow composting systems. Based on data, global warming potential of 63.9 kg CO_2 eq, acidification potential of 7.13 kg SO_2 eq, eutrophication potential of 1.51 kg PO_4^{3-} eq, human toxicity potential of 15.9 kg 1,4-DB eq, ozone layer depletion potential of 1.66×10^{-5} kg CFC-11 eq, and photochemical oxidation potential of 0.13 kg C_2H_4 eq per tonne of OFMSW, were reported for the tunnel composting system. On the other hand, global warming potential of 63.2 kg CO_2 eq, acidification potential of 3.7 kg SO_2 eq, eutrophication potential of 0.77 kg PO_4^{3-} eq, human toxicity potential of 14.5 kg 1,4-DCB eq, ozone layer depletion potential of 2.77×10^{-5} kg CFC-11 eq, and photochemical oxidation potential of 3.11 kg C_2H_4 eq, were reported for the confined windrow composting.

Based on the study conducted by Colón et al. (2010) on home composting, abiotic depletion potential of 0.192 kg Sb eq, acidification potential of 0.126 kg SO_2 eq, eutrophication potential of 1.55×10^{-2} kg PO_4^{3-} eq, global warming potential of 82.6 kg CO_2 eq, ozone layer depletion potential of 2.44×10^{-6} kg CFC-11 eq, the photochemical oxidation potential of 0.140 kg C_2H_4 eq and cumulative energy demand of 468 MJ, were reported.

The study conducted by Martínez-blanco et al. (2010), evaluated the full-scale industrial composting facility and compared it with the home composting system. Based on the obtained data, abiotic depletion potential of 0.768 kg Sb eq, acidification potential of 0.777 kg SO_2 eq, eutrophication potential of 0.223 kg PO_4^{3-} eq, global warming potential of 153 kg CO_2 eq, ozone layer depletion potential of 1.33×10^{-5} kg CFC-11 eq, photochemical oxidation potential of 0.535 kg C_2H_4 eq and cumulative energy demand of 1910 MJ, were reported for the industrial composting system.

Also, the study conducted by Pergola et al. (2020) evaluated light and heavy composting using LCA and presented total impacts after 20 years of working. The obtained data revealed that construction of the facility, collection and transportation of raw material, transportation of compost to its final destinations, and emissions during the decomposition phase could cause a global warming potential between 1,668,000 and 1,678,000 kg CO_2 eq, an abiotic depletion potential of 44 kg Sb eq, ozone layer depletion potential of 0.13 kg CFC-11 eq, photochemical oxidation between 613-620 kg C_2H_4 eq, acidification potential between 14,558 and 14,581 kg SO_2 eq and eutrophication potential of 5,965 kg PO_4^{3-} eq.

The environmental impacts of MSW incineration and anaerobic digestion processes were assessed using LCA by Chaya and Gheewala (2007). Based on that data global warming potential of -276 kg CO_2 eq, acidification potential of -1.57 kg SO_2 eq, nutrient enrichment of 7.37 kg PO_4^{3-} eq, photochemical oxidation potential of -0.0253 kg C_2H_4 eq, stratospheric ozone depletion -1.9×10^{-5} kg CFC-11 eq, heavy metals -0.0036 kg Pb and 372 kg of solid waste, were reported in the anaerobic digestion plant.

However, the study conducted by Ishikawa, Hoshiba, Hinata, Hishinuma and Morita (2006), focused only on global warming and fossil energy consumption. A total of 2,700 tonnes of CO_2 emissions and an energy investment of 42,000 GJ, were reported from the centralized biogas plant.

Table 2.5 Review of life cycle assessment studies on composting and anaerobic digestion

	Scenarios	Impact categories	Reference
Composting	Tunnel composting Confined windrow composting	Global warming, acidification, eutrophication, human toxicity, photochemical oxidation, ozone layer depletion	(Cadena, Colón, Artola, Sánchez & Font, 2009b)
	Home composting	Global warming, acidification, eutrophication, photochemical oxidation, ozone layer depletion, cumulative energy (CML 2001)	(Colón et al. 2010)
	Home composting Industrial composting (tunnel)	Global warming, acidification, eutrophication, ozone layer depletion, cumulative energy demand (CML 2001)	(Martínez-blanco et al. 2010)
	Home composting	Global warming, acidification, eutrophication, photochemical oxidation, ecotoxicity, human toxicity	(Andersen, Boldrin, Christensen & Scheutz, 2012)
	Light composting Heavy composting	Global warming, acidification, ozone layer depletion, photochemical oxidation, abiotic depletion (CML 2001)	(Pergola et al. 2020)
Anaerobic digestion	Anaerobic digestion Incineration	Global warming, acidification, nutrient enrichment, stratospheric ozone depletion, impacts from heavy metals, photo-oxidant formation, solid waste, energy (Eco indicator 95)	(Chaya and Gheewala 2007)
	On-farm biogas plant Centralized biogas plant	Global warming, fossil energy consumption	(Ishikawa, Hoshiba, Hinata, Hishinuma & Morita, 2006)
Anaerobic digestion and composting	Tunnel composting Confined windrow composting Turned windrow composting Home composting Anaerobic digestion with composting	Global warming, acidification, photochemical oxidation, eutrophication, human toxicity, abiotic depletion (CML 2001)	(Colón et al. 2012)

Also, a comparison of the environmental impacts of OFMSW treatment facilities was conducted by Colón et al. (2012). Tunnel composting, confined windrow composting, turned windrow composting, and anaerobic digestion plus composting were assessed and compared with the home composting. Table 2.6 shows the potential environmental impacts of waste treatment facilities.

Table 2.6 Potential environmental impacts of selected waste treatment facilities.

Impact categories	Tunnel	Confined windrow	Turned windrow	Anaerobic digestion + Composting
Acidification (kg SO_2 eq)	1.30	3.75	14.0	0.162
Global warming (kg CO_2 eq)	150	123	196	45.2
Photochemical oxidation (kg C_2H_4 eq)	0.192	2.59	2.38	0.358
Eutrophication (kg PO_4^{3-} eq)	9.40E-02	0.721	3.03	6.71E-02
Human toxicity (kg 1,4-DCB eq)	23.5	11.7	5.82	4.64
Abiotic depletion (kg Sb eq)	0.872	0.434	0.144	-0.155
Ozone layer depletion (kg CFC-11 eq)	7.12E-06	5.42E-06	2.37E-06	2.67E-07

2.7 Municipal solid waste management in Sri Lanka

2.7.1 Waste generation

Sri Lanka is one of Asia's developing countries, suffering from accelerated MSW and its inappropriate management. The estimated average MSW in Sri Lanka was 6,500 tonnes/day in 1999 and 7,250 tonnes/day in 2009. And the predicted average per capita MSW generation was 1 kg/capita/day by 2025. (Bandusena, Mallak, & Samah, 2019; Menikpura, Gheewala & Bonet, 2012; Vidanaarachchi, Yuen & Pilapitiya, 2006).

2.7.2 Waste composition

A study conducted by Bandara (2008) showed that the typical waste composition in Sri Lanka consists of a high organic fraction, a moderate amount of plastic and paper, and less metal and glass content (Figure 2.5). Almost 62% of collected MSW was organic matter while, paper, plastic, metal, and glass were 6%, 8%, 3%, and 3%, respectively.

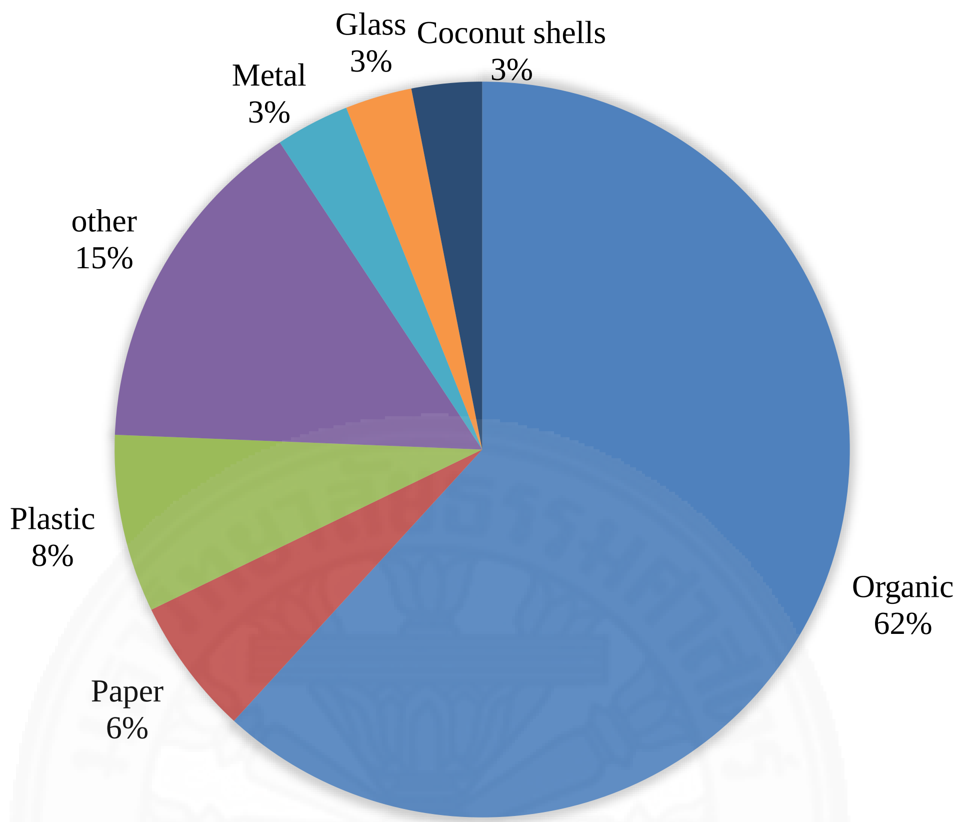

Figure 2.5 Waste composition in Sri Lanka (Liyanage Gurusinghe, Herat & Tateda, 2015).

2.7.3 Waste collection and transportation

Local authorities in Sri Lanka (municipal council, urban council, and pradeshiya sabha) are responsible for the waste collection within the jurisdiction (Dissanayaka & Vasanthapriyan, 2019; Liyanage et al. 2015). However, only half of the generated waste (about 3500 tonnes per day) is collected and disposed of by the local authorities (Menikpura, Gheewala & Bonet, 2012). House to house collection is a widely used collection method. However, community and curbside collection are also being performed in a few local authorities (APO, 2007; Menikpura, Gheewala & Bonet, 2012). The main vehicles used for MSW collection were compact trucks, two-wheeled tractors, four-wheeled tractors, carts, and wheelbarrows (Vidanaarachchi, Yuen & Pilapitiya, 2006).

2.7.4 Resource recovery and recycling

Proper MSW management incorporates the material recovery and recycling, reuse, and reduction steps. To initiate the material recovery and recycling, source separation is much needed (Vidanaarachchi, Yuen & Pilapitiya, 2006). However, source separation of cardboard, paper, plastic, glass, and metal is being practiced in a few local authorities to reduce the disposal waste quantity.

2.7.5 Waste processing/ treatments

Only a few local authorities have been tried out composting, anaerobic digestion, and sanitary landfilling as waste treatment methods. (Menikpura, Gheewala & Bonet, 2012). According to APO (2007), a few local authorities such as Colombo, Dehiwala, Moratuwa, Galle, Matara, Rathnapura, and Sri Jayawardhanapura Kotte have implemented the composting facility to manage their organic waste by producing compost. Recently, Moratuwa municipal council and Sri Jayawardhanapura Kotte municipal council used to produce biogas from MSW. Colombo, Kandy, Galle, Anuradhapura, Matara, Badulla, Rathnapura, Nuwaraeliya, and Matale are some examples of landfills.

2.7.6 Waste disposal

Recently, open dumping is the main disposal method in Sri Lanka (Maheshi, Steven & Karel, 2015; Menikpura, Gheewala & Bonet, 2012). However, leachate management and pollutant control facilities are not undertaken in the open dumps and daily topsoil cover is the only protective measure taken in the open dumps (Liyanage, Gurusinghe, Herat & Tateda, 2015; Maheshi, Steven & Karel, 2015).

2.8 Environmental impact assessments in Sri Lanka

Only a limited number of impact assessments were carried out on open dumping (Maheshi, Steven, & Karel, 2015; Menikpura, Gheewala, & Bonet, 2012). Therefore, data on impact assessments of MSW treatments are limited and not publicly available in Sri Lanka.

According to the conducted studies, the lack of leachate management systems and the air pollution control systems in the open dumps has been recognized as major causes for the environmental impacts. Therefore, pollutants found in leachate (organic compounds, dissolved methane, sulfate, nitrate, nitrite, phosphate, calcium, sodium, chloride, magnesium, potassium, and a variety of heavy metals) released into the ground and surface water accelerates the water pollution. Further, it causes aquifer pollution and eutrophication in the ground and surface water, respectively. Also, the release of the uncontrolled pollutants in the open dumpsite causes severe damages to the atmosphere such as global warming, odor problems, and health issues (APO, 2007; Bandara & Hettiaratchi, 2010; Maheshi, Steven & Karel, 2015).

Since no studies are carried out to evaluate the environmental impacts on composting and anaerobic digestion either. Thus, it is much needed to conduct LCA on composting and anaerobic digestion to select the most appropriate biological treatment for OFMSW. The majority of these studies have been conducted based on the secondary data available in the databases and literature, leading to the risk of uncertainty Therefore, the utilization of actual data on full-scale plants would serve to minimize the uncertainty, thereby making this kind of study more highly recommended.

CHAPTER 3
METHODOLOGY

3.1 Experimental site selection

To evaluate the environmental impacts of anaerobic digestion and composting systems, an anaerobic digestion plant and composting plant both treating sources separated OFMSW, located in Kaduwela municipal council, Sri Lanka, were selected in this study.

3.1.1 The anaerobic digestion plant

The anaerobic digestion plant was designed to treat about 7 tonnes of sources separated OFMSW per day for waste management and electricity production. The facility consists of three feeding tanks (length 4.5 m× widths 4.5 m × height 3.3 m). It includes two waste storage tanks and a leachate collection tank, six closed digesters, and a 40- kW generator (Figure 3.1).

Figure 3.1 Main components of the anaerobic digestion plant.

As shown in Figure 3.2, the collected sources separated OFMSW from Kaduwela municipal area is unloaded and accumulated in the waste storage tanks. Then the generated leachate during the waste accumulation phase is drawn into the leachate collection tank. The collected leachate is gradually fed to the closed digesters. Finally, the anaerobic digestion process is performed by the closed digesters for 30 days of retention time. The produced biogas is directed to the 40-kW generator to produce the electricity. Recently, produced electricity is used by the facility itself. In the future, it plans to scale up to and contribute to the national grid.

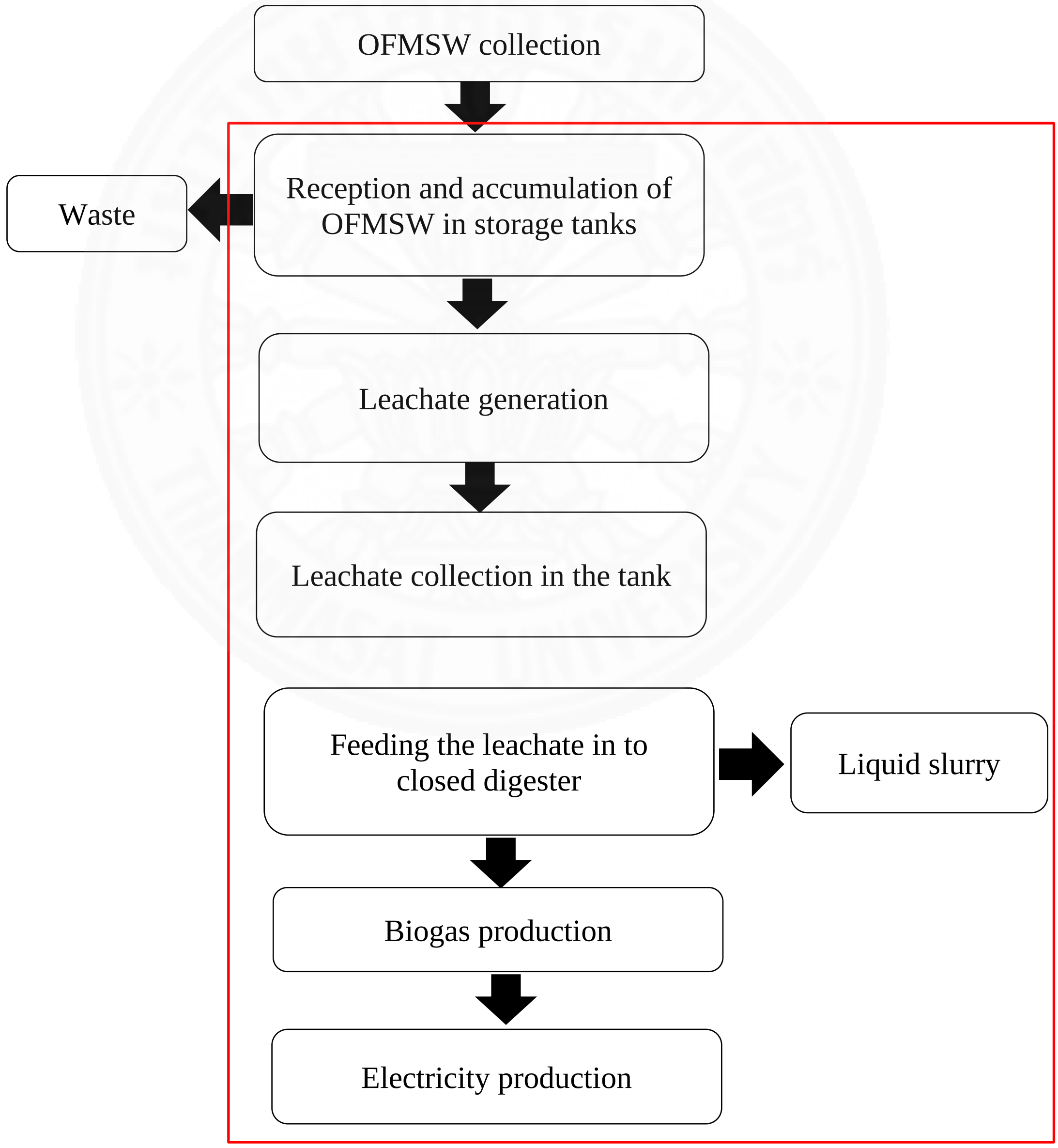

Figure 3.2 Flow diagram of the anaerobic digestion plant.

3.12 The composting plant

The composting plant was initiated to treat source-separated OFMSW (20 tonnes OFMSW per day) and to decrease the amount of waste that goes to open dumpsites. The facility mainly consists of a waste reception area, a pile preparation area, and a fine separation and storage area (Figure 3.3).

Figure 3.3 Key components of the composting plant.

Only the sources separated OFMSW is composted using the open windrow technique. As shown in Figure 3.4, collected sources separated OFMSW is transported and unloaded to the reception area for the manual pile preparation. The decomposition and curing phases are carried out in 5-inch waste piles known as compost windrows located on a concrete floor. The front loader tractors are used for mixing to maintain well-aerated conditions. The produced leachate during the decomposition phase is collected and reutilized for the irrigation of organic waste. After 90 days, fine separation is carried out using a compost huller machine to separate compost. Finally, produced compost is utilized as organic fertilizer by vegetable growers and tea plantations.

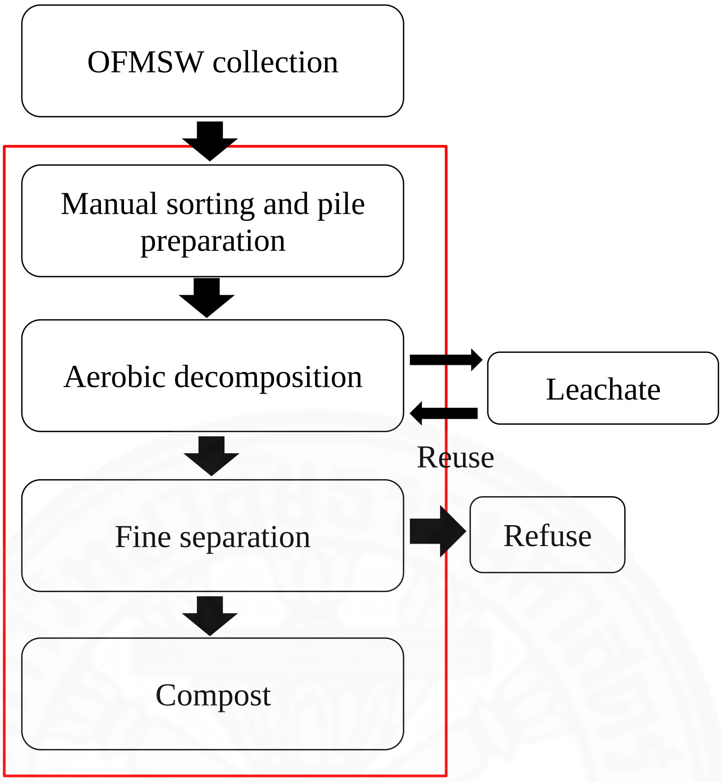

Figure 3.4 Flow diagram of the composting plant.

3.2 Environmental impacts investigations of anaerobic digestion and composting by LCA

In the present study, LCA is used for the evaluation of the environmental impacts of both treatments. Based on the ISO 14040: 2006, four different phases: (i) scope and goal definition (ii) inventory analysis (iii) impact assessment (iv) interpretation were used for the study.

3.2.1 Goal and scope definition

The goals of the study were to evaluate the environmental effects of OFMSW treatment by anaerobic digestion, composting, and to compare the environmental impacts between composting and anaerobic digestion. The results can be utilized by LCA experts, scientists, engineers, designers, and other related stakeholders involved in the waste management field for the process improvements, decision-making processes, and policymaking in waste management in Sri Lanka.

Under the scope definition, waste management and fertilizer production were recognized as the main functions of the studied composting facility. Waste management and electricity production were identified as the main functions of the anaerobic digestion facility. To compare both processes, "treatment of 1 tonne of OFMSW" was considered as the functional unit of the study.

Waste degradation, electricity production, and liquid slurry handling were included in the system boundary of anaerobic digestion (Figure 3.2). For the composting facility, waste degradation (decomposition and curing phases) and compost production (Figure 3.4) were included in the system boundary.

However, the transportation of OFMSW to the facility, and the transportation of residues, liquid slurry and produced compost into its final destinations were excluded since the waste origin and final destinations are common for both facilities, and will not influence the comparative results (Chaya & Gheewala, 2007). Construction of the facility and capital equipment were also excluded from the system boundary as the emissions are small, compared to the use phase (Liamsanguan & Gheewala, 2008b). Also, leachate treatment was omitted from the system boundary in the composting as it is reutilized.

3.2.2 Inventory analysis

The methodology used for the inventory analysis was a combination of the direct interviews of the concerned person and systematic onsite sampling. The methodology used for both anaerobic digestion and composting systems is explained below.

3.2.2.1 Anaerobic digestion

The methodology proposed by Cadena, Colón, Sánchez, Font and Artola (2009a), was used for the data collection phase. Therefore, the methodology used for the inventory analysis was a combination of the direct interview of the concerned person and systematic onsite sampling for primary data. The secondary data were obtained from specific databases (Ecoinvent version 3.5), literature, and reports developed for the inventory analysis.

(a) Data collection on plant characteristics and operations:

Information such as plant capacity, treated waste amount and characteristics, amount of final product obtained (electricity), and resource consumption including water, electricity, and fuel was obtained from the direct interviews. As presented in Figure 3.5, main input flows are treated OFMSW, electricity, and water whereas produced electricity from biogas, solid waste, liquid slurry, and emissions to air, and soil, are considered as the main output flows.

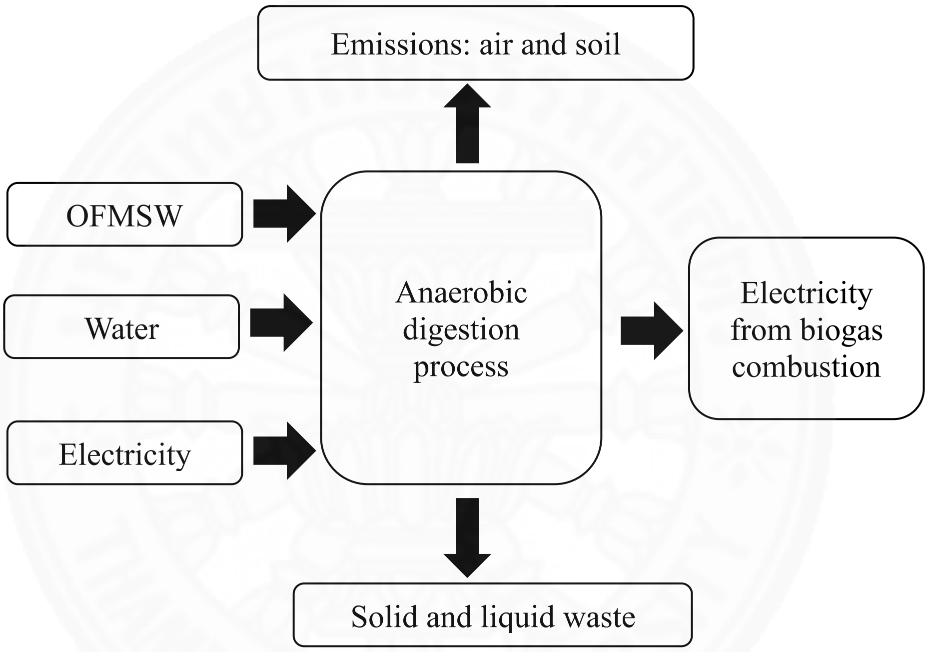

Figure 3.5 Input and output flows of the anaerobic digestion plant.

(b) Emissions to air:

The determination of atmospheric emissions in the anaerobic digestion plant was performed using direct emission measurement as described below. Liebetrau et al. (2013) reported that substrate storage tanks, feeding devices, digesters, digestate storage tanks, gas transfer pipes, and gas utilization units, are the most relevant technical components for gaseous determination. In the present study, waste storage tanks, leachate collection tanks, and exhaust pipes were considered as the main gaseous emission sources since gaseous emissions from the closed digesters and transportation pipes were supposed to be negligible. The study mainly focused on the emissions of

NH_3, CH_4, and, N_2O since these emissions are considered as the main emissions of both anaerobic and aerobic digestion degradation (Martínez-Blanco et al. 2010). However, CO_2 emissions are not taken into accounts as it is biogenic. Assuming that gaseous emissions released to the atmosphere come from the external surfaces of emission sources, a systematic data collection on gaseous compound concentrations and output velocity was undertaken by the following procedure (Figure 3.6).

First, different sampling points were established according to the emission surface measurements (height, length, and width, diameter). The exhaust gas velocity and contaminant concentration were simultaneously measured at each sampling point. The exhaust gas velocity was measured using an anemometer (Testo 410i vane anemometer and Hotwire anemometer ThermoAir3). Gaseous samples in each sampling point were taken into the 1L Tedlar bags using an air pump. The collected samples were taken into the laboratory for analysis and contaminant concentrations (NH_3, CH_4, and N_2O) were obtained. NH_3 concentration was analyzed using the wet chemical method (EPA ICS part ii method-401: Indophenol blue method) by a certified external laboratory (National Building Research Organization, Colombo, Sri Lanka). CH_4 and N_2O concentrations were analyzed using gas chromatography (Shimadzu gas chromatography) with Flame Ionization (FID) and Thermal conductivity (TCD) detectors, respectively, by a certified laboratory (National Institute of Fundamental Studies, Kandy, Sri Lanka). The contaminant mass flow in each unit surface area was calculated using the measured contaminant concentrations, gas velocity, and surface area. Afterward, the daily contaminants released from the plant were calculated by summing all the values. Subsequently, these events were conducted on several days during the study period, and the total quantity of contaminants emitted into the atmosphere was calculated.

(c) Emissions to soil:

Available records on the liquid slurry application were used to calculate the emissions to the soil. For this, nitrate (NO_3^-), phosphate (PO_4^{3-}), and ammonium (NH_4^+) emissions were considered.

Determination of dimensions and sampling points of the external surfaces

↓

Collection and analysis of gaseous samples for each sampling point

↓

Determination of air velocity of each sampling point

↓

Calculation of contaminant mass flow
(contaminant mass flow per surface area × surface area)

↓

Repetition of gaseous emission measurements throughout the study period

Figure 3.6 Procedure for the gaseous emissions measurement.

(d) Indirect emissions:

Indirect emissions from background processes, including electricity, diesel, and tap water production, were also included in the study. Therefore, inventory data available in the Ecoinvent database (version 3.5) with approximate modification according to Sri Lanka, were used for computing the emissions from those background processes.

(e) Avoided products:

Credits were provided to the anaerobic digestion from avoided electricity generation by biogas combustion. The conventional electricity generation in Sri Lanka includes 55% by conventional thermal energy (24% from oil and 31% coal), 42% by hydropower, and 3% by renewable energy (2% from wind energy and 1% from other sources). A portion of conventional thermal energy was assumed to be replaced by electricity generation in the anaerobic digestion process (CEB, 2018).

3.2.2.2 Composting

(a) Data collection on plant characteristics and operations:

Same as the anaerobic digestion, identification, and quantification of input and output flows were performed using direct interviews and systematic onsite sampling. Treated OFMSW, water, electricity, and fuel were identified as the key input flows into the composting facility. Produced compost, solid waste, leachate, and emissions to air, were considered as main output flows from the facility (Figure 3.7). Among these input flows, the treated OFMSW, electricity, and water consumptions and output flow as produced compost, solid waste, and leachate, were considered via direct interview.

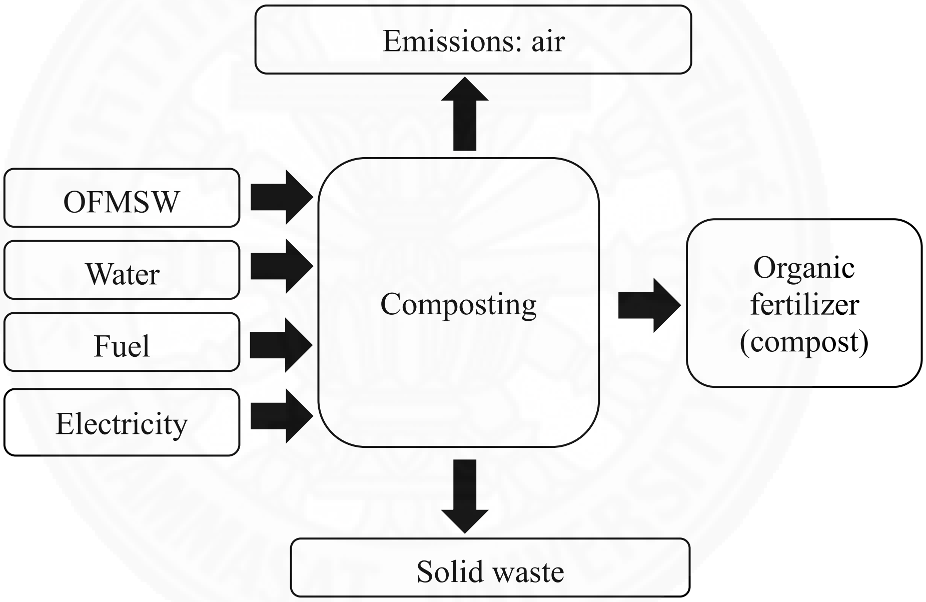

Figure 3.7 Input and output flows of the composting plant.

(b) Emissions to air:

The gaseous emission determination in the compost plant was carried out using the stoichiometry approach along with mass balance. The procedure followed in emission determination is explained below. To enable the stoichiometry approach, the elemental compositions of waste were determined. The characterization of solid materials; OFMSW, compost, and refuse was done using a systematic sampling campaign. It was performed three times over the three months study period.

The sampling of the input OFMSW was performed systematically according to Hansen, Jansen, Spliid, Davidsson and Christensen (2007) and Jansen, Spliid, Hansen, Svärd and Christensen (2004) to obtain a representative and homogenous sample. The screened waste from one truck (approximately 1 tonne) was piled on the concrete slab in the reception area. Approximately 10% of waste, typically 100 kg was subsampled and was shredded. The shredded waste was mixed thoroughly and approximately 10 kg were collected and was taken to the laboratory.

Grab samples were taken from the compost piles. The collected grab samples were mixed thoroughly to make a composite sample. Then the composite sample was permitted for size reduction and mass reduction to have a representative sample.

Also, sampling was performed on the refuse material by taking grab samples. A large number of collected grab samples were mixed and permitted for the size and mass reduction to have a representative and homogeneous sample.

The collected solid samples were transferred into the laboratory for analysis of moisture content, total solids (TS), ash content, carbon (C), volatile solids (VS), nitrogen (N), hydrogen (H), and oxygen (O). The TS of the input OFMSW and output materials was determined by drying the samples at 105 ℃ for about 24 hours. The VS content was determined as the mass loss after heating the samples at 550 ℃ until constant weight in a muffle furnace. The remaining fraction after the oxidation at 550 ℃ is known as the ash content.

For the chemical composition analysis, collected samples were further blended, mixed, dried at 80 ℃, and ground to a powder (<0.5 mm). Then the finely grained input and output material samples, typically 1-2 g were analyzed in terms of chemical composition by a certified laboratory (National Institute of Fundamental Studies, Kandy, Sri Lanka). An elemental analyzer (The PerkinElmer 2400 series ii CHNS/O Elemental Analyzer (2400 series ii)) was employed to measure the basic elements C, H, and N of input and output materials, and O content was calculated using measured C, H, N, TS and ash content values based on Equation 3.1 (Razmjoo, Pourzamani, Teiri & Hajizudesh, 2015).

$$\text{Oxygen \%} = 100 - (\text{C\%} + \text{H\%} + \text{N\%} + \text{Ash\%}) \qquad (3.1)$$

Afterward, elemental compositions of input and output materials were calculated based on the analytical data.

Under the stoichiometry approach, the following Equation (3.2) represents the general aerobic biological transformation of solid waste (Liwarska-Bizukojc & Ledakowicz, 2003).

$$\text{Organic matter} + O_2 + \text{nutrients} \rightarrow \text{new cells} + \text{resistant organic matter} + CO_2 + H_2O + NH_3 + SO_4^{2-} + PO_4^{3-} + \cdots + \text{heat} \quad (3.2)$$

If the biosynthesis of new cells and the production of sulfate and phosphate is not taken into account, the following Equations (3.3) and Equation (3.4) represent the aerobic biological transformation of solid waste, whereas $C_aH_bO_cN_d$ and $C_wH_xO_yN_z$ represent the organic material at the beginning and the end of the process, respectively. Equation (3.3) and Equation (3.4) represent the incomplete conversion and complete conversion of aerobic biodegradation, respectively which is used for the gaseous emission determination in the composting process (NH_3 and CO_2).

$$C_aH_bO_cN_d + 0.5(ny+2s+r-c)\,O_2 \rightarrow nC_wH_xO_yN_z + sCO_2 + rH_2O + (d-nz)NH_3 \quad (3.3)$$

$$C_aH_bO_cN_d + [(4a+b-2c+3d)/4]\,O_2 \rightarrow aCO_2 + [(b-3d)/2]\,H_2O + dNH_3 \quad (3.4)$$

The stoichiometry approach gives only emissions of NH_3 and CO_2. Therefore, the Intergovernmental Panel on Climate Change (IPCC) default values for composting (4 kg CH_4 and 0.3 kg N_2O per tonne of OFMSW) were used for computation of CH_4 and N_2O emissions since there are no site-specific measured values (IPCC, 2006).

(c) Indirect emissions:

Besides the above direct air emissions associated with the composting process, indirect emissions from electricity, diesel, and tap water production were also included. Therefore, emissions related to electricity, diesel, and tap water production were derived from the life cycle inventory data published in the Ecoinvent database (version 3.5) present in the LCA software with relevant alteration according to the Sri Lankan standards.

(d) Avoided products:

The recovered compost by the facility is used as organic fertilizer instead of chemical fertilizer (Nitrogen fertilizer as N, phosphorous fertilizer as P_2O_5, and potassium fertilizer as K_2O). According to Rathnathilaka, Weerakkody, Kannangara and Grau (2017), the average amounts of N, P_2O_5, and K_2O in 1 tonne of compost are 6.9, 1.61, 7.3 kg, respectively. Therefore, inventory data in the Ecoinvent (version 3.5) were used to calculate the credits from using recovered compost.

3.2.3 Impact assessment

SimaPro 9.1.0.11 was used as the LCA assessment tool for setting up the model of composting and anaerobic digestion processes. The impact assessment of both systems was performed by ReCiPe 2016 midpoint (Hierarchist version, H). It mainly includes impact categories of global warming (kg CO_2 eq), stratospheric ozone depletion (kg CFC-11 eq), ozone formation, human health (kg NO_x eq), ozone formation, terrestrial ecosystems (kg NO_x eq), terrestrial acidification (kg SO_2 eq), fine particulate matter formation (kg $PM_{2.5}$ eq), marine eutrophication (kg N eq), freshwater eutrophication (kg P eq), terrestrial ecotoxicity (kg 1,4 DCB), marine ecotoxicity (kg 1,4-DCB), freshwater ecotoxicity (kg 1,4-DCB), human carcinogenic toxicity (kg 1,4-DCB), human non-carcinogenic toxicity (kg 1,4-DCB), land use (m^2a crop eq), mineral resource scarcity (kg Cu eq), fossil resource scarcity (kg oil eq), and water consumption (m^3).

The ReCiPe endpoint (Hierarchist version, H/A) method was used for the comparison of environmental impacts between anaerobic digestion and composting. The endpoints: damage to human health, damage to ecosystem quality, and damage to resource availability are related to the three areas of protection of human health, ecosystem, and resource scarcity, respectively. The endpoint unit for human health damage is indicated as disability-adjusted life years (DALYs). The local species loss integrated over time (species. year) is considered as the units of ecosystem damage. The dollar (USD) is known to be the unit of resource scarcity which, signifies the extra expense for resource extraction.

3.2.4 Interpretation

As the final step of the LCA methodology, results from the existing inventory analysis and impact assessment were discussed and conclusions are drawn. Finally, a sensitivity analysis was performed to assess the reliability of the results by evaluating the effect of key assumptions on the overall results. Therefore, the effects of gaseous emissions and electricity country mix were assessed in the composting system while the effect of electricity country mix was assessed in the anaerobic digestion.

CHAPTER 4
RESULTS AND DISCUSSION

The results and discussion part has been divided into three: first, impact assessment of anaerobic digestion of OFMSW; next, impact assessment of the composting of OFMSW; and finally, the comparison of impact assessment between anaerobic digestion and composting systems.

4.1 Impact assessment of the anaerobic digestion of OFMSW

4.1.1 Waste characterization

The typical waste composition in Sri Lanka consists of a high organic fraction, an average amount of plastic and paper, and a low percentage of glass and metal (Bandara, 2008; Vidanaarachchi, Yuen & Pilapitiya, 2006). The composition of Sri Lanka MSW and the selected case study site, Kaduwela municipal council within the Colombo district are presented in Table 4.1.

Table 4.1 MSW composition in Sri Lanka and Colombo district.

Composition	Sri Lanka (%) (Liyanage, Gurusinghe, Herat & Tateda, 2015)	Colombo district (%) (Bandara, 2008)
Organic	61.8	79.7
Plastic	7.81	6.69
Paper	6.03	5.1
Metal	3.25	1.85
Glass	2.94	1.64
Other	18.2	5.02

As Liyanage, Gurusinghe, Herat and Tateda (2015) specified, the other features of Colombo city’s MSW are 300-350 kg/m^3 of specific density, 600-1200 kcal/kg of calorific value, and 55%-65% of moisture content. However, the analytical results show that the moisture content, ash content, and VS content of the generated OFMSW in the Kaduwela municipal area are 73.9±1.05%, 15.5±1.14%, and 84.5±1.14%, respectively.

4.1.2 Gaseous and liquid slurry emissions - anaerobic digestion system

Emissions of CH_4, NH_3, and N_2O were determined in the anaerobic digestion system. As shown in Table 4.2, CH_4 and NH_3 were detected, however, N_2O was not detected in the anaerobic digestion system.

Table 4.2 Inventory data for the anaerobic digestion plant (per 1 tonne of OFMSW).

Units			Anaerobic digestion
Process inputs	Electricity	kWh/tonne OFMSW	0.0948
	Water usage	L/tonne OFMSW	28.8
	Diesel	L/ tonne OFMSW	0
Process outputs	Electricity	kWh/tonne OFMSW	3.83
Atmospheric emissions	NH_3	kg/tonne OFMSW	$1.47\times10^{-6}\pm0.99$
	CH_4	kg/tonne OFMSW	6.82 ± 0.02
	N_2O	kg /tonne OFMSW	0
Waste flows	Refuse	kg/tonne OFMSW	135
	Liquid slurry	L/tonne OFMSW	588
	PO_4^{3-}	kg/tonne OFMSW	0.0291
	NH_4^+	kg/tonne OFMSW	0.243
	NO_3^-	kg/tonne OFMSW	0.00141
Avoided Products	Electricity	kWh/tonne OFMSW	3.73

About 6.82 ± 0.02 kg CH_4/tonne OFMSW and $1.47\times10^{-6}\pm0.99$ kg NH_3/tonne OFMSW of emissions were detected from the anaerobic digestion system mainly from the feeding devices including waste and leachate storage tanks. The higher quantity of CH_4 emissions can be described by the lower oxygen due to the absence of aeration and adequate mixing in the feeding devices.

Phong (2012) reported emissions of CH_4, NH_3, and N_2O for different anaerobic digestion systems. According to their study, CH_4 ranged from 1.25-16.6 kg CH_4/tonne biowaste with a median of 3.83 kg CH_4/tonne biowaste. The NH_3 emissions ranged from 0.041-6.03 kg NH_3/tonne biowaste with a median of 0.101 kg NH_3/tonne biowaste. Also, N_2O emissions ranged from 0.009-0.172 kg N_2O/tonne biowaste with a median of 0.064 kg N_2O/tonne biowaste. However, the measured CH_4 value is higher than the median, and the measured NH_3 value is lower than the median.

Similarly, Liebetrau et al. (2013) stated that all feeding components emit an average of 15.4×10^{-5} kg CH_4/kWh, 7.58×10^{-6} kg NH_3/kWh, and 2.50×10^{-7} kg N_2O/kWh. On the contrary, the present study shows a higher CH_4 emission of 1.85 kg/kWh and lower NH_3 emissions of 4×10^{-7} kg/kWh. Therefore, it can be concluded that the gaseous emissions depend on the technology adapted for the anaerobic digestion system depending on emission sources such as waste storage tanks, feeding devices, combined heat and power (CHP) units, biofilters, and digestate treatment systems.

As presented in Table 4.2, emissions of 0.243 NH_4^+, 0.00141 NO_3^-, and 0.0291 PO_4^{3-} kg/tonne OFMSW were lost from the liquid slurry and were assumed to be emission to the soil.

4.1.3 Main input and output flows- anaerobic digestion system

Table 4.2 shows the input flows and output flows of the anaerobic digestion system related to the functional unit (1 tonne of OFMSW). According to the input inventory results, electricity, and water are the main inputs to the anaerobic digestion system. Regarding water consumption, the anaerobic digestion system consumes 28.8 L water/tonne OFMSW for the irrigation of organic waste. Also, it consumes 0.0948 kWh electricity/tonne OFMSW only for the startup of the generator. However, there was no diesel oil consumption in the anaerobic facility since no other types of machinery are used.

Concerning the output flows, generated electricity through biogas combustion is known as the main output flow. It generates 3.83 kWh electricity/tonne OFMSW by creating 3.73 kWh net electricity/tonne OFMSW which is considered as the avoided product. Also, waste storage tanks produce 135 kg refuse/tonne OFMSW and the digesters produce about 588 L liquid slurry/tonne OFMSW as waste flows. The produced liquid slurry and waste from storage tanks are directed to the outside landfill without any treatment.

4.1.4 Impact assessment - anaerobic digestion system

Inventory data of the anaerobic digestion system was used to compute the environmental impacts using the ReCiPe 2016 midpoint (Hierarchist version, H) method including characterization and normalization stages. In the characterization step, the relative contribution of each impact category is scaled as 100%. Figure 4.1 illustrates the characterization results of the environmental impacts of the treatment of 1 tonne of OFMSW by anaerobic digestion.

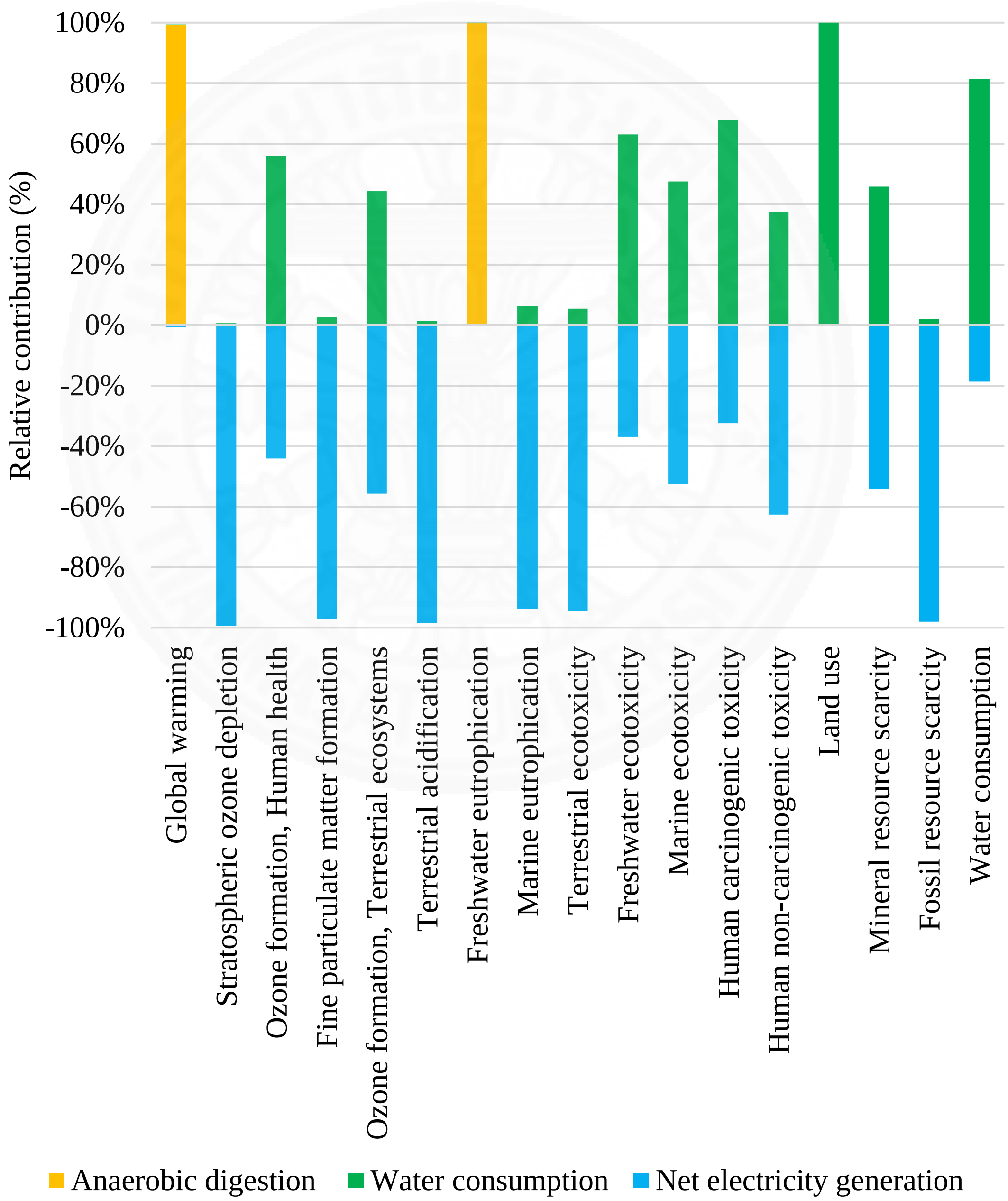

Figure 4.1 Environmental profile of the anaerobic digestion plant – characterization.

Numerical results of environmental burdens and benefits are denoted as plus values and minus values, respectively, for both characterization and normalization. As shown in Figure 4.1, net electricity production shows significant environmental benefits on all impact categories, except land use due to the avoided electricity production.

As per the numerical results of the characterization (Table 4.3), the anaerobic digestion system yields environmental burdens of 230 kg CO_2 eq on global warming; 6.15×10^{-6} kg NO_x eq on ozone formation, human health; 2.92×10^{-3} kg P eq on freshwater eutrophication; 9.27×10^{-5} kg 1,4-DCB on freshwater ecotoxicity; 3.98×10^{-4} kg 1,4-DCB on human carcinogenic toxicity; 1.32×10^{-4} m^2a crop eq on land use and 2.23×10^{-2} m^3 on water consumption per tonne of OFMSW.

Also, it yields benefits of -8.76×10^{-7} kg CFC-11 eq on stratospheric ozone depletion; -1.04×10^{-3} kg $PM_{2.5}$ eq on fine particulate matter formation; -7.46×10^{-6} kg NO_x eq on ozone formation, terrestrial ecosystems; -3.30×10^{-3} kg SO_2 eq on terrestrial acidification; -5.72×10^{-6} kg N eq on marine eutrophication; -0.174 kg 1,4-DCB on terrestrial ecotoxicity; -3.31×10^{-5} kg 1,4-DCB on marine ecotoxicity; -4.02×10^{-3} kg 1,4-DCB on human non-carcinogenic toxicity; -6.04×10^{-6} kg Cu eq on mineral resource scarcity, and -0.158 kg oil eq on fossil resource scarcity per tonne of OFMSW due to the avoided emissions from the electricity production.

However, the characterization stage does not allow us to compare the various impact categories as they are expressed in different units. Therefore, normalization was performed to convert all impact categories into the same units by calculating the magnitude of category indicator results relative to normalization reference values.

Although these normalized category indicators are not equally important, the total environmental impact of this study was calculated assuming that all impact categories are equally important.

Based on the normalized environmental impacts (Table 4.4), the aggregated value of the total environmental impact was 3.31×10^{-2}. The anaerobic digestion process contributes largely (3.35×10^{-2}), followed by the 9.40×10^{-4} burden from water consumption and 1.35×10^{-3} benefit from the avoided electricity production on the total impact.

Therefore, the anaerobic digestion process itself was identified as the main contributor to environmental impacts including 2.88×10^{-2} impacts from global warming and 4.49×10^{-3} impacts from freshwater eutrophication.

Table 4.3 Impact characterization results for the anaerobic digestion plant.

Impact category: Units (per tonne OFMSW)	Total	Anaerobic digestion	Water	Electricity generation
Global warming (kg CO_2 eq)	230	232	1.29E-02	-1.55
Stratospheric ozone depletion (kg CFC-11 eq)	-8.76E-07	0	5.00E-09	-8.81E-07
Ozone formation, Human health (kg NO_x eq)	6.15E-06	0	2.88E-05	-2.26E-05
Fine particulate matter formation (kg $PM_{2.5}$ eq)	-1.04E-03	3.53E-07	3.05E-05	-1.08E-03
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-7.46E-06	0	2.90E-05	-3.65E-05
Terrestrial acidification (kg SO_2 eq)	-3.30E-03	2.88E-06	4.69E-05	-3.35E-03
Fresh water eutrophication (kg P eq)	2.92E-03	2.91E-03	6.11E-06	-1.98E-07
Marine eutrophication (kg N eq)	-5.72E-06	0	4.07E-07	-6.13E-06
Terrestrial ecotoxicity (kg 1,4-DCB)	-0.174	0	1.06E-02	-0.184
Freshwater ecotoxicity (kg 1,4-DCB)	9.27E-05	0	2.23E-04	-1.30E-04
Marine ecotoxicity (kg 1,4-DCB)	-3.31E-05	0	3.15E-04	-3.48E-04
Human carcinogenic toxicity (kg 1,4-DCB)	3.98E-04	0	7.63E-04	-3.65E-04
Human non-carcinogenic toxicity (kg 1,4-DCB)	-4.02E-03	0	5.94E-03	-9.96E-03
Land use (m^2a crop eq)	1.32E-04	0	1.32E-04	0
Mineral resource scarcity (kg Cu eq)	-6.04E-06	0	3.29E-05	-3.89E-05
Fossil resource scarcity (kg oil eq)	-0.158	0	3.29E-03	-0.161
Water consumption (m^3)	2.23E-02	0	2.89E-02	-6.65E-03

Table 4.4 Normalized environmental impact of the anaerobic digestion plant.

Impact category	Total	Anaerobic digestion	Water consumption	Electricity generation
Global warming	2.88E-02	2.90E-02	1.62E-06	-1.93E-04
Stratospheric ozone depletion	-1.46E-05	0	8.36E-08	-1.47E-05
Ozone formation, Human	2.99E-07	0	1.39E-06	-1.09E-06
Fine particulate matter formation	-4.08E-05	1.38E-08	1.19E-06	-4.21E-05
Ozone formation, Terrestrial ecosystems	-4.19E-07	0	1.63E-06	-2.05E-06
Terrestrial acidification	-8.06E-05	7.03E-08	1.15E-06	-8.18E-05
Fresh water eutrophication	4.49E-03	4.48E-03	9.41E-06	-3.05E-07
Marine eutrophication	-1.24E-06	0	8.83E-08	-1.33E-06
Terrestrial ecotoxicity	-1.67E-04	0	1.02E-05	-1.78E-04
Freshwater ecotoxicity	7.55E-05	0	1.82E-04	-1.06E-04
Marine ecotoxicity	-3.21E-05	0	3.05E-04	-3.37E-04
Human carcinogenic toxicity	1.44E-04	0	2.75E-04	-1.32E04
Human non-carcinogenic toxicity	-2.69E-05	0	3.99E-05	-6.68E-05
Land use	2.14E-08	0	2.14E-08	0
Mineral resource scarcity	-5.03E-11	0	2.74E-10	-3.24E-10
Fossil resource scarcity	-1.61E-04	0	3.36E-06	-1.64E-04
Water consumption	8.36E-05	0	1.09E-04	-2.49E-05

Global warming potential

The anaerobic digestion process generated more GHGs, particularly methane, resulting in 232 kg CO_2 eq/tonne OFMSW. Moreover, it says that avoided emissions that are from electricity production could not balance the gross impact resulting in a net positive impact of 230 kg CO_2 eq/tonne OFMSW. Therefore, direct methane emissions during the anaerobic digestion process were identified as the main contributor to the global warming impact category. The open waste storage and leachate collection tanks were considered as the main gaseous emission sources from the anaerobic digestion system and it should be addressed to minimize these direct emissions. Therefore, the use of closed systems for waste storage and collection tanks instead of open systems can be incorporated into the anaerobic digestion plants to minimize the direct gaseous emissions. Also, the utilization of gas treatment systems such as biofilters and scrubbers can be used to minimize these impacts associated with gaseous emissions.

Freshwater eutrophication

As per the obtained results, the main contribution to freshwater eutrophication is produced by the discharge of nutrients (N and P) via liquid slurry. Therefore, a total of 2.92×10^{-3} kg P eq/tonne OFMSW freshwater eutrophication was reported hence the avoided impact from electricity generation could not offset the gross impact. The emissions from the liquid slurry can be reduced by recovering the soil conditioners instead of disposing of soil.

Considering past literature on the environmental impacts on anaerobic digestion, Chaya and Gheewala (2007) evaluated the environmental impacts of MSW incineration and anaerobic digestion systems using LCA. Based on that data, global warming potential of -276 kg CO_2 eq, acidification potential of -1.57 kg SO_2 eq, nutrient enrichment of 7.37 kg PO_4^{3-} eq, the photo-oxidant formation of -0.0253 kg C_2H_4 eq, stratospheric ozone depletion of -1.9×10^{-5} kg CFC-11 eq and heavy metals of -0.0036 kg Pb eq and generation of solid waste to landfill of 372 kg, was reported. Therefore, potentials of global warming, acidification, photo-oxidant formation, stratospheric ozone formation, and heavy metals are avoided by electricity and fertilizer production while it creates a significant burden of 7.37 kg PO_4^{3-} eq on the nutrient enrichment impact category. Therefore, Chaya and Gheewala (2007) specified that emissions of substances to water that contribute nutrient enrichment should be addressed hence the potential burden is more significant for the studied anaerobic digestion system.

4.2 Impact assessment of the composting system

4.2.1 Characterization of input waste and compost

Since both composting and anaerobic digestion systems treat source-separated OFMSW collected from Kaduwela municipal council, the composition is almost the same as illustrated in Table 4.1. The physiochemical characteristics of input and output materials were determined from three sampling campaigns and average values were calculated (Table 4.5).

Regarding input OFMSW; 73.9±1.05% moisture content, 15.5±1.14% TS of ash content, 84.5±1.14% TS of VS content, 41.3±3.38% TS of carbon content, 2.53±0.47% TS of nitrogen content, 6.64±0.53% TS of hydrogen content, and 34.0±4.49% TS of oxygen content were accounted.

Table 4.5 Characterization of input and output materials.

Parameters	Unit	OFMSW: average	Compost: average	Refuse: average
TS	%	26.1±1.05	79.4±2.16	75.1±2.56
VS	% TS	84.5±1.14	60.7±0.89	71.4±0.77
Ash	% TS	15.5±1.14	39.3±0.89	28.6±0.77
C	% TS	41.3±3.38	29.5±2.47	29.0±3.18
H	% TS	6.64±0.53	3.95±0.59	4.24±0.38
N	% TS	2.53±0.47	3.36±0.32	2.73±0.13
O	% TS	34.0±4.49	23.9±3.06	35.4±3.63
Formula		$C_{19}H_{37}O_{12}N$	$C_{10}H_{16}O_6N$	$C_{12}H_{22}O_{11}N$

Based on analysis results of final compost, 20.6±2.29% moisture content, 39.3±0.89% TS of ash content, 60.7±0.89% TS of VS content, 29.5±2.47% TS of carbon content, 3.36±0.32% TS of nitrogen content, 3.95±0.59% TS of hydrogen content, and 23.9±3.06% TS of oxygen content were taken into account.

And, physicochemical properties of refuse materials were 24.9±2.58% moisture content, 28.6±0.77% TS of ash content, 71.4±0.77% TS of VS content, 29.0±3.18% TS of carbon content, 2.73±0.13% TS of nitrogen content, 4.24±0.38% TS of hydrogen content, and 35.4±3.63% TS of oxygen content.

Therefore, the calculated empirical formulas were $C_{19}H_{37}O_{12}N$, $C_{10}H_{16}O_6N$, and $C_{12}H_{22}O_{11}N$ for OFMSW, compost, and refuse materials, respectively. Then the gaseous emissions were determined using stoichiometry.

4.2.2 Gaseous and leachate emissions - composting system

For the composting system, NH_3 emissions were determined using the stoichiometry approach. CH_4 and N_2O emissions were obtained based on the IPCC default values for composting (4 kg CH_4 and 0.3 kg NH_3 per tonne of OFMSW, respectively). Table 4.6 presents a summary of the inventory data for the composting plant.

About 3.17 kg NH_3/tonne OFMSW was estimated through the stoichiometry approach while 4 kg CH_4/tonne OFMSW, and 0.3 kg N_2O/tonne OFMSW were estimated according to the IPCC default values for the composting.

Table 4.6 Inventory data for the composting plant (per 1 tonne of OFMSW).

Units			Composting
Process inputs	Electricity	kWh/tonne OFMSW	3.12
	Water usage	L/tonne OFMSW	29.1
	Diesel	L/ tonne OFMSW	1.59
Process outputs	Compost	kg/tonne OFMSW	97.1
Atmospheric emissions	NH_3	kg/tonne OFMSW	3.17
	CH_4	kg/tonne OFMSW	4
	N_2O	kg /tonne OFMSW	0.3
Waste flows	Refuse materials	kg/tonne OFMSW	14.6
	Leachate	L/tonne OFMSW	239
	PO_4^{3-}	kg/tonne OFMSW	0.0616
	NH_4^+	kg/tonne OFMSW	0.0938
	NO_3^-	kg/tonne OFMSW	1.42
Avoided Products	N	kg/tonne OFMSW	0.669
	P_2O_5	kg/tonne OFMSW	0.156
	K_2O	kg/tonne OFMSW	0.709

The graphical representation of material flow analysis (Figure 4.2) of the composting system was performed through the mass balance model STAN (version 2.0) for the verification of the theoretical gaseous emission by the stoichiometry approach.

According to Figure 4.2, 6,411 kg OFMSW was treated by the composting plant, resulting in 622 kg of compost, 93.3 kg of refuse, and 1,533 L of leachate per day. Therefore, 4,349 kg of materials (including water) was lost to the atmosphere. Considering the whole three months period, the mass of gaseous emissions and percent losses are presented in Table 4.7.

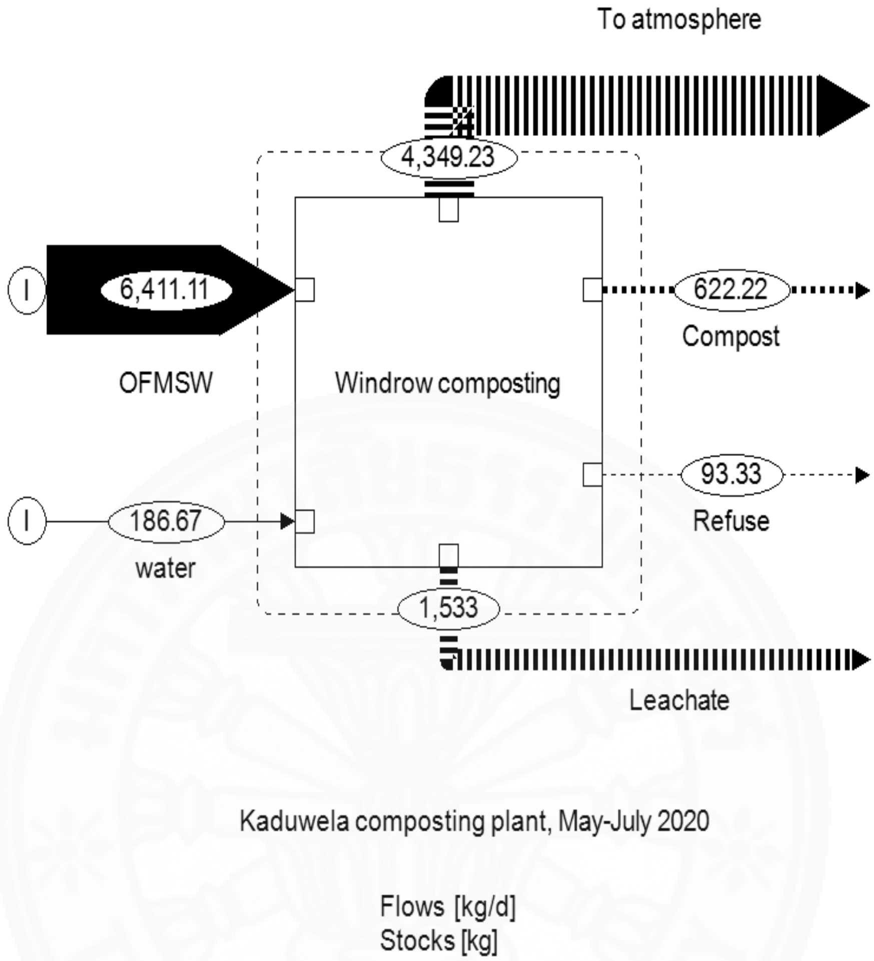

Figure 4.2 Material flow analysis of the composting system (kg material per day).

Table 4.7. Emissions of CO_2, N_2O, CH_4, and NH_3 expressed in kg per three months period and percent loss of gaseous emissions to the atmosphere.

Parameters	CO_2	N_2O	CH_4	NH_3
Gaseous emissions (kg)	154,151	173	2308	1833
Percent of loss (%)	26.7	0.03	0.40	0.32

During the studied three months, 154,151 kg CO_2, 173 kg N_2O, 2,308 kg CH_4, and 1,833 kg NH_3 were emitted into the atmosphere. Therefore, 26.7%, 0.03%, 0.40%, and 0.32% of losses accounted for the CO_2, N_2O, CH_4, and NH_3. The remaining fraction accounted mainly for the moisture losses and other trace gases which are not focused on the present study. Therefore, the quantification of mass losses to the atmosphere was in agreement with the mass balance calculated in STAN.

Considering NH_3 emissions, Cadena, Colón, Artola, Sánchez and Font (2009b) reported 3.9 kg NH_3/tonne OFMSW for tunnel composting. On contrary, the emissions related to the confined windrow were 2 kg NH_3/tonne OFMSW which is lower than the measured value.

As Martínez-blanco et al. (2010) specified, 0.034 kg CH_4, 0.11 kg NH_3, and 0.092 kg N_2O per tonne of OFMSW were emitted from the tunnel composting system which was significantly lower than the present values due to the availability of the biofiltration process.

The produced leachate from the composting system is known as a source of N and P losses. Based on the obtained data, 0.0616 kg PO_4^{3-}, 0.0938 kg NH_4^+ 1.42 kg NO_3^- were accounted for the leachate. However, the emissions were not taken into the environmental impact assessment since the collected leachates were reutilized in the composting plant.

4.2.3 Main input and output flows - composting system

The main input flows and output flows related to the functional unit (1 tonne OFMSW) of the composting plant are presented in Table 4.6. Electricity, water, and fuel consumption are the main input flows.

The composting system consumes 3.12 kWh electricity/tonne OFMSW for the operation of the compost huller machine. However, several authors reported higher electricity consumption values than the present study. For example, the study conducted by Martínez-blanco et al. (2010) reported 50.5 kWh electricity/tonne OFMSW for aeration, plant lighting, and operation of machinery. The other study conducted by Cadena, Colón, Artola, Sánchez and Font (2009b) stated that the tunnel composting and confined windrow composting consumes 95 and 65.5 kWh electricity/tonne OFMSW, respectively for the forced aeration.

Regarding water consumption, the composting system consumes 29.1 L water/tonne OFMSW. Following Cadena, Colón, Artola, Sánchez and Font (2009b), the water consumption in the confined windrow composting system was 20 L/tonne

OFMSW and 330 L/tonne OFMSW for the tunnel composting. Also, Martínez-blanco et al. (2010) revealed that the industrial composting system consumes 437 L/tonne OFMSW for cleaning and for irrigating the organic waste.

Also, the studied composting system utilizes 1.59 L diesel oil/tonne OFMSW for the operation of the front loader tractor. Based on Cadena, Colón, Artola, Sánchez and Font (2009b), diesel consumption was 3.6 and 9 L diesel oil/tonne OFMSW for tunnel and confined windrow composting systems, respectively. Diesel oil is mainly used for mixing and post-treatment processes performed with diesel machinery and trucks and tractors for onsite transportation.

Moreover, 97.1 kg compost/tonne OFMSW is produced from the composting system which can be used as an organic fertilizer. It mainly consists of 6.9 kg N, 1.61 kg P_2O_5, and 7.3 kg K_2O per tonne of compost.

Therefore, 0.669 kg of nitrogen fertilizer, 0.156 kg of phosphorous fertilizer as P_2O_5, and 0.709 kg of potassium fertilizer as K_2O per tonne of OFMSW are avoided by the recovering of compost.

Considering the other outflows, 239 L leachate/tonne OFMSW and 14.6 kg refuse/tonne OFMSW are produced from the composting plant.

4.2.4 Impact Assessment – composting system

Inventory data from the composting system was used to assess the environmental impacts using the ReCiPe 2016 midpoint method (Hierarchist version, H). Figure 4.3 and Table 4.8 shows the characterization results of the environmental impacts of the treatment of 1 tonne of OFMSW by composting.

Figure 4.3 shows the relative contributions of each impact categories and it implies that the replacement of chemical fertilizer (nitrogen, phosphorus, and potassium fertilizers) by produced compost yields environmental benefits for all impact categories. However, for the composting process, water, diesel, and electricity consumption yield significant burdens on the impact categories.

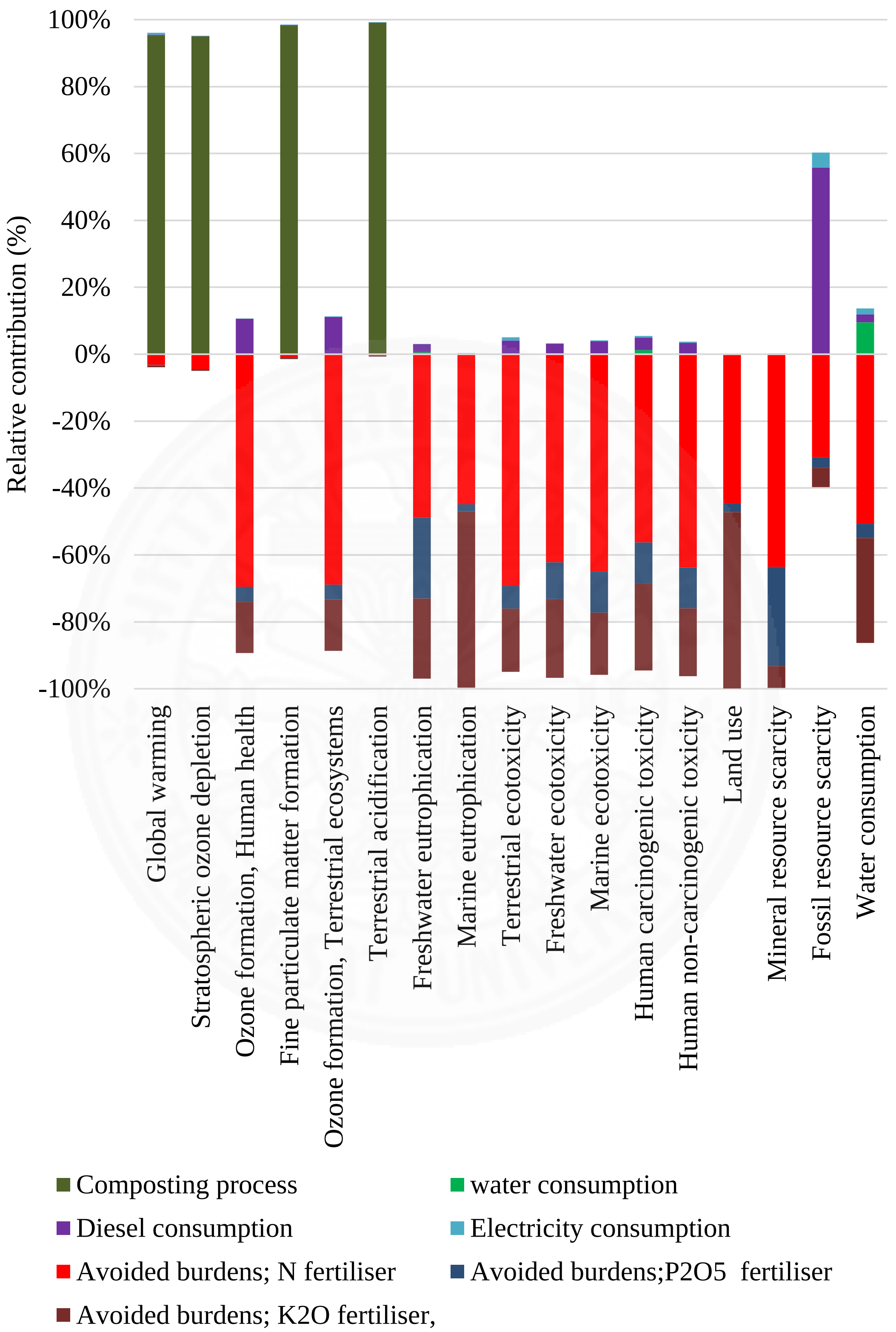

Figure 4.3 Environmental profile of the composting plant - characterization results.

Table 4.8 Impact characterization results for the composting plant.

Impact category	Unit	Total	Composting process	water	Diesel	Electricity	Fertilizer Production
Global warming	kg CO_2 eq	218	225	1.31E-02	0.610	1.29	-9.23
Stratospheric ozone depletion	kg CFC-11 eq	3.13E-03	3.30E-03	5.07E-09	1.16E-06	7.35E-07	-1.71E-04
Ozone formation, Human health	kg NO_x eq	-1.51E-02	0	2.91E-05	1.99E-03	1.89E-05	-1.71E-02
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.75	0.761	3.09E-05	1.84E-03	8.97E-04	-1.14E-02
Ozone formation, Terrestrial ecosystems	kg NO_x eq	-1.51E-02	0	2.94E-05	2.15E-03	3.04E-05	-1.74E-02
Terrestrial acidification	kg SO_2 eq	6.17	6.21	4.76E-05	5.64E-03	2.80E-03	-4.62E-02
Fresh water eutrophication	kg P eq	-1.07E-03	0	6.18E-06	2.83E-05	1.65E-07	-1.10E-03
Marine eutrophication	kg N eq	-3.68E-03	0	4.12E-07	7.8E-06	5.11E-06	-3.69E-03
Terrestrial ecotoxicity	kg 1,4 DCB	-13.27	0	1.07E-02	0.586	0.154	-14.0
Freshwater ecotoxicity	kg 1,4 DCB	-8.13E-02	0	2.26E-04	2.49E-03	1.09E-04	-8.42E-02
Marine ecotoxicity	kg 1,4 DCB	-0.100	0	3.18E-04	3.95E-03	2.90E-04	-0.105
Human carcinogenic toxicity	kg 1,4 DCB	-5.48E-02	0	7.72E-04	2.27E-03	3.04E-04	-5.81E-02
Human non-carcinogenic toxicity	kg 1,4 DCB	-2.71	0	6.02E-03	9.49E-02	8.31E-03	-2.82
Land use	m^2a crop eq	-2.26	0	1.34E-04	1.15E-03	0	-2.27
Mineral resource scarcity	kg Cu eq	-3.69E-02	0	3.33E-05	3.27E-05	3.25E-05	-3.69E-02
Fossil resource scarcity	kg oil eq	0.613	0	3.33E-03	1.66	0.134	-1.18
Water consumption	m^3	-0.222	0	2.93E-02	7.17E-03	5.55E-03	-0.264

Table 4.9 Normalization results for the composting plant.

Impact category	Total	Composting process	water	Diesel	Electricity	N fertilizer	P_2O_5 fertilizer	K_2O fertilizer
Global warming	218	2.82E-02	1.64E-06	7.64E-05	1.62E-04	-9.39E-04	-3.50E-05	-1.81E-04
Stratospheric ozone depletion	3.13E-03	5.51E-02	8.46E-08	1.94E-05	1.23E-05	-2.64E-03	-7.17E-06	-2.02E-04
Ozone formation, Human	-1.51E-02	0	1.42E-06	9.71E-05	9.17E-07	-6.48E-04	-4.15E-05	-1.43E-04
Fine particulate matter formation	0.75	2.97E-02	1.21E-06	7.18E-05	3.51E-05	-3.00E-04	-4.29E-05	-1.03E-04
Ozone formation, Terrestrial ecosystems	-1.51E-02	0	1.65E-06	1.21E-04	1.71E-06	-7.58E-04	-4.87E-05	-1.70E-04
Terrestrial acidification	6.17	0.152	1.16E-06	1.38E-04	6.83E-05	-7.78E-04	-6.43E-05	-2.85E-04
Fresh water eutrophication	-1.07E-03	0	9.52E-06	4.36E-05	2.54E-07	-8.53E-04	-4.23E-04	-4.18E-04
Marine eutrophication	-3.68E-03	0	8.94E-08	1.69E-06	1.11E-06	-3.61E-04	-1.70E-05	-4.24E-04
Terrestrial ecotoxicity	-13.27	0	1.03E-05	5.66E-04	1.48E-04	-9.88E-03	-9.62E-04	-2.69E-03
Freshwater ecotoxicity	-8.13E-02	0	1.81E-04	2.04E-03	8.87E-05	-4.41E-02	-7.79E-03	-1.67E-02
Marine ecotoxicity	-0.100	0	3.09E-04	3.82E-03	2.81E-04	-6.87E-02	-1.31E-02	-1.96E-02
Human carcinogenic toxicity	-5.48E-02	0	2.79E-04	8.18E-04	1.10E-04	-1.25E-02	-2.75E-03	-5.75E-03
Human non-carcinogenic toxicity	-2.71	0	4.04E-05	6.37E-04	5.58E-05	-1.25E-02	-2.40E-03	-4.00E-03
Land use	-2.26	0	2.17E-08	1.86E-07	0	-1.64E-04	-9.73E-06	-0.000194
Mineral resource scarcity	-3.69E-02	0	2.77E-10	2.72E-10	2.7E-10	-1.96E-07	-9.16E-08	-2.02E-08
Fossil resource scarcity	0.613	0	3.40E-06	1.69E-03	1.37E-04	-9.36E-04	-9.71E-05	-1.75E-04
Water consumption	-0.222	0	1.09E-04	2.69E-05	2.08E-05	-5.83E-04	-4.88E-05	-3.6E-04

According to the numerical results of the characterization (Table 4.8), the composting system yields environmental burdens of 218 kg CO_2 eq on global warming; 3.13×10^{-3} kg CFC-11 eq on stratospheric ozone depletion; 0.752 kg $PM_{2.5}$ eq on fine particulate matter formation; 6.17 kg SO_2 eq on terrestrial acidification; 0.613 kg oil eq on fossil resource scarcity per tonne of OFMSW.

Also, it yields benefits of -1.51×10^{-2} kg NO_x eq on ozone formation, human health; -1.07×10^{-3} kg P on freshwater eutrophication; -8.13×10^{-2} kg 1,4-DCB on freshwater ecotoxicity; -5.48×10^{-2} kg 1,4-DCB on human carcinogenic toxicity; -2.26 m^2a crop eq on land use; -0.222 m^3 on water consumption; -1.51×10^{-2} kg NO_x eq on ozone formation, terrestrial ecosystems; -3.68×10^{-3} kg N eq on marine eutrophication; -13.27 kg 1,4-DCB on terrestrial ecotoxicity; -0.100 kg 1,4-DCB on marine ecotoxicity; -2.71 kg 1,4-DCB on human non-carcinogenic toxicity and -3.69×10^{-2} kg Cu eq on mineral resource scarcity per tonne of OFMSW due to the avoided emissions from the fertilizer production.

However, the characterization stage does not permit us to make a comparison of the various impact categories as they are expressed in different units. Therefore, to identify the most significant contribution to the total environmental impact, the normalization is performed. Although the normalized impact category indicators are not equally important, total environmental impact was calculated with the assumption of all impact categories are equally important. Therefore, the total environmental impact was calculated as 4.10×10^{-2} in the composting system including burdens of 0.265 from the composting process, 9.54×10^{-4} from water consumption, 1.03×10^{-2} from diesel, 2.09×10^{-3} from electricity, and benefits of -0.237 from the avoided fertilizer production. Therefore, the composting process contributes significantly to global warming, stratospheric ozone depletion, fine particulate matter formation, terrestrial acidification by creating environmental burdens. However, ecotoxicity potentials (terrestrial, freshwater, marine, human carcinogenic, and human non-carcinogenic) are avoided by the fertilizer production.

Global warming potential

The composting process generated more GHGs resulting in 225 kg CO_2 eq/tonne OFMSW. However, a total global warming potential of 218 kg CO_2 eq/tonne OFMSW was determined which could not be avoided by the fertilizer production. The main contributor to the high global warming potential is methane and nitrous oxide emissions during the composting process.

Stratospheric ozone depletion

Mainly, the nitrous oxide emission from the composting process resulted in 3.30×10^{-3} kg CFC11 eq/tonne OFMSW of impact on the stratospheric ozone formation. However, stratospheric ozone depletion impact from fertilizer production could not offset the gross impact resulting in 3.13×10^{-3} kg CFC11 eq/tonne OFMSW.

Fine particulate matter formation

The composting process was seen to have more potential than water, fuel, and electricity consumption because of the high ammonia emissions into the air. Therefore, it generated 0.752 kg $PM_{2.5}$ eq/tonne OFMSW of a total burden on the fine particulate matter formation impact category.

Terrestrial acidification

The ammonia emission from the composting system resulted in the terrestrial acidification potential of 6.17 kg SO_2 eq/tonne OFMSW which was not significantly avoided by the fertilizer production.

Ecotoxicity (terrestrial, freshwater, marine, human carcinogenic, and human non-carcinogenic)

The ecotoxicity potentials were avoided by the fertilizer production in the composting systems creating benefits of -13.27 kg 1,4 DCB on terrestrial, -8.13×10^{-2} 1,4 DCB on freshwater, -0.100 kg 1,4 DCB on marine, -5.48×10^{-2} kg 1,4 DCB on human carcinogenic, and -2.72 kg 1,4 DCB on human-non carcinogenic impact categories.

Therefore, the direct gaseous emissions such as CH_4, NH_3, and N_2O from the composting system were identified as the main contributor to the associated burdens. Continuous aeration and proper mixing of the composted materials allow for reducing methane emissions. Also, exhaust gas treatment systems such as biofilters and scrubbers can be identified as the potential emission reduction measures for the composting system.

Considering the past literature, Martínez-Blanco et al. (2010) conducted a study to compare industrial composting and home composting. It was mentioned that the industrial composting could cause abiotic depletion potential of 0.768 kg Sb eq, acidification potential of 0.777 kg SO_2 eq, eutrophication potential of 0.223 kg PO_4^{3-} eq, global warming potential of 153 kg CO_2 eq, ozone layer depletion potential of 1.33×10^{-5} kg CFC-11 eq and cumulative energy demand of 1910 MJ.

Based on the study conducted by Cadena, Colón, Artola, Sánchez & Font, (2009b), environmental impacts of tunnel composting and confined windrow composting systems were compared. As they quantified, tunnel composting could cause global warming potential of 63.9 kg CO_2 eq, acidification potential of 7.13 kg SO_2 eq, eutrophication potential of 1.51 kg PO_4^{3-} eq, human toxicity potential of 15.9 kg 1,4-DCB eq, ozone layer depletion potential of 1.66×10^{-5} kg CFC-11 eq, and photochemical oxidation potential of 0.13 kg C_2H_4 eq per tonne of OFMSW.

On contrary, the confined windrow composting system could cause global warming potential of 63.2 kg CO_2 eq, acidification potential of 3.7 kg SO_2 eq, eutrophication potential of 0.77 kg PO_4^{3-} eq, human toxicity potential of 14.5 kg 1,4-DCB eq, ozone layer depletion potential of 2.77×10^{-5} kg CFC-11 eq, and photochemical oxidation potential of 3.11 kg C_2H_4 eq per tonne of OFMSW.

4.3 Comparison of environmental impacts between anaerobic digestion and composting

4.3.1 Comparison of inventory analysis

As shown in Table 4.10, the anaerobic digestion plant consumes 0.0948 kWh electricity, 28.8 L water to treat 1 tonne of OFMSW. The composting plant consumes 3.12 kWh electricity, 1.59 L diesel, and 29.1 water to treat 1 tonne of OFMSW.

Regarding water consumption, both systems utilize almost equal amounts of water for irrigation of the organic waste. On the other hand, the composting system has higher electricity consumption. Unlike anaerobic digestion, the composting system consumes diesel oil for the machinery operations.

Therefore, based on the obtained results, higher resource consumption is recorded in the composting system. Concerning output flows, about 97.1 kg compost/tonne OFMSW is produced in the composting plant, and 3.73 kWh net electricity/tonne OFMSW is produced in the anaerobic digestion plant. Comparing the gaseous emissions, a higher amount of NH_3 is recorded in the composting system than the anaerobic digestion system (3.17 and $1.47\times10^{-6}\pm0.99$ kg NH_3/tonne OFMSW, respectively). But the higher methane emissions are reported in the anaerobic digestion plant (6.82±0.02 and 4 kg CH_4/tonne OFMSW, respectively). N_2O emissions were only detected in the composting plant (0.3 kg /tonne OFMSW).

Table 4.10 Life cycle inventory summary for the anaerobic digestion and composting.

Units			Composting	Anaerobic digestion
Process inputs	Electricity	kWh/tonne OFMSW	3.12	0.0948
	Water	L/tonne OFMSW	29.1	28.8
	Diesel	L/tonne OFMSW	1.59	0
Process output	Compost	kg/tonne OFMSW	97.1	0
	Electricity	kWh/tonne OFMSW	0	3.83
Atmospheric emissions	NH_3	kg/tonne OFMSW	3.17	$1.47\times10^{-6}\pm0.99$
	CH_4	kg/tonne OFMSW	4	6.82±0.02
	N_2O	kg /tonne OFMSW	0.3	0
Waste flows	Refuse	kg/tonne OFMSW	14.6	135
	Leachate	L/tonne OFMSW	239	0
	Liquid slurry	L/tonne OFMSW	0	588
	PO_4^{3-}	kg/tonne OFMSW	0.0616	0.0291
	NH_4^+	kg/tonne OFMSW	0.0938	0.243
	$NO_3^{-,}$	kg/tonne OFMSW	1.42	0.00141
Avoided Products	Electricity	kWh/tonneOFMSW	0	3.73
	N	kg/tonne OFMSW	0.669	0
	P_2O_5	kg/tonne OFMSW	0.156	0
	K_2O	kg/tonne OFMSW	0.709	0

4.3.2 Impact assessment

Inventory data presented in Table 4.10 were used to evaluate and compare the environmental impacts between anaerobic digestion and composting systems. The ReCiPe 2016 endpoint method (Hierarchist version, H/A) was used for the evaluation, and the characterization results are shown in Table 4.11.

Table 4.11 Endpoint characterization results for composting and anaerobic digestion.

Impact category	Unit	Anaerobic digestion	Composting
Global warming, Human health	DALY	2.14E-04	2.03E-04
Global warming, Terrestrial ecosystems	species.yr	6.45E-07	6.11E-07
Global warming, Freshwater ecosystems	species.yr	1.76E-11	1.67E-11
Stratospheric ozone depletion	DALY	-4.7E-10	1.66E-06
Ozone formation, Human health	DALY	5.58E-12	-1.4E-08
Fine particulate matter formation	DALY	-6.6E -07	4.73E-04
Ozone formation, Terrestrial ecosystems	species.yr	-9.6E-13	-2E-09
Terrestrial acidification	species.yr	-7E-10	1.31E-06
Freshwater eutrophication	species.yr	1.96E-09	-7.1E-10
Marine eutrophication	species.yr	-9.8E-15	-6.3E-12
Terrestrial ecotoxicity	species.yr	-2E-12	-1.5E-10
Freshwater ecotoxicity	species.yr	6.4E-14	-5.6E-11
Marine ecotoxicity	species.yr	-3.5E-15	-1.1E-11
Human carcinogenic toxicity	DALY	1.32E-09	-1.8E-07
Human non-carcinogenic toxicity	DALY	-9.2E-10	-6.2E-07
Land use	species.yr	1.17E-12	-2E-08
Mineral resource scarcity	USD2013	-1.5E-06	-6.58E-03
Fossil resource scarcity	USD2013	-0.038	0.373
Water consumption, Human health	DALY	4.94E-08	-1.9E-07
Water consumption, Terrestrial ecosystem	species.yr	3.01E-10	-1.4E-09
Water consumption, Aquatic ecosystems	species.yr	1.35E-14	-4.9E-13

Considering the characterization results, a total burden of 6.77×10^{-4} DALY on human health, 1.89×10^{-6} species.yr on the ecosystem, and 0.366 USD on resource were calculated for the composting system. The anaerobic digestion plant yields a burden of 2.13×10^{-4} DALY on human health, 6.46×10^{-7} species.yr on the ecosystem, and a benefit of -3.85×10^{-2} USD on resource scarcity.

Therefore, the composting system creates more environmental burden on each endpoint than the anaerobic digestion. However, the characterization stage does not allow for comparing the various impact categories as they are expressed in different units. Therefore, to identify to what extent an impact category has a significant contribution to total environmental impact and which process performs better, the normalization and weighting were performed. Normalized results for both anaerobic digestion and composting are presented in Table 4.12 and Figure 4.4.

Table 4.12 Endpoint normalization results for composting and anaerobic digestion.

Impact category	Anaerobic digestion	Composting
Global warming, Human health	9.01E-03	8.53E-03
Global warming, Terrestrial ecosystems	9.00E-04	8.52E-04
Global warming, Freshwater ecosystems	2.46E-08	2.33E-08
Stratospheric ozone depletion	-1.96E-08	6.99E-05
Ozone formation, Human health	2.35E-10	-5.78E-07
Fine particulate matter formation	-2.76E-05	1.99E-02
Ozone formation, Terrestrial ecosystems	-1.34E-09	-2.73E-06
Terrestrial acidification	-9.78E-07	1.83E-03
Freshwater eutrophication	2.73E-06	-9.98E-07
Marine eutrophication	-1.36E-11	-8.73E-09
Terrestrial ecotoxicity	-2.76E-09	-2.11E-07
Freshwater ecotoxicity	8.94E-11	-7.87E-08
Marine ecotoxicity	-4.87E-12	-1.47E-08
Human carcinogenic toxicity	5.57E-08	-7.65E-06
Human non-carcinogenic toxicity	-3.85E-08	-2.61E-05
Land use	1.64E-09	-2.81E-05
Mineral resource scarcity	-5.31E-11	-2.35E-07
Fossil resource scarcity	-1.37E-06	1.33E-05
Water consumption, Human health	2.08E-06	-7.99E-06
Water consumption, Terrestrial ecosystem	4.19E-07	-1.98E-06
Water consumption, Aquatic ecosystems	1.88E-11	-6.89E-10

Considering the normalized endpoint results, the composting system yields a significant burden of 2.85×10^{-2} on human health, 2.65×10^{-3} on ecosystems, and 1.31×10^{-5} on resource scarcity. On the other hand, the anaerobic digestion system creates burdens of 8.99×10^{-3} on human health and 9.02×10^{-4} on ecosystems. Also, it yields a benefit of -1.37×10^{-6} on resource scarcity.

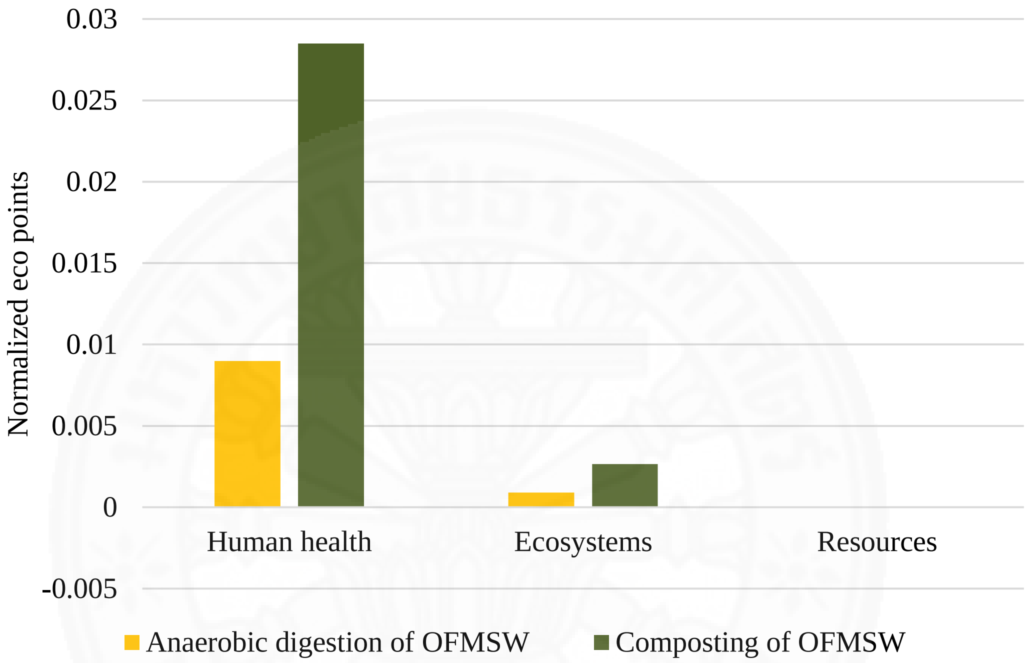

Figure 4.4 Comparison of normalized environmental profile for composting and anaerobic digestion.

Since normalized impact category indicators are not equally important, weighting was performed to calculate a single score for both treatments. Therefore, weighting was performed by multiplying the normalized values of each impact category by the corresponding weighted factor. Based on the results, global warming, human health, and global warming, terrestrial ecosystems are considered as the most significant impact categories for anaerobic digestion systems. And, global warming, human health, global warming, terrestrial ecosystems, fine particulate matter formation, and terrestrial acidification are considered as the most significant impact categories for the composting system. According to Figure 4.5, the anaerobic digestion plant accounted for a total environmental load of 3.95 points, including 3.59 on human health, 0.36 on ecosystem health, and -2.70×10^{-4} on resource scarcity. The total environmental load for the composting plant was 12. 46 points including 11.39 on human health, 1.06 on ecosystem health, and 2.62×10^{-3} on resource scarcity.

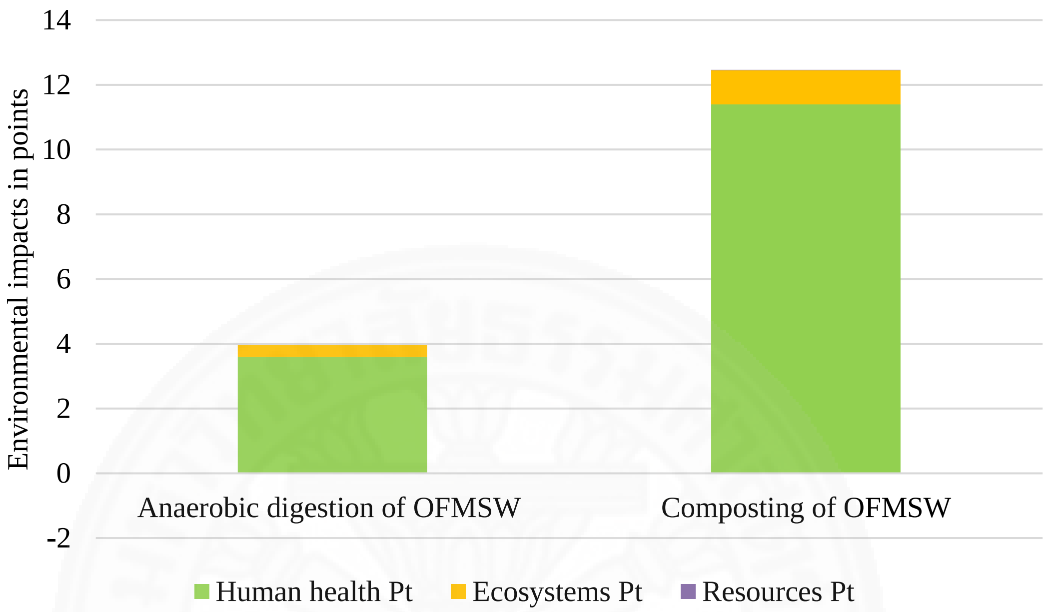

Figure 4.5 Single score values for the anaerobic digestion and composting

Therefore, the composting system has a higher environmental load than the anaerobic digestion process. The human health endpoint is considered as the highly influenced impact category for both systems. However, ecosystem health is comparatively low for both systems. Therefore, the environmental impact of composting is three times higher than the environmental impact of the anaerobic digestion process. Considering the total environmental load, there is a higher possibility to use the anaerobic digestion process that seems better instead of the composting process for the treatment of OFMSW in Sri Lanka. However, these environmental impacts highly depend on the treatment technology adopted for both composting and anaerobic digestion. Therefore, these values can be different from the treatment system to system.

Although the environmental load in anaerobic digestion is lower, initiation is still a difficult challenge owing to its higher capital cost and lack of knowledge, skills, and experiences. However, the complexity is much lower in composting than in anaerobic digestion, which makes it suitable for treating MSW. Sri Lanka is also an agricultural country where paddy, tea, coconut, rubber, and other crops are grown. The agriculture sector contributes 7.6% of the national Gross Domestic Production (GDP). Recently, 43.7% of the total land area is being used for agriculture; covering 35% for paddy, 28% for plantation, and 37% for other crops (Sri Lanka Export Development Board, 2019). Therefore, chemical fertilizers such as urea, potash, and phosphate fertilizers are introduced for crop production to increase productivity and ensure food security. In 2017, fertilizer consumption per hectare of arable land was 139 kg/ha (World Bank, 2014). Since Sri Lanka is experiencing adverse impacts of the chemical fertilizer, it has a higher possibility to use this produced compost as an organic fertilizer. Thus, MSW composting seems better to be used in Sri Lanka. However, the present study only focused on the environmental aspects, therefore social aspects and economical aspects should be incorporated for the decision making.

4.3.3 Sensitivity analysis

4.3.3.1 Sensitivity analysis of the composting system

Sensitivity analysis was calculated to evaluate the effect of key assumptions on the overall results. The sensitivity analysis for both anaerobic digestion and composting systems were separately assessed and results are presented in Table 4.13 and Table 4.14. For the composting system, the effects of gaseous emissions and electricity country mix were assessed using five scenarios.

Table 4.13 Comparison of environmental impacts for six scenarios considered for the composting system.

Endpoints	Initial scenario 1	Sensitivity analysis of other scenarios (%)				
		2	3	4	5	6
Human health	2.85×10^{-2}	206	83	92	100.1	99.9
Ecosystem	2.65×10^{-3}	204	82	92	100.1	99.9
Resources	1.31×10^{-5}	100	100	100	105.9	94.1

Scenario 1: Initial scenario (100% of the contribution of each endpoint).

Scenario 2: NH_3 emission from the complete conversion of aerobic biodegradation.

Scenario 3: CH_4 emission reported by Pergola et al. (2020).

Scenario 4: N_2O emission reported by Pergola et al (2020).
Scenario 5: 10% increase in conventional fossil energy in the electricity country mix.
Scenario 6: 10% decrease in conventional fossil energy in the electricity country mix.

The assumption used for the calculation of NH_3 was assessed in scenario 2. Therefore, the estimated NH_3 value (7.9 kg NH_3 per tonne of OFMSW) from complete aerobic biodegradation was used instead of the obtained value from incomplete aerobic biodegradation. Since there is a high difference between the emissions considered, a higher increase of 106% was measured in human health and a 104% increase was measured in the ecosystem endpoint.

Concerning methane emissions, the IPCC default value (4 kg/tonne OFMMSW) for composting was used for emission determination. But, this value is considerably high than the emissions reported by Pergola et al (2020). Therefore, CH_4 emission reported by Pergola et al. (2020) was assessed in scenario 3 using an average of 0.4 kg/tonne of OFMSW. Since there is a high difference between the emission factors considered a decrease of 17% in human health and a decrease of 18% in the ecosystem was determined due to the less CH_4 emissions.

Also, the IPCC default value for N_2O (0.3 kg/tonne OFMSW) was used for the emission determination. Therefore, the N_2O emission reported by Pergola et al (2020) was used for scenario 4 to evaluate the sensitivity. Therefore, 0.12 kg N_2O/tonne OFMSW was considered for scenario 4. A decrease of 8% in human health and ecosystems was measured due to the reduction of N_2O emissions.

The electricity country mix was assumed as 55% of conventional thermal energy (24% from oil and 31% from coal), 42% of hydropower, and 3% of renewable energy (2.12% from wind energy and 1.78% from other) for the calculation of emissions from electricity. Therefore, scenarios 5 and 6 assessed the effects of a 10% increase and decrease of the conventional fossil energy in the electricity country mix. The increase of 5% in oil and coal, a simultaneous decrease of 10% in hydropower were considered in scenario 5. And, scenario 6 included a decrease of 5% in oil and coal, a simultaneous increase of 10% in hydropower. Therefore, an increase of 0.1% in human health and ecosystem endpoints, and an increase of 5.9% in resource scarcity were calculated due to a 10% increase in conventional fossil energy. In scenario 6, a 0.1% decrease in human health and the ecosystem, and a 5.9% decrease in resource scarcity were calculated due to the decrease of 10% of conventional fossil energy. Therefore, the effect of resource scarcity endpoint is significantly high in both 5 and 6 scenarios due to the increase of fossil resources.

4.3.3.2 Sensitivity analysis of the anaerobic digestion system

The sensitivity analysis for the anaerobic digestion was assessed using two scenarios including a 10% increase and a 10% decrease of conventional fossil energy for electricity production same as the composting system.

Table 4.14 Comparison of environmental impacts for three scenarios considered for the anaerobic digestion system.

Impact categories	Initial scenario 1	Sensitivity analysis of other scenarios (%)	
		2	3
Human health	8.99×10^{-3}	97.4	100.3
Ecosystem	9.02×10^{-4}	99.6	100.3
Resources	-1.37×10^{-7}	120.3	79.7

Scenario 1: Initial scenario (100% of the contribution of each category).
Scenario 2: 10% increase in conventional fossil energy in the electricity country mix.
Scenario 3: 10% decrease in conventional fossil energy in the electricity country mix.

In scenario 2, an increase of 20.3% was measured in the resource scarcity endpoint while a 2.6% decrease in human health and a 0.4% decrease in the ecosystem were measured due to an increase of 10% conventional fossil energy. However, with the decrease of 10% of conventional fossil energy, a 0.3% increase in the human health and ecosystem was measured while a 20.3% decrease was measured in the resource scarcity endpoint. Here also, the effect on resource scarcity endpoint is considerably higher than the other two. However, when comparing anaerobic digestion and composting, the effects of 10% increasing and decreasing of conventional fossil energy in the electricity country mix are higher in the anaerobic digestion system due to the avoided electricity production.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

LCA is used to evaluate the environmental impacts of both composting and anaerobic digestion plants. Several conclusions can be obtained from the results of inventory analysis and impact assessment.

The resource consumption data such as water, electricity, and fuel are different for both plants and depend on the treatment technology adopted. The compost plant consumes 3.12 kWh of electricity, 29.1 L of water, and 1.59 L of diesel for the treatment of 1 tonne of OFMSW resulting in 97.1 kg of compost/tonne OFMSW. The anaerobic digestion plant consumes 0.0948 kWh of electricity and 28.8 L of water for the treatment of 1 tonne of OFMSW resulting in 3.73 kWh of net electricity. Therefore, based on the obtained results, higher resource consumption is recorded in the composting system than in the anaerobic digestion.

The direct emissions of the anaerobic digestion and composting processes are identified as the main contributors to the calculated environmental impacts. Regarding direct gaseous emissions, 6.82±0.02 kg CH_4 and 1.47×10^{-6} kg NH_3 per tonne OFMSW were emitted from the anaerobic digestion plant while 4 kg CH_4, 3.17 kg NH_3, and 0.3 kg N_2O per tonne of OFMSW were emitted from the composting plant.

In reference to the ReCiPe 2016 midpoint (H) with world (2010) normalization, normalized results show a total of 3.31×10^{-2} aggregated environmental impact for the anaerobic digestion by assuming all impact categories are equally important. The highest contribution 3.35×10^{-2} was identified from the anaerobic digestion process particularly from global warming and freshwater eutrophication thus it should be addressed to minimize. The composting system reported total normalized points of 4.10×10^{-2} creating the highest contribution of 0.265 points from the composting process. Therefore, the composting process contributes significantly to global warming, stratospheric ozone depletion, fine particulate matter formation, terrestrial acidification by creating environmental burdens. However, ecotoxicity potentials (terrestrial, freshwater, marine, human carcinogenic, and human non-carcinogenic) are avoided by the fertilizer production.

The comparison between anaerobic digestion and composting was carried out using the ReCiPe endpoint (H/A) using world (2010) normalization and weighting.

Considering the characterization results, a total burden of 6.77×10^{-4} DALY on human health, 1.89×10^{-6} species.yr on the ecosystem, and 0.366 USD on resource were calculated for the composting system. The anaerobic digestion plant yields a burden of 2.13×10^{-4} DALY on human health, 6.46×10^{-7} species.yr on the ecosystem, and a benefit of -3.85×10^{-2} USD on resource scarcity.

As per the normalization and weighting, global warming human health, global warming terrestrial ecosystems, fine particulate matter formation, and terrestrial acidification are known as the most significant impact categories for the composting plant, whereas global warming human health and global warming terrestrial ecosystems are identified as the most significant impact categories for the anaerobic digestion plants. Finally, the anaerobic digestion plant accounted for a total environmental load of 3.95 points, including 3.59 on human health, 0.36 on ecosystem health, and -2.70×10^{-4} on resource scarcity. The total environmental load for the composting process was 12.46 points including 11.39 on human health, 1.06 on ecosystem health, and 2.62×10^{-3} on resource scarcity.

Therefore, the environmental load is three times higher in the composting system than in the anaerobic digestion system. Based on the present study, the anaerobic digestion plant contributing to the lowest environmental impacts, thus it motivates to select the most viable option to treat OFMSW. However, MSW composting is also an advantageous option for Sri Lanka, since produced compost can be utilized as an organic fertilizer.

5.2 Recommendations

The study has contributed to the identification of environmental impacts of OFMSW treatment by anaerobic digestion and composting. The obtained results can be used for the selection of the most viable option for the treatment of OFMSW. Therefore, the findings can support the decision-makers and help in the policy formation in Sri Lanka to overcome waste management issues. However, evaluation of social impacts and economic impacts are recommended to incorporate with the environmental impacts for future works. Also, the present study can be used to evaluate the environmental impacts of anaerobic digestion and composting plants with similar characteristics.

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