COMPARATIVE LIFE CYCLE ASSESSMENT OF DIFFERENT ORGANIC MUNICIPAL WASTE TREATMENTS

A CASE STUDY OF THE RESTORE PROJECT IN THE AMSTERDAM NEIGHBOURHOOD

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Comparative Life Cycle Assessment of Different Organic Municipal Waste Treatments

A Case Study of the ReStore Project in the Amsterdam Neighbourhood

By

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in partial fulfilment of the requirements for the degree of

Master of Science
in Industrial Ecology

at Leiden University and Delft University of Technology
to be defended publicly on Wednesday, July 8, 2020 at 10:30 AM

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“There is no such thing as away.
When we throw anything away it must go somewhere.”

Annie Leonard

“Waste itself is a human concept; everything in nature is eventually used. If human beings carry on in their present ways, they will one day be recycled along with the dinosaurs.”

Peter Marshall

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Acknowledgements

For the last two years I had the immense pleasure to pursue my master's degree in two universities at the same time. It has been nothing but an exhilarating journey. I have gained a deeper understanding on how sustainability intertwines with a diverse field of knowledge, I have learnt a lot of multi-discipline concepts, and also not forgetting the new experiences I have owned through adapting to new cultures and surroundings. Two years went by rapidly until I finally concluded my life as an Industrial Ecology master student with this thesis project. The past six months were a really challenging moment, yet it was noteworthy and rewarding. I would like to take this opportunity to thank all these people whose assistance was a milestone in the completion of this project.

First of all, I would like to deliver my sincere gratitude to Dr. Ir. Gijsbert Korevaar and Drs. Lauran van Oers for their guidance and thoughtful feedback throughout this project. I would also love to express my appreciation to Ir. Kasper Lange for being available as my first reference person to provide suggestions and useful advice through each stage of the process. My gratitude also belongs to Yannick Schrik, B.Sc as the external supervisor from Amsterdam University of Applied Science (HvA) for making himself reachable for discussions along with his help and advice during this project.

I would like to extend my thanks to my family, especially my mom and my sister for being my foremost support system. Thank you for always having faith in me. You have inspired me to be a brave and committed person. You have taught me to persevere and to never give up on my dreams. I deeply dedicate this work to my mom. She is the terrific role model, the main reason for me to keep holding on. Realising that what I can do is definitely incomparable to her unconditional kindness and support, I hope this will at least prove to her how much I adore her.

Last but certainly not the least, I want to thank my fellow IE classmates for sharing laughter, joy, and tears together during this challenging and exciting two-years ride. I would also like to thank my friends in Indonesia for their endless encouragement. Regardless of the distance and time differences, I thank them that they are still willing to cherish and stand by me. I also want to send my genuine appreciation to Christian Marvelous as my forever best friend. You have always been there through the ups and downs and shower me with countless motivation. Thank you for always listening to my story and being one of the most insightful people with whom I can even discuss my thesis.

By this, I will close the chapter of my master's journey. Reflecting back, I have never imagined that I would step out of my comfort zone, moved out 7,000 miles away from my hometown, and left my beloved families and friends. Despite the hard decisions and the devastating yearning, I am surprised by how far I have grown and developed as a person. I am deeply grateful for what I have achieved up till now. The future is certainly uncertain, yet I am thrilled for whatever new rides life will bring.

Leiden, June 2020

Veronica Grace

Executive Summary

The unprecedented growth of urban population and wealth has caused an exponential rise in the amount of waste being generated. The amount of waste generated in urban areas is projected to increase by 70% in 2050, amounting to 3.4 billion tonnes. Within the Netherlands, approximately 8.5 million tonnes of solid waste are produced annually. Being the capital city with the most populated district in the Netherlands, higher municipal solid waste accumulation in Amsterdam is in existence. A substantial portion of the municipal waste in Amsterdam is categorized as organic waste, with a percentage of 36%.

By far, the waste separation in Amsterdam is further less than the national average. The best performance is observed for metal, glass, and paper while the separation rate for organic waste does not even reach 0.1%. One of the reasons is the lack of space to build the infrastructure due to the high population density. Eventually, most of the organic waste is often commingled with residual waste and being collected altogether. This waste is directed to the central treatment plant to be incinerated collectively. As organic waste is high in nutrient content, other waste treatment practices that can conserve its value as much as possible are started to be considered. Some of the well-known examples are composting and bio-digestion.

A project called ReStore contributed to this by developing a measurement method on centralised and decentralised organic waste management options by means of composting, vermicomposting, and bio-digestion towards the existing practice, waste-to-energy (WtE). The model aimed to simulate these organic waste management options to provide companies and municipalities with the financial, ecological, and social insight of these practices. However, it is not yet known the extent to which the outcome of this model can be accurately interpreted. Thus, an evaluation within a systematic approach is needed to ensure that the outcome of this model appears to be valid. Although the impact of waste management has been documented in the numerous previous research, the typical configuration, feature, infrastructure, and process design made up the unique characteristic of organic waste management. Thus, there is a need for detailed analysis that is capable of considering specific waste properties and process characteristics through a chain perspective.

Taking the ReStore method as a point of departure, this study seeks to investigate the environmental impact of composting, bio-digestion, and WtE using the Life Cycle Assessment (LCA) method and finally point out how both models can complement one another. This leads to the main research question addressed in this study: *What is the carbon footprint of bio-digestion and composting as organic waste management alternatives in the Amsterdam neighbourhood towards the current practice of Waste-to-Energy (WtE) based on the LCA methodology compared to the model developed by ReStore?* To that end, this study is divided into several stages.

First, a literature review was carried out along with model observation of ReStore to gain lessons learned as well as to collect and compile the required data for the next step. Next, an environmental impact modelling was performed using the CMLCA software v.6.1, building on the characteristics from the ReStore model for the foreground system and Ecoinvent v.3.4 database for the background system. Through comparative analysis, the outcome of the LCA study was then compared with the outcome from the ReStore model to pinpoint the underlying comparisons and the degree of complementary of

both models. Finally, recommendations were formulated on how the concept of LCA helps in providing suggestions on modelling waste management for the ReStore model and vice versa.

The literature review informed that organic waste management and its evaluation within LCA have become a common practice. The conceptualization on the ReStore model provided an insight on the measured important indicators to develop a measurement system and simulation model of different organic waste scenarios on centralised and decentralised scale. The model covered the ecological, economical, and social assessment, yet, this LCA study will only evaluate the environmental impact. The environmental model of ReStore directed its investigation by assessing the several organic waste diversion scenarios in terms of its CO_2-equivalent emission. The model took into account all direct activities related to the organic waste collection up to the point of products application.

The second stage was the environmental impact assessment where an LCA model was constructed based on the system boundary and assumptions as addressed in ReStore with some introduced adjustments. The system boundary of the LCA study was arranged to be as close as possible as what was defined in ReStore. The initial system boundary which included decentralised processing options were omitted and so does the application of the end-products. The functional unit of the object under-studied was defined as managing organic municipal waste in the Amsterdam neighbourhood within a year. The alternatives addressed in this study are Waste-to-Energy (WtE), centralised bio-digestion, and centralised composting. The characterisation results of the climate change score in the LCA model for WtE, bio-digestion, and composting are 35,557 kg CO_2-eq, 55,386 kg CO_2-eq, and 51,184 kg CO_2-eq respectively. Meanwhile the result from ReStore model for WtE, bio-digestion, and composting are 36,350 kg CO_2-eq, 57,152 kg CO_2-eq, and 51,026 kg CO_2-eq in respective order. It can be seen that at this point, the results between both models were obtained within a close range. Further similarity is perceptible when examining the impact from each stage. Both models have a nearly equivalent hotspot distribution. For all alternatives, the highest emission is associated with processing, accounted for around 80% of the total impact. The remaining stages result in diverse contribution per each alternative, yet, the percentage of contribution is shown to be similar in both models.

A certain part of the process chain is multifunctional where there are two functions being delivered at once from one process. The LCA study firstly employed system expansion as the baseline method to overcome the multifunctional issue. Other choices of methods in solving multifunctional process such as substitution and economic allocation were also applied as a part of sensitivity analysis. This allows for a comparison of how different solutions for multifunctionality influence the final outcome of both models. It is also important because there is no method to solve multifunctionality problem that can be considered as the best or preferred method. The sensitivity towards changes in methods to solve multifunctional issue showed that the results are heavily dependent on the type of selected solution. All methods agreed on WtE to be the most preferably option, while the impact is swapped occasionally between bio-digestion and composting when other methods were used. During the system expansion method, bio-digestion is granted with the largest impact. Meanwhile, when substitution and economic allocation were performed, composting becomes the alternative to have the highest climate change score. All results obtained from different allocation method are represented with positive values with an exception for substitution. In substitution, the impact of WtE becomes negative because the burdens avoidance are larger than the impacts associated with the incineration process. These results indicated the importance of assessing different methods to handle multifunctional issue, where this adds to the point of contribution of the LCA to the ReStore model.

This study conducted several sensitivity analysis where several parameters were changed. The assumption made on the type of product to be equivalent with electricity and compost were tested out to determine how this will affect the result and to improve the interpretation of results. This will help in discovering the influencing factors to cause the difference between results of both models. The first sensitivity analysis was carried out by selecting different types of electricity to be replaced, which in this case are electricity from combined-cycle gas power plant and electricity from coal, towards the baseline scenario where the produced electricity from the investigated system was initially assumed to be equivalent with the Dutch electricity mix. Both models behave similarly with regard to this alteration, where similar trend of increment and reduction were shown. The results showed that both models are not particularly sensitive to a switch from the Dutch electricity mix to natural gas, while it is more sensitive to a shift towards coal The second analysis was conducted within the context of compost. The produced compost from bio-digestion and composting was originally assumed to be equivalent with potassium fertiliser. The sensitivity analysis performed an evaluation on this assumption by changing the type of fertiliser to urea and phosphate fertiliser. It was observed that the results did not change significantly when this adjustment were executed. Additionally, some deviations occurred in how both models response to changes, which indicate point of differentiation. Finally, when peat was chosen to be equivalent with compost, it was noticed that the ReStore model is more sensitive towards this scenario since the result was found to be higher in ReStore.

The outcome from these sensitivity analysis signify that one of the influencing factors shall directed from mineral fertilisers and peat, as both models behave differently when these parameters were examined. It was later discovered that the GHG emission of mineral fertilisers and peat are fairly different between the values defined in the ReStore model and in the LCA model. This sensitivity analysis informed that the results were tentative, depends on which assumptions were used. The results were also subject to change if certain assumptions were modified. Furthermore, this analysis indicated the importance of further evaluation because each parameter causes different level of sensitivity to each model, which also serves as additional suggestion for the ReStore model.

Based on the preceding findings, it was concluded that the ReStore model and the LCA model share the same response, where not either bio-digestion and composting are deemed to have better environmental performance than WtE. Though differences between both models are not really prominent, yet, the knowledge of LCA embraces essential contributions towards performance improvement for ReStore to model a better organic waste management scenario. It is recommended for ReStore to be clearer in defining the system boundary by recognising the concept of functional flow and multi-functionality. It is also suggested to make the interpretation more extensive by including more impact categories. The complete characterisation result enlightens the far-reaching outcome from different impact categories, indicating that visualizing the findings from various impact categories is considered fundamental. The performed sensitivity analysis provides evidence on how dependent the results are on the modelling decisions and assumptions proposed in the study. Thus, it is suggested to further evaluate crucial parameters such as the allocation method and types of competing products to complement the analysis. Additionally, further research should be directed to incorporate the economic and social evaluation as an integration towards the environmental perspective addressed in this study. This research has managed to perform the comparison of both models, which will open the path for each model to reflect on better organic waste management modelling and interpretation.

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List of Abbreviations

AD	Anaerobic Digestion
CC	Centralised Composting
CHP	Combined Heat and Power
EI	Ecoinvent database
FU	Functional Unit
GHG	Greenhouse Gasses
HN	High-Nutrient
ISO	International Organization for Standardization
LN	Low-Nutrient
OFMSW	Organic Fraction Municipal Solid Waste
WtE	Waste-to-Energy

Glossary of Selected LCA Terms

Alternative

One of a set of product systems studied in a particular LCA, e.g. for comparison (note: some LCA steps are carried out for all alternatives together (e.g. selection of impact categories), while others are repeated for each alternative (e.g. characterisation).

Background system/process

a system or process for which secondary data, viz. databases, public references, estimated data based on input-output analysis, are used in an LCA

Category indicator

a quantifiable representation of an impact category, e.g. infrared radiative forcing for climate change

(Category) indicator result

the numerical result of the characterization step for a particular impact category, e.g. 12 kg CO_2-equivalents for climate change

Category total

the category indicator result for a particular impact catgeory, a specified reference region and time period

Characterization

a step of Impact assessment, in which the elementary flows assigned qualitatively to a particular impact category (in classification) are quantified in terms of a common unit for that category, allowing aggregation into a single score: the indicator result

Characterization factor

a factor derived from a characterization model for expressing a particular elementary flow in terms of the common unit of the category indicator, e.g. $POCP_{methanol}$ (photochemical ozone creation potential of methanol)

Characterization model

a mathematical model of the impact of elementary flows with respect to a particular category indicator

Characterization result

the overall result of the characterization step: a table showing the indicator results for all the predefined impact categories, supplemented by any other relevant information

Completeness check

a step of the interpretation phase to verify whether the information yielded by the preceding phases is adequate for drawing conclusions in accordance with the Goal and Scope definition

Consistency check
: a step of the interpretation phase to verify whether assumptions, methods, and data have been applied consistently throughout the study and in accordance with the Goal and Scope definition

Contribution analysis
: a step of the Interpretation phase to assess the contributions of individual life cycle stages (groups of) processes, environmental interventions, and indicator results to the overall LCA result (e.g. as a percentage)

Economic flow
: a flow of goods, materials, services, energy or waste from one unit process to another; with either a positive (e.g. steel, transportation) or zero/negative (e.g. waste) economic value

Economic process
: see unit process

Elementary flow
: matter or energy entering or leaving the product system under study that has been extracted from the environment without previous human transformation (e.g. timber, water, iron ore, coal) or is emitted or discarded into the environment without subsequent human transformation (e.g. CO_2 or noise emissions, wastes discarded in nature)

Environmental impact
: a consequence of an elementary flow in the environment system

Functional unit
: the quantified function provided by the product system(s) under study, for use as a reference basis in an LCA, e.g. 1000 hours of light (adapted from ISO)

Foreground system/process
: a system or process for which primary, site-specific data are used in an LCA, for whatever reason

Goal and scope definition
: the first phase of an LCA, establishing the aim of the intended study, the functional unit, the reference flow, the product system(s) under study and the breadth and depth of the study in relation to this aim

Good(s)
: flow(s) between two processes with an economic value higher than or equal to zero

(Life Cycle) impact assessment
: the third phase of an LCA, concerned with understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study

Impact category
a class representing environmental issues of concern to which elementary flows are assigned, e.g. climate change, loss of biodiversity

Input
a product (goods, materials, energy, services), waste for treatment or elementary flow (including resource extraction, land use, etc.) modeled as 'entering' a unit process (adapted from ISO)

(Life Cycle) interpretation
the fourth phase of an LCA, in which the results of the Inventory analysis and/or Impact assessment are interpreted in the light of the Goal and scope definition (e.g. by means of contribution, perturbation and uncertainty analysis, comparison with other studies) in order to draw up conclusions and recommendations

(Life Cycle) inventory analysis
the second phase of an LCA, in which the relevant inputs and outputs of the product system(s) under study throughout the life cycle are, as far as possible, compiled and quantified

(Life Cycle) inventory (analysis) result
the result of the Inventory analysis phase: a table showing all the elementary flows associated with a product system, supplemented by any other relevant information (adapted from ISO)

Life Cycle
the consecutive, interlinked stages of a product system, from raw materials acquisition or natural resource extraction through to final waste disposal

Life Cycle Assessment (LCA)
compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle; the term may refer to either a procedural method or a specific study

Midpoint approach
problem-oriented approach definition of category indicators close to environmental interventions

Multifunctional process
a unit process yielding more than one functional flow, e.g. co-production, combined waste processing, recycling

Multifunctionality and allocation
a step of the Inventory analysis in which the inventory model is refined and the input and output flows of multifunctional processes are partitioned to the functional flows of those processes

Natural resource
a biotic or abiotic resource that can be extracted from the environment in a unit process

Normalisation
a step of Impact assessment in which the indicator results are expressed relative to well-defined reference information, e.g. relative to the indicator results for global elementary flows in 1995

Normalisation factor
the reciprocal of the indicator result for a particular impact category and reference system; used in the normalization step

Normalised indicator result
the numerical result of normalization for a particular impact category, e.g. 0.02 yr for climate change

Normalisation result
the result of the normalization step: a table showing the normalized indicator results for all the selected impact categories, supplemented by any other relevant information

Output
an economic flow (e.g. energy, waste for treatment) or elementary flow (e.g. pollutant or noise emission) modeled as 'leaving' a unit process (adapted from ISO)

Phase
any of the four basic elements of an LCA, viz. Goal and scope definition, Inventory analysis, Impact assessment and Interpretation

Product system
a set of unit processes interlinked by material, energy, product, waste or service flows and performing one or more defined functions

Sensitivity and uncertainty analysis
a step of the Interpretation phase to assess the robustness of the overall LCA results with respect to variations and uncertainties in the method and data used

System boundary
the interface between a product system and the environment system or other product systems

Unit process
the smallest portion of a product system for which data are collected in an LCA

Waste(s)
Flow(s) between two processes with an economic value smaller than zero

Weighting
a step of Impact assessment in which the (normalized) indicator results for each impact category assessed are assigned numerical factors according to their relative importance, multiplied by these

factors and possibly aggregated; weighting is based on value-choices (e.g. monetary values, standards, expert panel)

Sources: ISO (2006a); Guinée et al. (2002)

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Chapter 1

Introduction

1.1 Background

Globally, nearly 2.01 billion tonnes of solid waste are generated annually in urban areas (Hoornweg & Bhada-Tata, 2012). Moving forward, this number will likely increase by 70%, reaching 3.4 billion tonnes of waste being generated in 2050 (Kaza et al.2018). This sharp rise is strongly influenced by an upsurge in the urban population, from 43% in 1990 to 55% in 2018 (World Bank, 2019). More population leads to more demand and consumption, which allows the production trend to escalate. As a consequence, this has predominantly caused an unpleasant increase in the amount of municipal solid waste in the city (Mukhtar et al. 2016). Moreover, the development of the economy promotes improved lifestyles and living standards which trigger more activities, and this, inevitably imply to more waste being generated (Gardiner & Hajek, 2017). Despite these external factors being said, it is often forgotten that an ever-increasing amount of waste often occurs as a result of inefficient energy and materials management by industry sectors (European Environment Agency, 2016).

Within the Netherlands, approximately 8.5 million tonnes of municipal solid waste is produced every year (CBS, 2016). Out of this number, organic waste holds the largest composition where it dominates 33% of the total amount of municipal solid waste (Bijleveld et al. 2016). The city addressed in this study, Amsterdam, is the capital of the Netherlands that is perceived as one of the busiest and most populated districts in the country. Reflecting upon this fact, it is undeniable that the city of Amsterdam comprises a significant amount of domestic waste (Sperl, 2016). A similar tendency is observed with the situation on a country level where a substantial portion of the municipal waste in Amsterdam also belongs to organic waste with a share of 36%. This organic waste mostly consists of kitchen scraps, food leftovers, and garden waste (Gemeente Amsterdam, 2014).

In most Amsterdam neighbourhoods, different types of waste separation are made available where glass, metal, paper and cardboard, plastic packaging and drink cartons, and textiles and shoes are disposed in different bins. Among these waste streams, metal, glass, and paper are monitored to have a quite high separation rate of 80%, 59%, and 38% respectively (Gemeente Amsterdam, 2015). Whereas the separation percentage for these materials has successfully coped with the objective set by the city, this is still relatively scarce for the case of organic waste (Zhang et al. 2020). It is reported that the organic waste separation rate in Amsterdam is even less than 0.1% (Mulder et al. 2019; Gemeente Amsterdam, 2015).

One of the main challenges in doing source separation of organic waste in urban areas like Amsterdam is the large proportion of high-rise buildings, reaching almost 88% (Midden, 2015). Likewise, the fact that Amsterdam is a crowded, built-up municipality with an intense population density of nearly 5,000 inhabitants per km^2 does not allow the city to have enough open space (Zhang et al. 2020) Consequently, there is an insufficient place to store and dispose organic waste. Besides geographical challenges, the low percentage of organic waste separation is also subjected to the social factor. The separation of organic waste is still considered voluntary, and as such, the majority of households have not yet fully implemented it. For this reason, residents will eventually bring their waste altogether to underground containers for residual waste. These accumulated waste are then picked up within a certain period to be delivered to the central collection point. The organic waste is then directly sent to the incineration plant and being incinerated together with the residual waste.

In point of fact, organic waste contains high valuable-structure materials and is rich in nutrients and organic matter (Six et al. 2016). A wide range of solutions is proposed to preserve as much value of organic waste as possible such as making compost out of it and treat the organic waste through anaerobic digestion. Other solutions become apparent within the local initiatives for instance by developing worm hotels and independently collect their organic waste at home (Eneh & Oluigbo, 2012). On the other hand, the city of Amsterdam has the ambition to increase its waste separation rate by 70% in 2030 (Gemeente Amsterdam, 2014). Align with this target, a number of circular waste management schemes as previously mentioned might be worth the search to support the implementation of this goal.

A project called ReStore focused on this by developing a simulation model to measure the impact and added value of various organic waste processing, either on the centralised or decentralised scale. Within the project, composting, vermicomposting, and bio-digestion were chosen as scenarios to be compared with the ongoing implementation, which is Waste-to-Energy (WtE) (Mulder et al. 2019). These scenarios were evaluated based on the environment, economic, and social perspective. As a result, the model developed by ReStore provides opportunities for companies and municipalities to get more insight at the ecological, financial, and social impacts of various organic waste management forms.

By all means, the implementation of each alternative has its particular drawbacks and benefits and this made up the dynamic performance of the waste management system. To this, the environmental performance of the given alternatives cannot be validated without any evaluation and comparison within a systematic approach. Life Cycle Assessment (LCA), which will be the gist of this research, is an environmental assessment tool that can be used to assess the environmental impact of various waste treatments (Ekvall *et al.*2007). The outcome of this analysis will be the breeding ground to define the long-term sustainability performance of alternative organic waste management options over the current waste management practice. Therefore, the use of LCA will be beneficial to lead the model developed by ReStore through the LCA methodology to provide opportunities on how the theory works and to portray how the ReStore model will be done in the manner of LCA. In this case, the LCA approach may serve as a comparison and an alignment can then be made between the model developed by ReStore with the model developed by implementing the LCA approach. This conveys a full picture of the model overview where the coherency level of the ReStore model and the LCA model can be evaluated.

1.2 Problem Statement

Amsterdam is the most densely populated area where waste generation keeps showing a consequent increase. It was mentioned by Gemeentee of Amsterdam (2015) that most of the constituent of municipal solid waste generated in the city is organic waste. However organic waste collection in strong urban areas such as Amsterdam is barely implemented as confirmed by CBS (2018). Typically, in most of the districts in Amsterdam, most residents do not make the effort to separate their waste at home.

Moreover, there is lack of space to build infrastructure for separate organic waste collection. This makes the organic waste to be combined as household residual waste category and being dumped to the underground containers like so.

On the ground of this, Mulder et al. (2019) developed a measurement method of centralised and decentralised organic waste processing system under a project called ReStore. The model allowed the quantification of the environmental burden, the cost-effectiveness, and the social effect of the overall organic waste management system. The model developed by ReStore served as a good notion to support the goal set by the Amsterdam municipality to improve the performance in the waste separation and therewith recycling rates. It was then necessary to know which of the available alternatives is the most appealing in terms of the environmental score. However, as the environmental model becomes established, it seems that it is not sufficient to gain a complete and valid interpretation of the environmental performance between all proposed scenarios only based on the information provided by this model. A different attempt concerning the modelling, conceptualization, and approach needs to be approximated in order to gain a far-reaching and thorough interpretation. In this case, the LCA framework holds the role to accomplish this intention. While the model developed by ReStore serves a decent and in-depth analysis, the LCA method lies its focus on a generic analysis by taking a process chain perspective.

The non-exhaustive list of literature on organic waste management as portrayed in chapter 3 shows that there has been some initial research investigating organic waste treatment and its corresponds environmental impact. In one of the papers, Lou & Nair (2009) advocated the necessity to reproduce the same research objective but with the different geographical area as this is not a one-situation-fits-all context. Furthermore, Siew et al. (2019) emphasized how different features, infrastructure, and process design of waste management system can make up to a huge distinction to the final outcome. Nabavi-Pelesaraei et al. (2017) gave a more specific overview by breaking down the impact of different waste management options stage by stage in which it was strongly recommended to look from a more detailed parameter. Moreover, most of these studies lie their focus on another part of Europe where a big amount is found in Italy (Costa et al. 2019; Mondello, et al. 2017; Buratti et al. 2015; De Feo & Malvano, 2009), several are found in the United Kingdom (Siew et al. 2019; Parkes et al. 2015), some are available in Denmark and Sweden (Broogard, 2013; Eriksson et al. 2005), and some other are found in Spain or Portugal (Oliveira et al. 2016; Koneczny & Pennington (2007). Above it all, there is insufficient scientific evidence to back up the studies of organic waste management within the Netherlands context.

These previous knowledge gaps provide the opportunity for this study to fill in. It is noticed that the results of the organic waste management system vary considerably between countries since organic waste in certain countries is made up of different compositions, unexceptionally in the neighbourhood of Amsterdam. Moreover, the technical configuration of certain processing plants is a huge determinant of their operational performance. It is then crucial to analyse a particular country or even a specific city with specific plants separately rather than generalize the results of one study. Therefore, there is a need for detailed analysis that is capable of taking into account specific waste properties and process characteristics.

1.3 Research Objective

This research seeks to assess the carbon footprint of composting and bio-digestion as alternatives of organic waste treatment towards the existing system of WtE using the LCA methodology by taking the ReStore model as the starting point. Following the environmental assessment, this study will perform a comparative analysis to compare the result of the LCA model and the ReStore model. This stage aims to determine the level of differences and or similarities in both models. By aligning the LCA framework with the approach used in the ReStore model, this study aims to dive into the degree of complementary of both models. By this, the research also contributes to find areas of improvement for the ReStore model by providing recommendations to their current environmental model. This will also lead to scientific contributions where the concept used in the LCA model can possibly add to the knowledge of the ReStore model and the other way around.

1.4 Research Question

With respect to the above-mentioned research goal and knowledge gap, the following research question is addressed:

What is the carbon footprint of bio-digestion and composting as organic waste management alternatives in the Amsterdam neighbourhood towards the current practice of Waste-to-Energy (WtE) based on the LCA methodology compared to the model developed by ReStore?

In order to answer the previous main research question, the following sub-questions are developed:

1st sub-RQ : What are the characteristics of the ReStore model in evaluating the municipal organic waste management in the Amsterdam neighbourhood?

2nd sub-RQ : Taking the model developed by ReStore as a starting point, what is the carbon footprint of bio-digestion, composting, and WtE within the LCA perspective?

3rd sub-RQ : To what extent does the ReStore model differ with the LCA model in terms of environmental performance for organic waste management options and what are the influencing factors?

4th sub-RQ : How can the LCA model and the LCA framework contribute to the ReStore model for providing suggestions on modelling the organic waste management and vice versa?

1.5 Thesis Structure

In general, this report is constituted of seven chapters and is structured based on the following logical order. The first chapter is this introduction chapter which aims to deliver the research background, present the overview of the research topic, and formulate the research question. Chapter 2 describes the types of approach and method implemented in this study which includes the literature study, the underlying LCA concept, and the explanation on the comparative analysis. In this chapter, the elaboration on the ReStore case study which further details what ReStore project entails is also presented. Thereafter, the key concepts used in this study, the relation between them, and relevant theories based on the literature review are addressed in chapter 3. The fourth chapter is where the case study is analysed from the environmental perspective according to the methodological framework of LCA. Following this, the robustness of the result is evaluated in chapter 5 to find the main influencing factors. Chapter 6 discusses the level of comparison between both models and advises suggestions on how the ReStore model and the LCA model can complement and benefit from each other. Finally, everything is put into a nutshell in chapter 7, where the final conclusion is drawn along with the elaboration of study limitations, scientific and societal contribution, and recommendations for the ReStore model and future research. The complete structure of this thesis is summarized in the research flow diagram in Figure 1.1.

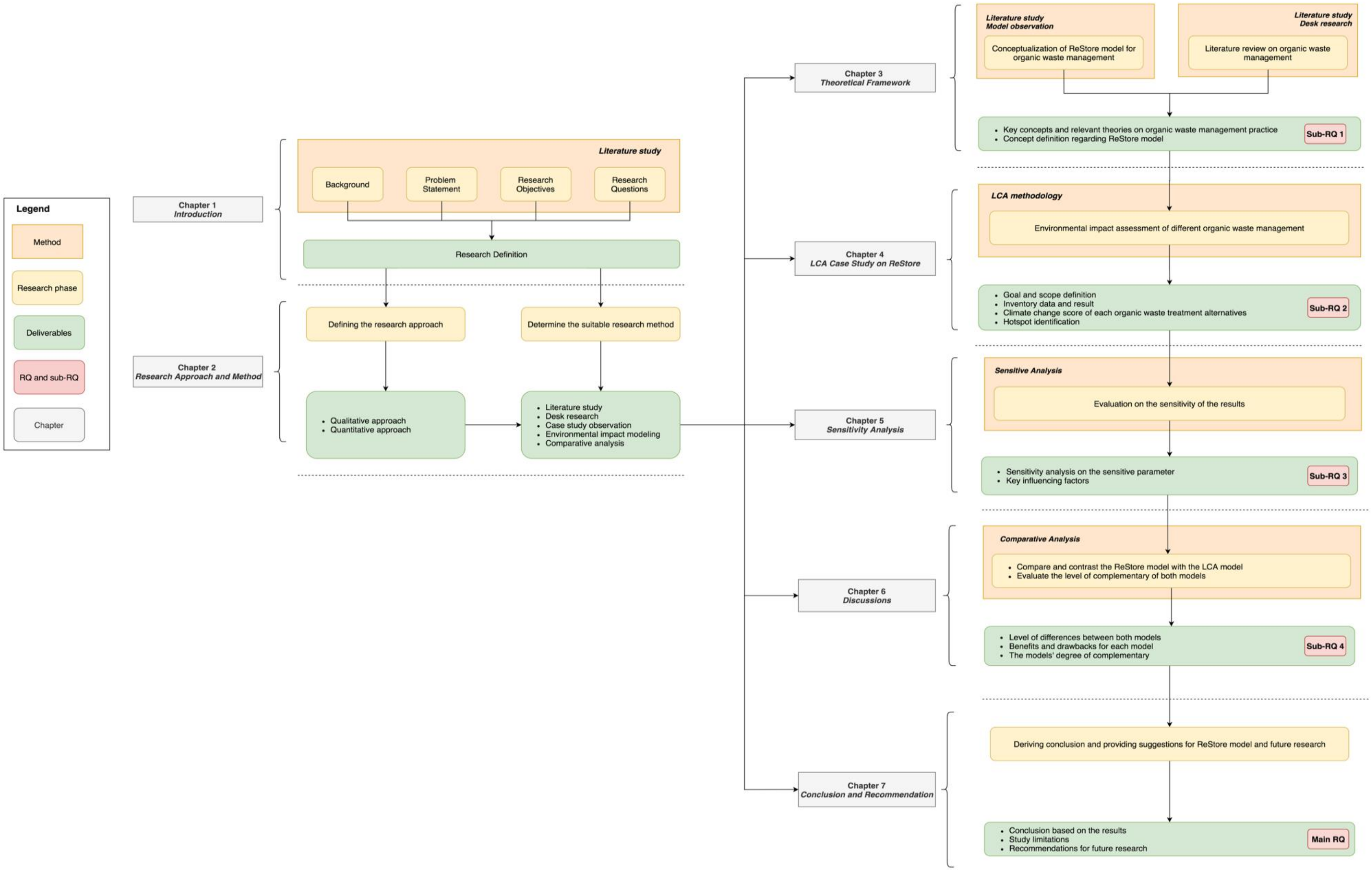

Figure 1.1 Research flow diagram

Chapter 2
Research Approach and Method

This chapter presents the approach and method used for this whole study. This chapter begins with a description of the types of research approaches used in this study. The next section identifies the research method which is detailed in the separate sub-chapter per each method. This includes the literature review, the case study, the framework of LCA along with its key principles, structure, and the benefit and the downside of LCA, and eventually the comparative analysis.

2.1 Research Approach

In order to answer the previously stated research question, this study applied mixed methods research where the elements of both qualitative and quantitative approaches were combined. Qualitative research focuses on answering the first and fourth sub-research questions while quantitative research is oriented to answer the second and third sub-questions. Qualitative research aims to gain an in-depth understanding of the fundamental principle of the LCA technique and procedure. Besides, this type of research digs deeper into the literature to discover existing key concepts, theories, and frameworks within the related field. This is also an exploratory research to uncover the state of the art of the ReStore model, including its system definition and its characteristics. Next to this, in quantitative research, the environmental performance of organic waste management is specified explicitly. This research is used to measure the climate change score for each alternative and to test and confirm assumptions.

2.2 Research Method

The research method explains which data are needed to reach the objective of each sub-research question and in what possible ways will that data be gathered. Every sub-research question is then linked to the relevant research method. Since this study aims to evaluate different functions from different perspectives, a set of method combinations were used, which are detailed in the following sub-section.

2.2.1 Literature Review

In order to satisfy the qualitative approach used in this study, a literature review was performed particularly during the early phase of the research. The literature review helps to create a conceptual model and construct a proper theoretical framework to gather supporting theories and determine the focus group to evaluate the research objective (Snyder, 2019). This study was started with the literature review in the field of organic waste and defining the key concept of the ReStore project as detailed in the previous chapter. Methods for collecting literature encompass the use of scientific databases such as Science Direct and Research Gate and academic search engines such as Google Scholar, Scopus, and university online catalogue. Publications through these platforms were retrieved with keywords of “Life Cycle Assessment”, “Organic Fraction of Municipal Solid Waste”, “Organic Waste Management”, “Waste-to-Energy treatment”, “Waste Incineration”, “Bio-digestion”, “Composting”, “Amsterdam”, and “the Netherlands”. This results in extensive literature research of scientific journals, review articles, relevant textbooks, academic and institution reports, master thesis, and Ph.D. dissertations.

2.2.2 Case Study on the ReStore Project

This study examines the sequence of processes within a bounded system where multiple sources and forms of data were included to execute an in-depth understanding. This is referred as a case study where specifically, attention is drawn to examine the carbon footprint of organic waste management by means of various treatment technologies based on the case study as defined in ReStore.

ReStore was a collaboration project initiated by Amsterdam University of Applied Science which aimed at developing a measurement method to assess the environmental impact of different organic waste management scenarios, on a small and large scale basis. It has been recognized that a lot of LCA studies about organic waste management were concentrated in either another part of Europe or part of other countries, yet, none can be found in the Netherlands. This is where the ReStore project attempted to direct their focus on. The project tried to take into account the dependencies between detailed waste properties, process characteristics, and consequential emissions.

The project came up with six different organic waste management scenarios, which includes centralised and decentralised composting, decentralised vermicomposting, centralised and decentralised bio-digestion, compared to waste-to-energy (WtE) as the baseline scenario. Each of the six scenarios covers sequential processes, starting from the collection, waste processing, transport, and application. Sub-indicators such as transport distances, fuel types, fuel and energy usage were used. The model provides options on their parameter where users can program the scenario based on their assumption. They can select how much separation rate they want to achieve, how often is the collection cycle, what type of vehicle they want to choose, what type of fuel they want to use, etc. Based on these input parameters and their pre-defined GHG emission factors, the environmental impact of each scenario was determined in terms of greenhouse gas emissions (kg CO_2-eq) by employing Excel-based modelling.

On top of evaluating the impact from the environmental perspective, ReStore also looked from the economic and social aspects. The economic aspect was measured using the Life Cycle Costing (LCC) method. This method assesses all costs associated with the whole performance of the organic waste management system by assigning prices for relevant flow and identifying additional cost elements (Swarr et al. 2011). The measurement took into account the required initial investment, the operational costs needed to keep the process running, and any benefits that may arise throughout the process. This information was applied to all developed scenarios and translated into a net financial investment in a monetary unit. The option with the least expensive total cost in aggregate becomes a key part to acquire a decision on how organic waste should be treated.

With regard to the social impact, three indicators were investigated which were social cohesion, participation between citizens in working together, and educational development. The social cohesion looked at the number of new connection initiated within the population and the value of new connections. The participation parameter focuses on the deployment of citizens who participated in the project. Lastly, education development deal with the knowledge, attitude, intention, and behaviour of residents in the concerned area towards the practice of organic waste separation and processing. As this LCA study only investigates the environmental performance of organic waste management, the economic and social aspect as addressed in ReStore are not part of this study's analysis.

2.2.3 LCA Framework and Definition

In another round, the quantitative approach was executed through the LCA procedure where the modelling process was conducted in CMLCA software version 6.1. The LCA model was built following the framework and characteristics of the ReStore model to define the required foreground process data. On the side, the supporting data for the background process was sourced from Ecoinvent database version 3.4 (Wernet et al. 2014). The environmental assessment was performed following the International Organization for Standardization (ISO) 14040 standardization and the CML2001 baseline method was adopted as the reference for the climate change impact category for this study (Guinée et al. 2002).

LCA is a technique for assessing the environmental aspects associated with a product system over its entire life cycle (Udo de Haes & Heijungs, 2009). While depicting the whole picture of the product's impacts, hotspots relating to where the largest emissions occur can also be determined. Once hotspots of environmental damage are detected, an action plan targeted for improvement can be proposed (Guinée & Heijungs, 2005). LCA is an iterative process that consists of four main stages named as goal and scope definition, inventory analysis, impact assessment, and interpretation (Guinée *et al.*2002) (Figure 2.1).

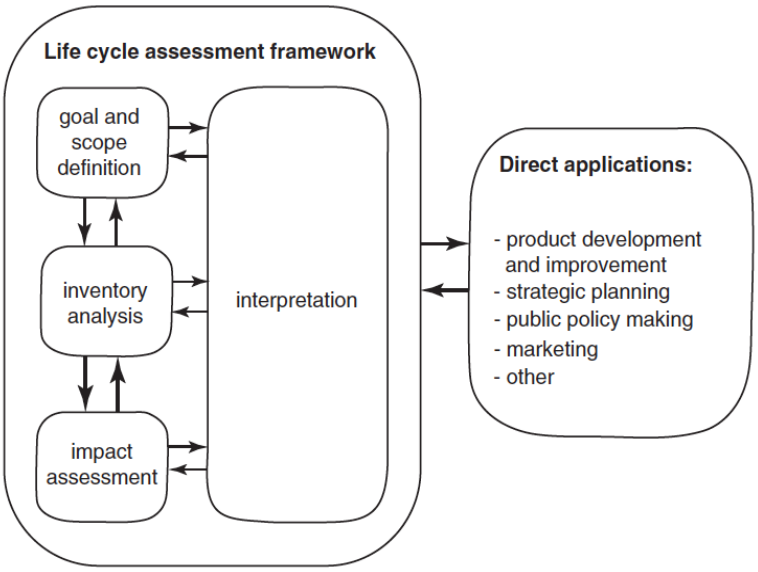

Figure 2.1 Phase of LCA (Udo De Haes & Heijungs, 2009)

2.2.3.1 Goal and Scope Definition

The goal and scope definition is the first phase of LCA which defines the purpose of the study. In the goal definition, questions with regard to reasons for carrying out the study, expected application of the results, and the intended audience are framed. While the scope definition includes main elements such as functional unit definition, level of detail required for the study such as temporal, geographical, and technological coverage, and elaboration on initial choices and product alternatives (Boersema & Reijnders, 2009)

2.2.3.2 Inventory Analysis

The goal and scope definition is then followed by inventory analysis where all data associated with the product system are gathered and compiled. This phase consists of four main steps. First is defining the system boundary where boundaries between product system and environment are differentiated. Next is to create flowcharts that represent the included unit processes and the pre-defined system boundary. Relevant data for these specified unit processes are then collected. Moreover, the approach on how to deal with multi-functional processes are also explained (Udo de Haes & Heijungs, 2009).

2.2.3.3 Impact Assessment

In the impact assessment phase, the potential environmental impact of the evaluated product system is quantified. The previous inventory analysis result is translated into the selected impact categories. This phase includes the selection and definition of impact categories along with the underlying characterisation model, classification, characterisation, normalisation, and aggregation (Udo de Haes & Heijungs, 2009).

2.2.3.4 Interpretation

The last phase of LCA is interpretation. During this phase, all results are explicated and discussed according to the goal and scope of the research. This is followed by examining significant issues, evaluating assumptions used throughout the study as well as the data quality and models used. Consistency check and completeness check are used as a starting point to evaluate whether all data, information, and assumptions are already complete and consistent with regard to the initially defined goal and scope. After that, a contribution analysis is performed to point out the hotspot where most emission occurs. In order to give information on the robustness of conclusions, which individual parameter is the most important, and how the system can be improved, sensitivity analysis is conducted afterwards (Guineé et al. 2002). In this study, the sensitivity analysis holds an important role to improve the interpretation of the results because it may help in finding the influencing factors to reason the models' difference. Finally, based on these discussions, conclusions are drawn and recommendations are provided.

2.2.3.5 Benefits and Limitations of LCA

In assessing the environmental impact of waste management options, LCA provides information on which waste management option is associated with the least different environmental risks in respective life cycle phases (Abeliotis, 2011). Thus, one can define that LCA has a high level of comprehensiveness with respect to environmental interventions, considered environmental issues, as well as process chains (Clift et al. 2000). This may assist the decision-makers to select the right objective and create better waste management policies. Another attribute of LCA is its ability to compare and contrast competing products, that it gives a framework to guarantee a fair comparison between alternatives that deliver the same function. This way, LCA can evaluate the environmental benefits that could potentially be generated through different processes, such as the case where energy from incineration can cover the energy production from the grid or the use of compost that can reduce the dependency on chemical fertilisers and its associated impacts, which then lead to resource savings (Costa et al. 2019). In another round, LCA is an inclusive tool that can easily be combined with other tools for investigating issues that cannot be sufficiently addressed in LCA (Ekvall et al. 2007).

On the other hand, LCA is a quite complex tool that requires detailed information. It takes quite a lot of time to have all the data and details complete, especially for larger project scope, which results in the impracticability of this tool. The fact that LCA involves a large range of data has become a major challenge. It is often difficult to get the complete inventory from the entirely geographical specific and up-to-date source (Haupt et al. 2018; Abeliotis, 2011). Therefore, it is rather impractical to use LCA as a tool for daily decision-making activities. Of all these restrictions, recommendations can be given in order to promote a more constructive use of LCA in the sector of waste management. One of them is by incorporating other complementary methods such as backcasting method, non-linear programming, and hybrid input-output analysis (Ekvall et al. 2007).

2.2.4 Comparative Analysis between the Organic Waste Treatment Models as Defined in ReStore and LCA

One of the methods used to approach the qualitative analysis is comparative analysis. The comparative analysis aims to perform a comparison on two or more comparable alternatives in order to reach result interpretation whilst also looking at causality between variables (Rihoux & Ragin, 2009). A comparative analysis was performed to show how two models are similar or different in any possible aspects. This is used to research the relationship between both models which plays a central role in defining concept formation by bringing into the similarities and contrasts among both models together. Therefore, this will become the basic scientific inquiry to determine the level of complementary between the ReStore model and the LCA model.

2.3 Chapter Summary and Conclusion

This chapter has detailed the approach and method used to outline this research. The qualitative approach was implemented in the form of a literature review, case study, and comparative analysis. On the side, the quantitative approach was accomplished by carrying out the LCA methodology. In a further round, this chapter also explained fundamental theories and principles of the LCA methodology to execute the environmental impact modelling on the case study addressed in this research.

The LCA methodology was carried out based on the ISO 14040 standardisation which composed of four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. First of all, the purpose and boundary of the study are specified. Here, the functional unit which determines the basis for comparison between the product system under-studied is also specified. In the second phase, the information concerning the data process in terms of economic and environmental flows for the specified unit process is retrieved. After compiling up the inventory data, the potential environmental damages are calculated following the chosen impact assessment method by translating the inventory data to standard units and aggregate them within the same impact category. At last, in the final phase of LCA, the results are discussed and commented according to its relevance to the predefined goal, the consistency and completeness of the study, and the conclusions, recommendations, and limitations. These phases of LCA do not stand alone but are all intertwined in a tangible lead. This makes up the iterative procedure of LCA instead of being a linear process in which changes take place straight from a certain starting point to a certain endpoint.

Chapter 3

Background Theory

The theoretical background underpinning this study is outlined in this chapter. The content of this chapter is divided into five sections. The first section provides elaboration on the ReStore model characteristics and system definitions. The second part is the literature review related to the characteristic of organic waste. The third section conveys the organic waste characteristic and it is followed with an explanation on the status quo of the organic waste management practice in the Netherlands. Lastly, the routes for organic waste disposal and treatment technologies along with the literature findings with regard to the application of LCA on organic waste management are described.

3.1 ReStore Project Characteristics

3.1.1 Environmental Model Definition

The environmental model created in ReStore is accessible to describe typical situations of the proposed organic waste diversion scenarios. The model was designed to adapt to specific parameters such as energy efficiency, conversion rate, inputs and outputs variables, and any other data features the user has on hand. The model was assembled through several steps. First, the model's purpose was determined which covers the definition of the so-called functional unit and the description on system boundaries. The functional unit was made to be the total amount of organic waste generated per year for the number of households in the neighbourhood of Amsterdam.

The simplified schematic representation of the described waste treatment system in ReStore is presented in Figure 3.1, while a more comprehensive illustration is explicated in section 4.2.2. Each step was described for each scenario made for organic waste diversion through composting, bio-digestion, vermicomposting, and incineration, as addressed in the previous section. The organic waste produced from households was collected and transported to the processing plant. During the process, organic waste was converted into recycled products. Products were then transported to end users and the modelling system ends with the products' application by end-users. The products released during processing were seen as a replacement for existing products with the similar feature on the market. However, the way in which the products were applied in terms of how efficient is the process until another cycle of waste is produced again was beyond the scope of the ReStore project. It was found complicated to assess the construction and demolition of processing installations, thus, this aspect was not included In estimating the ecological impact in the study. This information on the system definition and model characteristic is used as the breeding ground to define and construct the LCA model which will be referred on the next chapter.

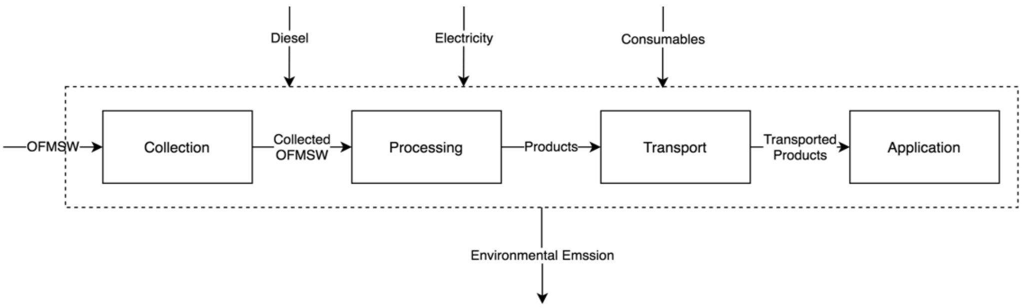

Figure 3.1 Basic layout of ReStore system boundary (adopted from Mulder et al. 2019)

3.1.2 Model Relevance

This project reported the background, choices, and substantiation of the measurement method to be developed. Next to this, the project described the choice of parameters to be measured as well as the design on the method used on the value systems of the urban organic residual flows. As such, the sustainability intervention of organic waste processing systems in an urban context can be approximated. In this regard, practitioners who need a comprehensible and flexible tool for daily decisions making in waste management activity may be the beneficiaries of this model. As decision-makers receive a large amount of information with limited information-processing capacity, the environmental system analysis must be intuitively clear to communicate and easy to understand for daily necessities, in which the model developed by ReStore would be a great fit. However, for stakeholders and parties who need a detailed and more accurate approximation from a system perspective might find that this model is less precise and less suitable to be used. Moreover, it is less practical to use the model for providing insight for system innovation and value chain improvements. It is also inadequate to employ the model within the public policy development process.

3.2 Organic Waste Characteristics

Organic waste or what is commonly known as bio-waste is a type of waste that has the potential to be recycled back into the natural system by the action of microorganisms (Taffese & Magette, 2008). A more specific definition of organic waste varies per country. The scope of organic waste in the United States of America includes food waste, yard and park debris, paper waste, wood, and pet waste (CEC, 2017; Kong 2012). In the context of the European Union, organic waste is classified into any biodegradable garden, kitchen, and food waste (European Commission, 2016). Unlike the original definition of waste which referred to any unwanted substance and or material that no longer has any particular function and purpose, organic waste is put on the contrary. The term biodegradable that lies within organic waste brings additional intrinsic value because this type of waste can be put into good use. Organic waste can be used as a resource that can be processed and utilized further instead of merely being discarded. Some of the possibilities to embrace are the use of organic waste as fertilisers, soil amendment, an energy source in the form of heat, electricity, and liquid, materials replacement such as sand and cement, and some chemicals production for alcohol, volatile organic acids, and ammonium products (Westerman & Bicudo, 2005).

With this special characteristic, it is important to select an appropriate and effective treatment system and technology so that the value of organic waste can be preserved as much as possible. One of the advantages that may arise is the environmental benefits. The nature of organic waste of being capable to be decomposed by living organisms is in great evidence to avoid pollution. This can contribute to land preservation, soil vitality, reforestation, and wetlands restoration (PWGSC, 2013). Moreover, further utilization of organic waste into fertiliser, energy, and chemicals can displace these products in the market, thus, leads to energy saving and avoids the negative impact exerted on the environment from the production processes of these products. Following this, the expense needed to produce this energy, fossil fuels, fertilisers, and chemicals can be reduced, where a major cost-saving can be achieved. Furthermore, the reduction in GHG emission allows companies to sell it as an offset through the cap and trade system, thereby generating additional revenue (Polprasert & Koottatep, 2017). Within the social aspect, proper organic waste management provides human health protection and habitat revitalization (PWGSC, 2013). In addition, diverting organic waste properly allows for job creation and offers opportunities for training, teaching, and exhibition to residents which can increase social engagement and participation (ISWA, 2013).

In the end, it is of great importance to realise that a proper management system and technology selection can enhance the potential of organic waste. A mismatch in handling organic waste will not only destroy its valuable component but also lead to adverse environmental and health problems such as increasing odour pollution and hosting insects and pets due to the natural decomposition process of organic waste (Kiyasudeen et al. 2016). To this, the concept of LCA as researched in this study, serves as a useful tool to assess the potential environmental impacts related to products, processes, or services delivered by the organic waste management system, where the proposal of environmentally-friendly solutions can be given.

3.3 Organic Waste Management in the Netherlands

With the rapid growth of the human population and activities, the world is now faced with an innumerable amount of waste. Waste management is needed to treat this ever-increasing waste based on the order of preference (Wilson et al. 2001). It has been explained in the previous section about the need for a suitable treatment for organic waste. This section will elucidate how should this be carried out according to the principle of waste management.

In order to keep the negative effect that is being exposed from waste to the environment and human health to be as minimum as possible, the treatment procedure shall be guided through a certain policy. Like most other European countries, the Dutch government has adopted the so-called *Lansink's ladder* for its waste policy, which is later renowned as the waste hierarchy from European Union Waste Framework Directive. The representation of waste hierarchy is visualized in Figure 3.2 and applies as a priority order in waste prevention and management. It is clearly shown on the diagram that prevention is the best option, ranging down to recycling, and finally, disposal to be the least preferable.

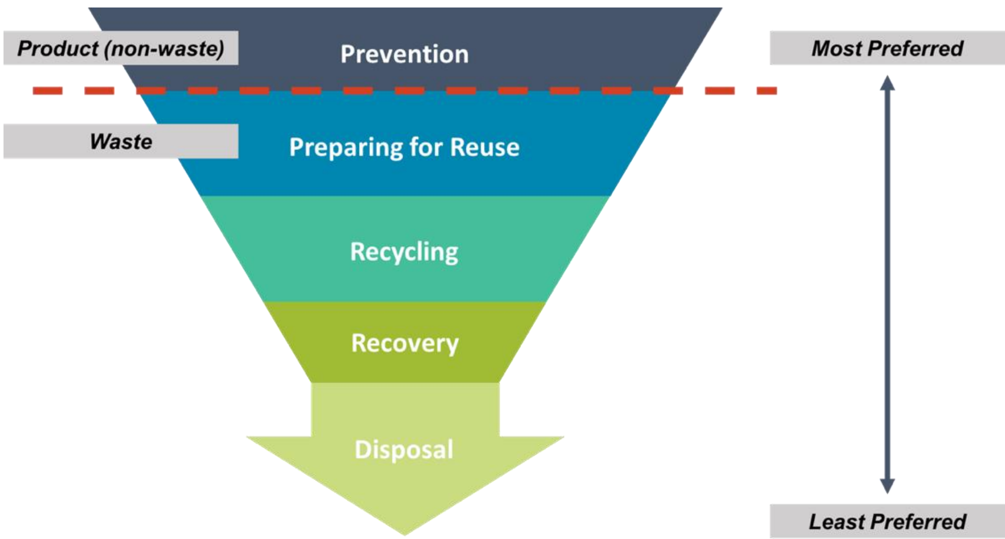

Figure 3.2 Waste Hierarchy (own illustration) according to EU Framework Directive (European Commission, 2010)

Waste prevention is encapsulated on the first level of the diagram, meaning that this is the most-recommended option where any activity related to waste production shall be avoided to the utmost. However, if this is no longer possible, waste is subjected to the next recommended step which is waste reduction through reuse. In the context of organic waste, this would not be possible because there is no part of the waste that can be cleaned, repaired, and fed back to the production process (Elwan et al. 2014). The next level of waste hierarchy deals with the recycling process in which composting is a part of it. In this stage, waste is recycled into new high-quality substances or products, such as producing compost out of the composting process to improve soil fertility. The fourth level of waste hierarchy belongs to any processes that enable the recovery of energy such as incineration, anaerobic digestion, gasification, and pyrolysis. The disposal stage is at the bottom of the waste management hierarchy, indicating that this is definitely the least acceptable decision. This should become the last effort if there is no higher treatment that is deemed suitable. This stage includes landfilling and thermal treatment without energy recovery.

The Netherlands has made an early start in waste recycling. Throughout the years, an average of 50% of the MSW in the Dutch municipalities was recycled, making the Netherlands is among the frontrunners and pioneer in the waste recycling sector (Dijkgraaf & Gradus, 2017). Another 45% of the waste goes to incineration, which is mostly equipped with an energy recovery facility. Landfill is hardly implemented in the Netherlands due to the enforcement of landfill tax and landfill ban (OECD, 2015). As organic waste holds the largest share in MSW composition, a separate collection regulation was prescribed. Nonetheless, the practice is still far-reaching as organic waste is often mingled with the residual waste due to practical reasons. This results in nearly half of the organic waste being incinerated as yet (Milios, 2013).

3.4 Organic Waste Treatment Methods

In the previous section, it has been explained about the concept and general principle of waste management. This section will add to the knowledge of the actualisation of waste management by discussing some renowned methods for waste diversion that has been commonly implemented in the Netherlands. Some of them are WtE, bio-digestion, and composting, where the detail of each management method is elaborated further in the following sub-section.

3.4.1 Incineration

Incineration is one of the most widely-executed waste disposal methods where a bulk of MSW and is burnt at high temperatures to produce heat energy. Compared to other western countries, a relatively large percentage of the waste is being incinerated in the Netherlands. The combustible fraction of waste is burnt when it is reacted with oxygen through an oxidation reaction after reaching the ignition temperature which ranges from 850°C to 1450°C (Mutz et al. 2017). In the case of autothermic combustion where no external fuels or energy is needed, a minimum calorific value of 4 MJ/kg of waste is needed to achieve a thermal chain reaction (Malinauskaite et al. 2017). However, as organic waste usually has a much lower calorific value and higher moisture content, an additional source of energy needs to be incorporated to aid the combustion process. The incineration process can reduce the waste volume up to 30% from its original volume which can save some space and avoid the unnecessary need for landfills (Mutz et al. 2017). Another benefit is that this process enables energy, materials, and metal recovery that can be fed to further good use.

The whole incineration process produces the main product in the form of heat energy and by-product in the form of flue gas and ash. The heat energy generated from the combustor goes through the recovery boiler to produce high-pressure steam which can either be directly used as a heat carrier or to power up steam turbines (IEA, 2013). These turbines are connected to the generator to convert the mechanical energy into electrical energy which can later be used to generate electricity or provide district heating or cooling to the neighbourhood. The flue gas contains nitrogen oxide, carbon dioxide, sulphur dioxide, as well as traces of particulate matter such as dust and soot. Together with the flue gas, fly ash is driven out of the boilers. Thus, the flue gas needs to be securely treated by sorption or filtration before being released into the atmosphere in order to cope with the standard emission requirement (Cyranka & Jurczyk, 2016). At last, the overall incineration process leaves the incombustible fraction in the form of fine particulates that falls to the bottom of the combustion chamber which referred to bottom ash. A mix of inert materials constitutes the composition of bottom ash, which includes sand, stone, glass, sand, metals, and porcelain (ISWA, 2006). Several studies have researched the potential of bottom ash to be used as road construction and foundation material due to the similarity in their chemical properties (Kamal et al. 2017; Nadig et al. 2015; Priyadharshini et al. 2011).

3.4.2 Bio-digestion

Besides incineration, there are other waste treatment options that can also recover energy. One of them is anaerobic digestion or similarly known as bio-digestion. Bio-digestion is a biological process where organic matter is decomposed by microbial consortium without the presence of oxygen under a controlled condition (Kiyasudeen et al. 2016; Khalid et al. 2011). The waste is digested in a sealed vessel in an oxygen-free environment during which methane-rich biogas is produced as the main product and digestate is obtained as the by-product (Gao et al. 2017). Bio-digestion takes place through the following stepwise process: 1) waste pre-treatment, 2) liquefaction or polymer breakdown, 3) acid formation which or acetogenesis, and 4) methane formation or methanogenesis (Saadabadi et al. 2019; Polprasert & Koottatep, 2017) as illustrated in Figure 3.3.

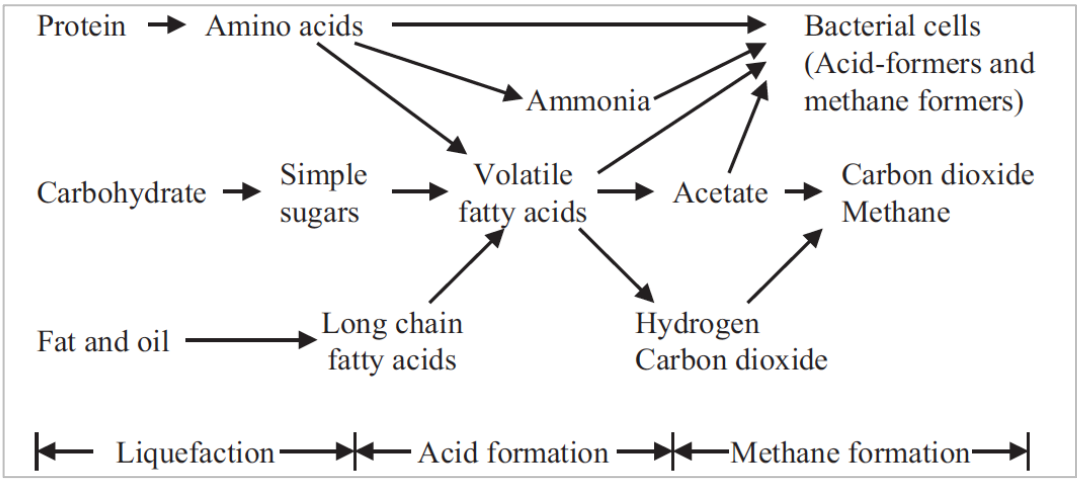

Figure 3.3 Bio-digestion degradation pathways (Kiyasudeen et al. 2016)

In the first round, the complex structure of organic matter is disintegrated in the pre-treatment stage to increase the waste methanogenic potential, thus, accelerate the digestion process. Several well-known examples of pre-treatment methods are mechanical process, chemical destruction, and thermal pre-treatment (Kiyasudeen et al. 2016). In the second stage, the complex polymers in organic waste are broken down with the help of extracellular enzymes secreted by hydrolytic bacteria. Through this hydrolysis process, the complex compounds are turned into simple monomers, where in this case protein is converted into amino acids, carbohydrate is converted into simple sugars, and fat is converted into long-chain fatty acids. Next, the acetogenic bacteria take up these soluble compounds and transform them into acetic acid, hydrogen, and carbon dioxide in the acetogenesis phase (Saadabadi et al. 2019; Polprasert & Koottatep, 2017). These compounds will become the substrate for the last step, which is methanogenesis driven by methanogenic bacteria. The acetic acid will undergo decarboxylation reaction and the hydrogen and carbon dioxide will enter the reductive methane formation (Saadabadi et al. 2019; Polprasert & Koottatep, 2017). Both reactions induce the production of methane and carbon dioxide and other end products, where methane and carbon dioxide will together form as biogas.

Once produced, biogas commonly has the composition of (by volume) 48-65% methane, 36-41% carbon dioxide, up to 17% nitrogen, less than 1% of oxygen, and traces of other gases (Rasi et al. 2007; Polprasert, 2007). As the methane content in biogas is relatively high, the end-use of biogas is vastly versatile. Biogas can be used as a source of renewable energy to produce heat through a combustion process in gas boilers or to generate electricity by the use of gas engines or turbines. Furthermore, biogas is suitable for small-scale household purposes such as cooking, running a refrigerator, and providing light, especially in rural areas in Asian countries. In most European countries, the utilization of biogas as a renewable source holds a high share, for instance in Germany, 74% of the total green electricity is sourced from biogas, while biogas has the role to provide 68% of the Finnish energy system (Purkus et al. 2018; Timonen et al. 2019). Specifically, in the Netherlands, there are over 250 functioning digesters with a production capacity of 2,408 TJ per year (WBA, 2017). When considering the spatial context of Amsterdam with only organic waste as the feedstock, the yield is estimated to be 40 TJ per year (Goossensen, 2017).

The other potential application of biogas is to use it as fuel to operate water irrigation pumps (Ashrf, 2008). Above that, biogas can be upgraded to biomethane to further be utilized as a transport fuel. Within the process, the CO_2 and other impurities are removed from biogas and the methane content is enhanced to achieve a vehicle fuel quality of biomethane. This can be done through several techniques such as chemical absorption, water scrubbing, membrane separation, pressure-swing adsorption, and even a greener method by integrating the activity of photosynthetic organisms such as microalgae (Jönsson & Persson, 2003; Ramaraj et al. 2016).

Like any other treatment alternatives, bio-digestion possesses its own advantages and disadvantages. Bio-digestion is seen as a mature, more sustainable application to harness the energy content of organic, therefore, minimise the GHG emissions (Rasi et al. 2007). Furthermore, bio-digestion allows nutrient reclamation where valuable nutrients contained in the digester slurry can be recycled back. In this context, bio-digestion also has the role of waste stabilization for producing a stabilised sludge which can be used as fertiliser or soil conditioner (Environment Agency, 2009). However, the high capital and operational cost of bio-digestion, complex operation and maintenance, and seasonal variations in gas production impede its implementation (WBA, 2017).

3.4.3 Composting

Composting is a decomposition of organic waste promoted by microorganisms through a controlled aerobic process where biowaste is oxidised to carbon dioxide and water vapour (Smith et al. 2001). A stabilised, hummus-like product with high organic matter content is then obtained (Kadir et al. 2016). Throughout the process, composting can provoke fairly high metabolic activities of microorganisms up to 10^{12} cells/gram (Polprasert & Koottatep, 2017). In the Netherlands, composting has become a prevailing technique to recycle organic waste where the country owns 14 installations for composting organic waste (Sperl, 2016).

The composting process consists of three main phases, each occurs with the role of a different organism, as represented in Figure 3.4. First, the decomposition process is initiated in the mesophilic phase with the temperature of 25-40^{o}C. The degradation is getting more intense as microbial activity increases during the next phase, which is the thermophilic stage. This induces a rapid temperature rise to 35-65^{o}C, reaching an active phase. In this stage, the disruption of degradable compounds is at its most efficient and fastest pace and this active phase may remain for several days, depends on the pile size, feedstock properties, and external condition (Lin et al. 2019). After reaches the peak temperature, the microbial activity decreases, followed by the reduction in temperature. This allows the mesophilic organism to recolonize the pile and let the pile cool down on the ambient temperature of 37^{o}C in the second mesophilic stage. Any remaining materials that have not been transformed during the thermophilic phase will still continue to degrade on this stage but at a much slower rate. As the quantity and activity of microorganisms subside, the decomposition is constantly slowed down and finally, a mature humic matter is formed as compost (Chen et al. 2011; Trautmann & Olynciw, 2006).

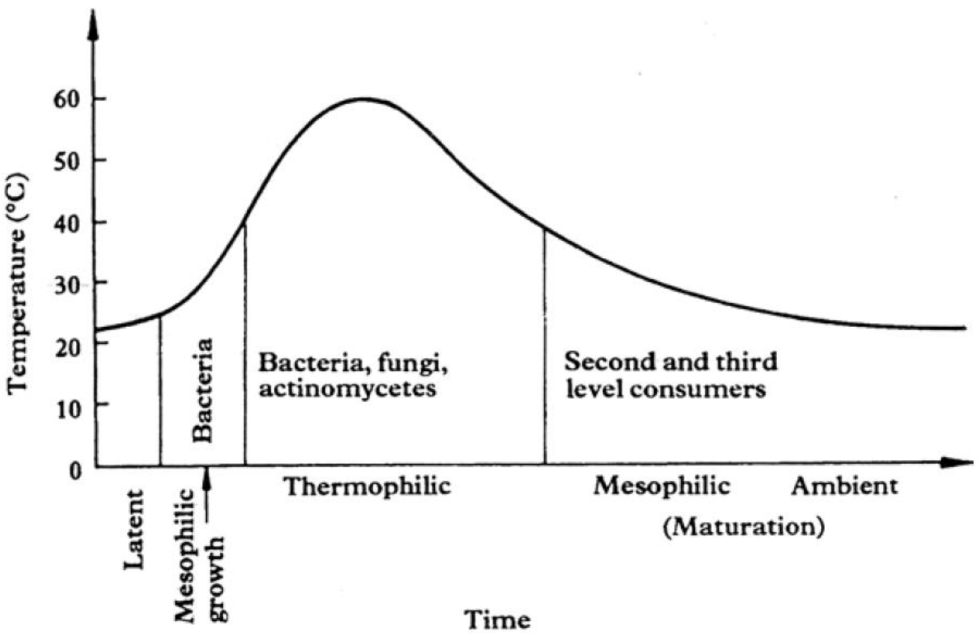

Figure 3.4 Microbial growth and temperature change in composting (Chen et al. 2011)

The produced compost serves various useful purposes where it is compatible as a soil improver in the agricultural and growing medium in horticulture. Furthermore, the nutrient content in compost can partially replace the nutrient content of fertilisers, which contribute to the reduction of artificial fertilisers dependency (Ministry of Foreign Affairs, 2019). The transformation of organic waste into compost brings along several benefits. First, it suits both heterogeneous and homogenous organic waste mixture from a diverse economy sector, thus promotes waste stabilization (Trautmann & Olynciw, 2006). Second, the composting process allows for phytotoxicity reduction of fresh non-stabilised organic matter, through the sufficient heat produced during the composting process. The temperature of waste heat can reach up to 60°C and is effective to inhibit the activity of pathogens, microbial agents, bacteria, and fungi, thus, their activity remains under control and prevent potential health risk (Lin et al. 2019). Moreover, composting is economically prospective because it only needs low-cost technology and equipment. Aside from these benefits, composting is a long-duration process that requires regular turning of materials which may trigger some nutrient loss (Kiyasudeen et al. 2016). Another drawback is related to the socio-economic issue where the practice of composting may cause odour pollution.

3.5 Organic Waste Management within LCA

In pursuit of more sustainable opportunities for municipal organic waste treatment, scientifically robust evidence on the environmental performance for each technical differentiation of organic waste management should be provided. Integrated assessment of all environmental impacts from beginning to end is the basis for achieving more sustainable products and services (Guinée & Heijungs, 2005). Based on some previous research (Buratti et al. 2015; Bernstad & Jansen, 2012; Jeswani *et al*., 2010), Life Cycle Assessment (LCA) is apt to provide a complete overview in assessing the potential environmental impacts as well as the environmental benefits related to different organic waste management options.

Within LCA, there is a wide range of studies that investigate different waste treatment scenarios with different waste characteristics from an environmental perspective. For instance, Lou & Nair (2009) investigated the environmental impact of composting compared to landfill as organic waste biotransformation methods. The result showed that the composting process produced up to 78% less GHG emission compared to conventional landfills. A study conducted by Eriksson et al. (2005) focused on OFMSW management option in Sweden where material recycling led to lower GHG emission value of 710 kg CO_2-eq/ton over 790 kg CO_2eq/ton for anaerobic digestion and 860 kg CO_2eq/ton for incineration with heat recovery and power generation. An experiment carried out by Koneczny & Pennington (2007) indicated that incineration with increased in recycling performed well over the composting method in the context of climate change but demonstrated poor performance when bio-digestion is applied. Most recently, Siew et al. (2019) researched the sustainability potential of domestic organic waste management in the United Kingdom with different technical configurations. Based on the study, adopting a fully decentralised gasification strategy demonstrated the highest GHG emission savings of 67%. This was then followed by the partial decentralised waste management strategy through anaerobic digestion and biogas conversion to electricity through CHP, and the least to be the same option but with biogas valorisation to transport fuel

The latest study conducted by Lin *et al* (2019) focused on energy and nutrients production from organic waste through anaerobic digestion and composting. The study showed that anaerobic digestion was more preferable from the economic and environmental perspective since it produces outputs which can be valorised into high-value end products such as fertilizer from digestate and energy source from biogas. Meanwhile, a more complete overview was presented by Mondello *et al* (2017) by performing a comparative LCA at five different organic waste disposal scenarios. The study covered the whole phase of activities involved in the management of food waste. Based on these categories, the author offered different potential reduction strategies based on the hotspot of where most emission occurs. Another similar study was executed by Brogaard (2013) where different waste treatment namely windrow composting, anaerobic digestion, landfill, and incineration were analyzed. The research covered material and energy production, construction of capital goods, waste management treatment, and waste disposal phase. These processes were assigned to certain impact categories before finally hotspot can be determined. Out of the context of Europe, a study performed by Nabavi-Pelesaraei et al. (2017) undertook an LCA study for organic waste disposal system in Iran. The study showed that reduced landfilling in favour of incineration led to lower GHG emission by 85%. The study further conducted hotspot analysis where later it was known that most of the impact was associated with transportation and incineration process.

3.6 Chapter Summary and Conclusion

This chapter has the intention to describe the theoretical framework of the research through which the main topics were addressed by means of a literature review. As the main take away, the literature review informed that technologies have revolved around in the field of organic waste management as it is getting more advanced and structured. Still, sustainability is of a great importance factor to be involved since it contributes to value-added, foster performance improvement, and increase the level of competitiveness of waste management sectors. This is why numerous LCA studies of organic have been conducted to research the sustainability potential of waste management industries.

Furthermore, this chapter explained the framework and characteristics of the ReStore environmental model. Thereby, the information from this chapter along with the case study description provided an answer to the first sub-research question of "*What are the characteristics of the ReStore model in evaluating the municipal organic waste management in the Amsterdam neighbourhood?*" ReStore is a simulation model that quantifies the organic waste management system in the Amsterdam neighbourhood through the environmental, economic, and social component of the collection, processing, and valorisation of organic waste. The environmental aspect looked at the pressure released to the environment in terms of GHG emissions. The economical section focused on the monetary value needed for investment and operational cost. Lastly, the social dimension investigated the social components of circular waste management which examined decisive partnerships, social cohesion, local participation and initiatives, and knowledge development.

The included activities of the whole organic waste management system assessed in ReStore started from the collection of organic waste which was then followed by organic waste processing to the treatment plant. The produced goods were then transported and used by end-users. This system boundary set by ReStore is the breeding ground to assemble the new LCA model. The environmental impact modelling and assessment is detailed on the next chapter

Due to its flexibility along with its comprehensive feature, the model is fairly easy to communicate. It will provide companies or municipalities with a quick insight into the sustainability performance of certain treatment options that will aid and accelerate the decision-making process. However, the model is less suitable for stakeholders who want a more critical screening of environmental footprint and for organisations who look for value chain improvement. Moreover, it would also be too shallow to use the model within the public policy development process.

Chapter 4

LCA Case Study of ReStore

This chapter performs the evaluation of different organic waste management alternatives through an ecological perspective. The model structure of ReStore is used as the basis to construct the LCA model through the LCA methodology, where both models are then compared accordingly. This chapter is closed with a conclusion intended to answer the second sub-research question which is: *Taking the model developed by ReStore as a starting point, what is the carbon footprint of bio-digestion, composting, and WtE within the LCA perspective?*

4.1 Goal and Scope Definition

4.1.1 Goal

The goal of this study is to evaluate the environmental impacts associated with bio-digestion and composting as organic waste treatment alternatives in the Amsterdam neighbourhood towards the existing scheme, which is WtE. The results from the LCA study are then compared with the outcome from the ReStore model to see how both models differ, thereby offering suggestions in the contribution of one model to another. This study results in a quantification of the existing alternatives for organic waste treatment in the Amsterdam neighbourhood, where the carbon footprint of each organic waste management alternative can then be determined. The intended audiences for this study are the municipality of Amsterdam, environmental parties having the authorities for decision making, and waste management companies.

4.1.2 Scope

The scope of the study is sub-divided into three coverage, namely geographical, temporal, and technological scope. The geographical scope covers the geographical area of where the data is sourced, the temporal scope defines the data age and the period of the data collection, and the technological scope includes relevant technology that is being studied (EeBGuide, 2012).

Geographical Scope

This study focuses on analysing the environmental impacts of different ways of treating organic municipal solid waste in the Amsterdam neighbourhood. Foreground processes, where unit processes were modelled manually are located within the geographical area of the Netherlands. In the case of data lacking, the geographical scope is extended to include the scope of the scientific literature and the databases used. The foreground processes are often used in conjunction with background processes, which are processes modelled using the data available from the life cycle inventory databases. Background processes such as the production of electricity, heat, and chemicals may be sourced from all over the world but the area within the European Union is prioritized.

Temporal Scope

To ensure that the LCA results represent the most-recent situation, data from the year 2009 to 2019 is preferred, acknowledging that the more recent the data is, the better it is to be used. The period of data collection started from January to March 2020.

Technological Scope

The technological scope covers relevant technologies that are used in practice for each alternative. The facility and equipment needed for organic waste treatment are thus taken into account in this LCA study in the form of their energy use.

4.1.3 Function, Functional Unit, Alternatives, Reference Flow

The function of the waste management as analysed in this study is to manage organic municipal waste in the Amsterdam neighbourhood. The system will investigate the process that is not only deliver a waste treatment function, but also takes into account the possible co-products. More explanation with regard to this detail is given in section 4.2.4. The functional unit is managing organic municipal waste generated in the Amsterdam neighbourhood within a year. The functional unit is managing organic municipal waste generated in the Amsterdam neighbourhood within a year. This amounts to 247 tons per annum, assuming that 80 kg/year organic waste is generated per capita with a total population of 3,085 people in the designated area. The alternatives regarding this study are Waste-to-Energy, centralised bio-digestion, and centralised composting. The functional unit together with the alternatives will make up the reference flows, which are:

- Managing municipal organic waste in the Amsterdam neighbourhood for a year through Waste-to-Energy (WtE)
- Managing municipal organic waste in the Amsterdam neighbourhood for a year through centralised bio-digestion
- Managing municipal organic waste in the Amsterdam neighbourhood for a year through centralised composting

4.2 Inventory Analysis

4.2.1 System Boundaries

This LCA study analyses different management options for organic municipal waste. The system boundary and assumptions as mentioned in the ReStore environmental model definition in section 3.1.2 are used as the reference to arrange the LCA model. All direct activities related to the organic waste management process starting from the waste collection up to its final treatment are taken into account. With this being said, the impact of organic waste generation is out of the scope of this study. In all alternatives, only the management of organic fraction of municipal solid waste is considered, thus, the rest categories of municipal solid waste are source-separated and recycled outside the studied system.

The construction of the waste treatment plant and capital goods such as incineration facility, digester, and composter is a cut-off in the environmental assessment considering the small emission they exert to the environment with regard to the lifetime and number of usage (Otoma et al. 1997; Ecoinvent, 2019). The same holds true for utilisation of products obtained from the treatment process, such as the use of HN compost on the land, the use of heat and electricity both from CHP and incineration facility, the use of green gas from biogas production as well as the use of treated bottom ash from the incineration process. This study also does not take into account human labour with the assumption that most of the organic waste management options are already mechanized and thus, the amount of energy from human labour is considered to be relatively low.

Of these explanations, some flowcharts have been made which are presented in the next section. Based on the system boundary of ReStore as depicted in Figure 4.1 and according to the system description of ReStore in the case study definition, ReStore brought five options of organic waste management together, which are centralised composting, centralised bio-digestion, decentralised composting, decentralised bio-digestion, and decentralised vermicomposting next to the baseline scheme, which is WtE. However, due to time constraints, this study will only take into account all centralised options and leave out the decentralised options.

For the sake of consistency, this study uses the ReStore model from the version of 6 March 2020 as the basis throughout this entire LCA study. Changes made after this version were not considered in this study. This study focuses on the comparative analysis between the LCA model and the ReStore with respect to the previously-addressed functional unit. As such, when discussing the ReStore model, this study solely uses the information provided by ReStore and not executing any validation in terms of their process data and data source.

4.2.2 Flowchart

Along with the goal of this study which is to distinguish between two methodologies on observing the carbon footprint of organic waste management options on a given functional unit as stated in Section 4.1.3, each model needs to have the same system boundary so that the comparison can be made on the same level. With these being said, the initial system boundary of ReStore is being modified to be able to reflect the system boundary defined in this study. The original flow diagram of ReStore will become the base to model the adjustment as illustrated in Figure 4.1.

The adjusted system boundary is highlighted in a yellow box where it has been adapted based on the following explanation. As mentioned earlier in Section 4.2.1, ReStore takes into account various organic waste management scenarios, being scaled from centralised to decentralised options. As this study will only look at the centralised options, the boundary is drawn to only incorporate these scenarios. Therefore, in the yellow box of Figure 4.1, all decentralised options are omitted. Furthermore, in the new system definition, the application phase is left out from the system boundary. As seen on the chart, products from the waste treatment process replace the existing products on the market where the effect of this replacement is included in the model, for example by finding the replacement of compost to fertiliser. However, the avoided production of these materials is not applied on the LCA model as the study will go through system expansion to tackle the multifunctional issue. More elaboration on the system expansion and multifunctionality is detailed in section 4.2.4.

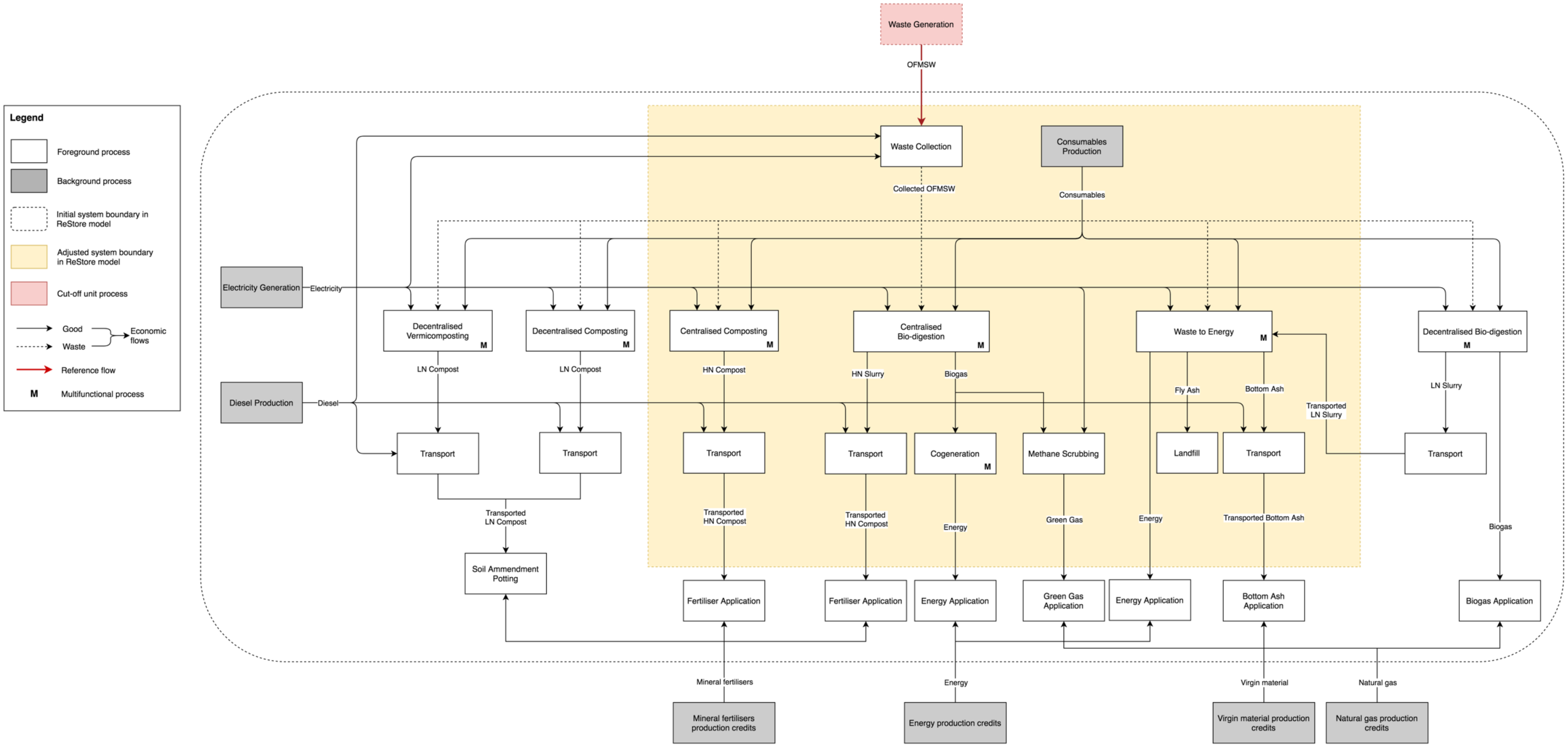

Figure 4.1 Initial and adjusted system boundary of organic waste management in the ReStore model

Following the previous explanation, the adjusted system boundary of ReStore is then implemented in the LCA model. The schematic representation of the system boundary described in the LCA model is shown in Figure 4.2, Figure 4.3. and Figure 4.4, each explaining certain types of organic waste management in a more detailed way.

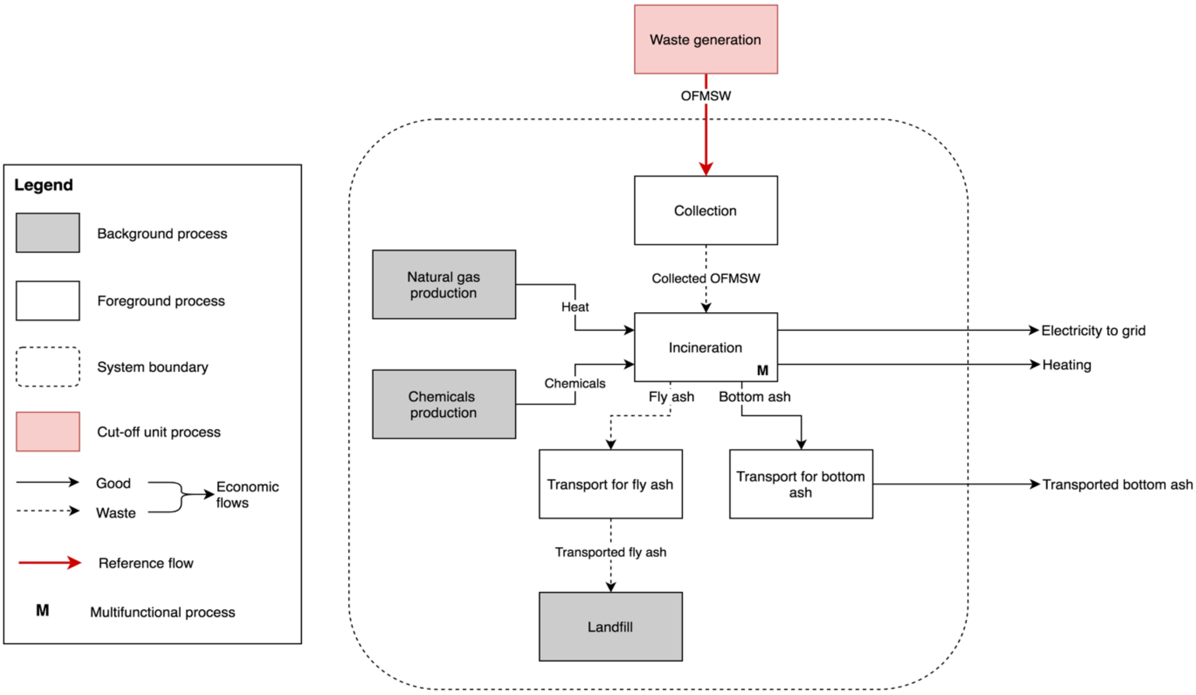

Figure 4.2 Flowchart of the LCA model of OFMSW management in the Amsterdam neighbourhood by means of WtE

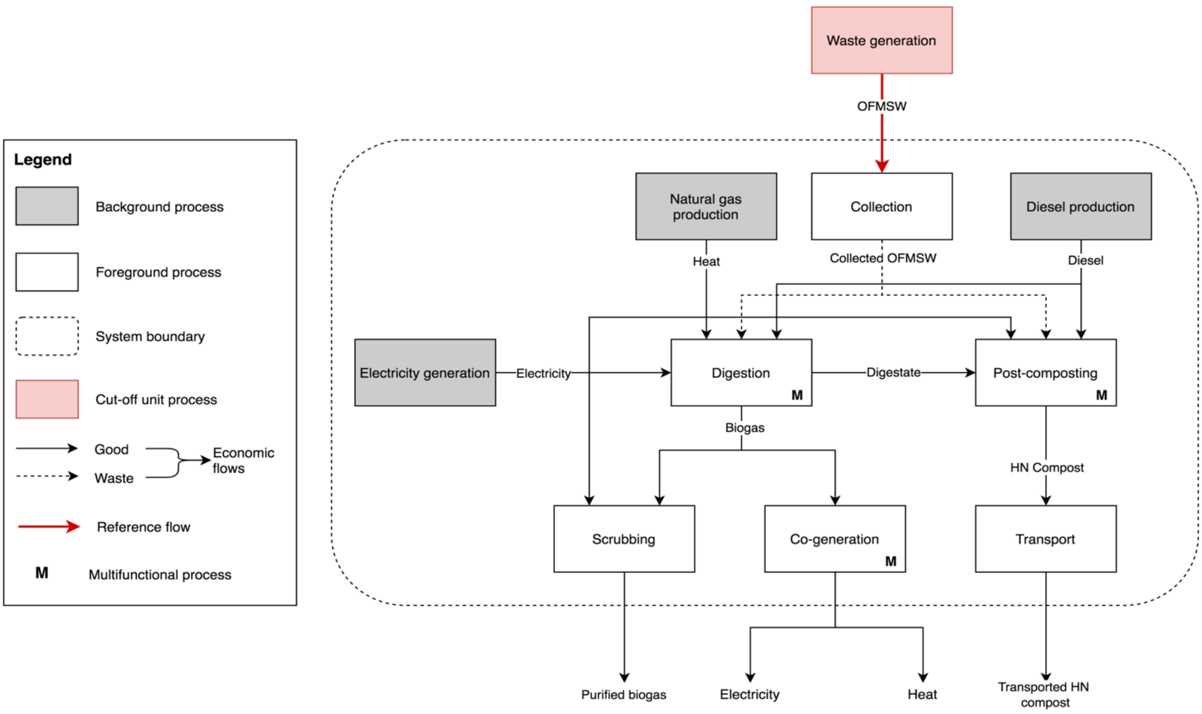

Figure 4.3 Flowchart of the LCA model of OFMSW management in the Amsterdam neighbourhood by means of bio-digestion

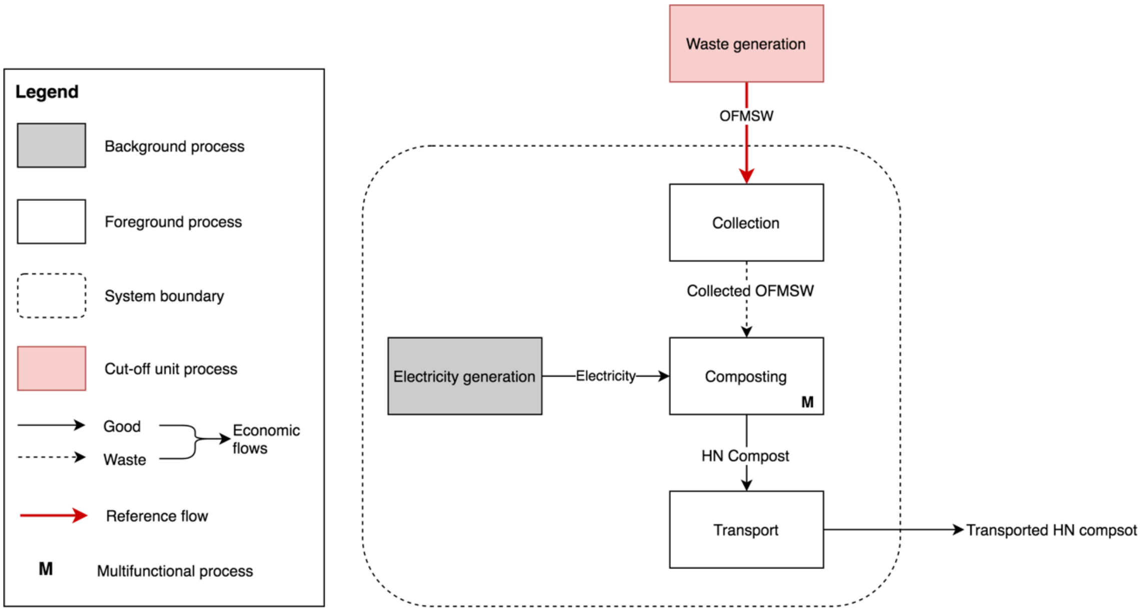

Figure 4.4 Flowchart of the LCA model of OFMSW management in the Amsterdam neighbourhood by means of composting

4.2.3 Data Collection

This LCA study was carried out based on ISO 14040 guidelines using the CMLCA version 6.1 software (Heijungs, 2018). The data gathering method included desk research along with regular contact with the commissioner, literature study, and discussion with experts. The quantification of GHG emissions was made out of two aspects. The first one was the evaluation of the climate change score based on the process chain and the process data as defined in the adjusted ReStore model. The second one was the calculation of the climate change score based on the process chain and the process data as described in ReStore by means of LCA methodology and using CMLCA. In this case, the process data from ReStore were used as foreground process and implemented as unit processes in CMLCA. Meanwhile, data for upchain processes and emissions such as energy and resource production were sourced from the background processes of Ecoinvent version 3.4. When data was lacking or incomplete, secondary data was gathered from relevant literature through academic platforms and national databases. Following this explanation, a complete overview of the data inventory is recorded in Appendix A.

4.2.3.1 Assumptions

There are several assumptions made in this study. Firstly, with regard to data entry in CMLCA, it is assumed that the best available option in Ecoinvent v3.4 has been selected for the economic flows although it is acknowledged that not all data are presented within the Netherlands. Furthermore, assumptions was made on the transportation mode for collection service where lorry with capacity of 16-32 ton was chosen because this type of transport is quite common for the purpose of large-scale transfers of waste. The EURO 6 emission standard was chosen as this is the current implemented regulation for heavy-duty vehicles (RIVM, 2013).

In ReStore, some parts of the system are multifunctional because more than one function is being delivered from a certain process. Incineration is one of the examples of a multifunctional process since it provides four services at the same time. In this process, the first function is the waste treatment itself, the second function is the production of electricity, the third function is the production of heat, and the fourth function is the production of bottom ash which later can be utilised as sand replacement. This multifunctional process is an issue in LCA and needs a solution. One of the possible ways to solve this is by doing system expansion, which becomes the default setting to solve the multifunctional issue presents throughout the study. Further explanation about system expansion is discussed in Section 4.2.4.

When performing system expansion, the system is expanded to include down chain processes. To this matter, it is assumed that the extra functions added to the functional unit fulfil the same function as the recovered product and or energy obtained from the multifunctional process. Another assumption following this is that the market demand for any given item is assumed to be constant in all sectors beyond organic waste management and is not affected by the waste management activities. This assumption concerns that, firstly, if the economic inflows to the waste management system are classified as finite resources and if there is an increase in the final demand of these resources, this condition is excluded because this will lead to other indirect environmental impacts on another system. Secondly, the demand market is assumed to be constant for the sake of avoiding surplus materials in the case where the recovered goods and energy do not sufficiently replace the competing items in the market. This can lead to another life cycle phase of the recovered products and energy which may need another LCA analysis on itself.

4.2.4 Multi-functionality and Related Solutions

A multi-functional process is known as a process that has more than one function. It can be observed that from the processing stage of all alternatives, collected organic waste fraction goes in as input and various products are produced as output, thereby making this process to serve more than one function, rendering it as a multifunctional process. The application of biogas to CHP also serves as a multifunctional process because it produces two goods at the same time, making the process to be a co-production process by having two functions, which are producing heat and electricity. These multifunctional processes need a solution in order to know to which of the economic flows and environmental extensions are to be allocated to the appropriate product system (Guineé et al. 2002)

Following the procedure regulated by ISO 14041, there are several methods to solve multifunctional process based on the order of preference (ISO, 2006). The first and most-preferred rule is to avoid allocation whenever possible. This can be done by expanding the system boundary of the product system. In system expansion, the system boundary is expanded to include the impacts of alternative production of the exported functions (Cederbeg & Stadig 2003). Each alternative is expanded to cover all services from other alternatives, hence each alternative yields identical outputs and lies in the same completeness. In this case, all expanded alternatives of WtE, bio-digestion, and composting should cover all co-products that are produced by other alternatives. For instance, when defining the alternative for WtE, it is expanded to include the conventional alternatives variant of the reference flows delivered by bio-digestion and composting aside from its own reference flows.

Looking back to the goal of this study, the GHG emissions calculated by the ReStore model and the LCA model are to be compared by assuming as much as possible the same system boundary. To make the comparison lies on the same level, it is necessary to adapt the initial system definition of ReStore as shown in Figure 4.1. As a baseline, the multifunctional problems present in this study are solved using system expansion. Nevertheless, system expansion is only one among several available methods to solve multi-functionality. As mentioned by Guineé et al. (2002), choices of allocation method need to be evaluated through sensitivity analysis which is detailed in Chapter 5.

All in all, multi-functional processes need to be solved through procedural steps. There are four sequential steps in solving the multi-functionality issue (Guinée et al. 2004). Firstly, each flow is determined whether it is considered as a good or a waste. For this, the economic value of the flow is the key determinant. If a certain flow has an economic value higher than zero, that flow is specified as a good and vice versa. The second step is to decide on flows which served as the functional flow since not all flows have a certain function. Having identified the functional flows of all processes, it is then possible to determine which processes are multifunctional. Finally, the solution for the identified multifunctional processes is selected. The step-by-step identification of the multifunctional process is presented in Appendix F on the supplementary excel file.

The graphical representation of system expansion is shown in Figure 4.5. As shown in the figure, product B serves as an extra function which delivers the same function as product A. The impact of this extra function is then added to the impact of the conventional system, which makes the system to be identical with the investigated system. In this study, it is assumed that the produced compost is equivalent to potassium fertiliser. The electricity generated from WtE and CHP plant is assumed to hold the same function as the electricity from the Dutch electricity mix. Later on, in the sensitivity analysis, the effect of using different types of equivalent products is further evaluated.

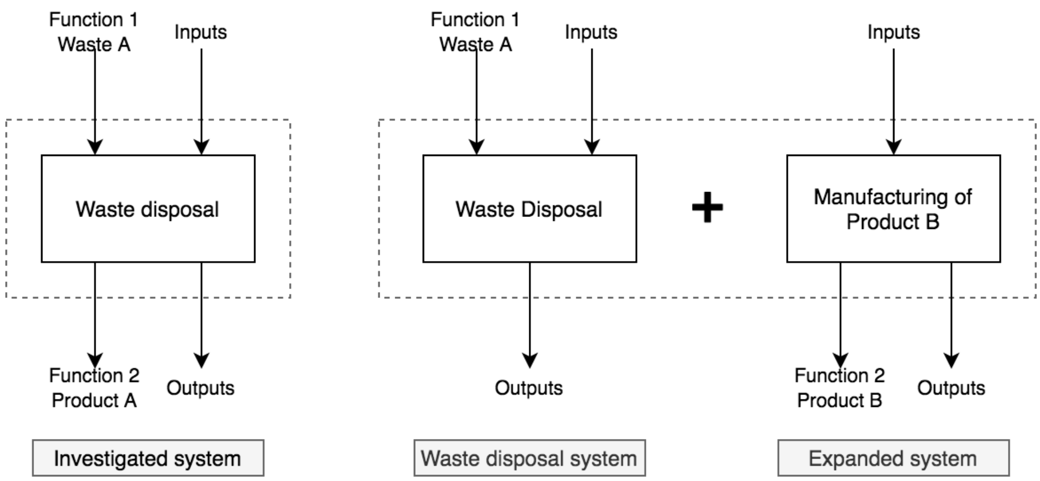

Figure 4.5 Hypothetical representation of solving multifunctional problem with system expansion

Several studies have described that allocation problems can be avoided through system expansion, especially when dealing with energy or material recovery (Tillman et al. 1998; Craighill & Powell, 1996; De Feo & Malvano, 2009; Eriksson et al. 2005). This shows that performing such method has been commonly implemented to avoid allocation problems. Apart from that, this method share some disadvantages. Having extra processes added to the investigated system signifies its complexity to a higher level. The system is now enlarged to include extra functions of co-products in the functional unit for all alternatives which leaves the quest whether an LCA that aims to deliver the assessment on one specific function, accomplishes this aims when the answer to several functional units are attained (Wardenaar et al. 2012). However, it is important to note that system expansion requires comparing alternative scenarios for the product of the same type as the investigated product. By this, it is expected that this method is largely dependent on the chosen expanded product and thus, data for this alternative production need to be sufficiently obtained to be used in both models (Ekvall & Finnveden, 2001). If there is not enough data and the data uncertainty is too large, the result might be ambiguous and such method will not add any valuable information. The details of the expanded system are shown in Table 4.1 to Table 4.3. The illustration of the simplified system boundary when system expansion is used to solve the multifunctional process is shown below in Figure 4.6.

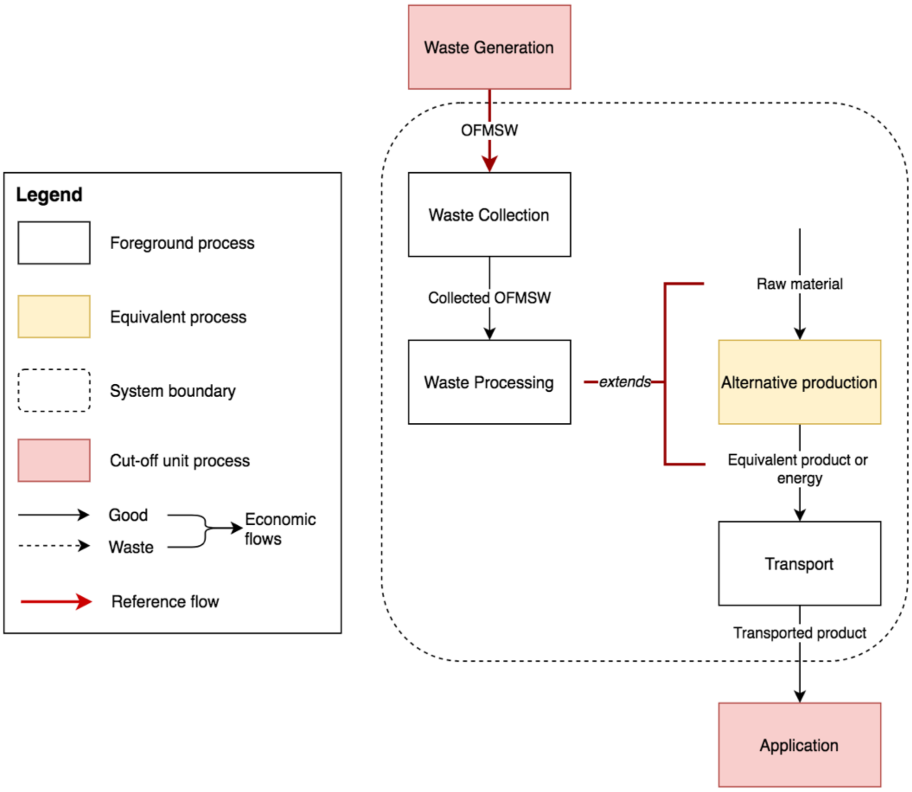

Figure 4.6 Illustration on the system boundary when system expansion is performed.

Table 4.1 WtE alternative, which is expanded with conventional variants of services that are delivered by the other two alternatives, which are bio-digestion and composting

Unit Process	Investigated System		Alternative Production from Conventional System	
	Functional flows	Amount	Functional flows	Amount
Incineration	Collected waste to WtE	246.8 ton	Natural gas [RoW[1]]	15,138 m^3
	Electricity from WtE	48,548 kWh	Potassium fertilizer [GLO[2]]	1.09 ton
	Heat from WtE	116,499 MJ	Electricity from natural gas co-generation [NL[3]]	2,246 kWh
	Bottom ash	1.75 ton	Potassium fertilizer [GLO[2]]	0.72 ton

RoW Location within the Rest of the World[1]
GLO Location within the global scale[2]
NL Location within the Netherlands[3]

Table 4.2 Bio-digestion alternative, which is expanded with conventional variants of services that are delivered by the other two alternatives, which are WtE and composting

Unit Process	**Investigated System**		**Alternative Production from Conventional System**	
	Functional flows	**Amount**	**Functional flows**	**Amount**
Digestion	Collected waste to digester	123.4 ton	Electricity from the Dutch electricity mix [NL[1]]	48,548 kWh
	Biogas	15,138 m^3		
Post-compost	Collected waste to post-compost	123.4 ton	Heat from natural gas co-generation [NL[1]]	116,499 MJ
	Digestate	105.99 ton		
	HN Compost	179.44 ton		
Cogeneration	Electricity	2,246 kWh	Sand [RoW[2]]	1.75 ton
	Heat	9,704.36 MJ	Potassium fertilizer [GLO[3]]	0.72 ton

NL Location within the Netherlands[1]
RoW Location within the Rest of the World[2]
GLO Location within the global scale[3]

Table 4.3 Composting alternative, which is expanded with conventional variants of services that are delivered by the other two alternatives, which are WtE and bio-digestion

Unit Process	**Investigated System**		**Alternative Production from Conventional System**	
	Functional flows	**Amount**	**Functional flows**	**Amount**
Composting	Collected waste to composting	246.8 ton	Electricity from the Dutch electricity mix [NL[1]]	48,548 kWh
			Heat from natural gas co-generation [NL[1]]	116,499 MJ
			Sand [RoW[2]]	1.75 ton
	HN Compost	113.4 ton	Natural gas [RoW[2]]	15,138 m^3
			Potassium fertilizer [GLO[3]]	1.09 ton
			Electricity from natural gas co-generation [NL[1]]	2,246 kWh

NL Location within the Netherlands[1]
RoW Location within the Rest of the World[2]
GLO Location within the global scale[3]

4.2.5 Result of Inventory Analysis

An aggregation of all unit processes is shown in the inventory table, where all emissions resulting from the whole process of three different options of organic waste management are explicated (see the supplementary excel Appendix B). What can be highlighted from the inventory table is that the results for all three alternatives tend to fluctuate and do not lie on the same range for different environmental extensions. Therefore, it is rather impractical to derive a particular decision solely based on the information from the inventory table as these results in a very complex and large dataset with extensive indicators diversity. This is why the long-list result from the inventory table needs to be aggregated to the relevant environmental impact categories before certain conclusions can be drawn. These Life Cycle Inventory (LCI) results are used as input for the next phase, which is the Life Cycle Impact Assessment (LCIA).

4.3 Impact Assessment

As stated in the previous section, the wide-range environmental extensions from the inventory table are inefficient for a decision making process. Thus, in the impact assessment phase, the linkage between the environmental impacts of the product or process is established. The result from the inventory table is assigned and classified into simple indicators that can be done through mid-point approach or end-point approach. This study uses the mid-point approach or the so-called problem-oriented method as the latter method is less comprehensive and is still in ongoing development.

4.3.1 Impact Categories

In the impact assessment phase, the environmental impact of a product system is evaluated. The CML 2001 baseline impact families were chosen since it includes an extensive variety of mid-point impact categories, which gives insight about the environmental impacts at an early stage of the cause-effect chain (Guinée et al. 2002). The focus of this study is to evaluate the GHG emission of the given functional unit, where this is assigned to the climate change impact category. Each impact category has its category indicator, characterization model, and characterization factor which together constitute the characterization method. This study will only look at the climate change impact, where the characterization method as described in Guineé et al (2002) was used.

4.3.2 Classification

Once the impact categories of the specific impact family are defined, the LCI results are assigned to the pre-defined impact categories. This study will only look at the climate change impact category, where environmental extensions such as CO_2, CH_4, and CO are assigned to this impact category. This is the basic feature included in the CMLCA v6.1, through which results are automatically obtained. Thus, no further elaboration is given in this section.

4.3.3 Characterisation Results

In this stage, the characterization factor is defined after assigning the inventory results to the climate change impact category. The GWP100 is known as the characterization factor for climate change which is measured in terms of kg CO_2-equivalent. Characterization factors reflect the relative contribution of different LCI results in the impact category. Thereafter, the inventory results are converted and aggregated using a characterization factor. It is important to note that only climate change impact category is calculated over all processes, thus, the complete characterization results which include other impact categories can be found in Appendix C. Characterization results of different organic waste management per functional unit for both the LCA model and the ReStore model is shown in Table 4.4.

Based on Table 4.4, the difference between results is fairly subtle. It can be seen that the climate change score shows a rather similar result for both models where in most of the cases, the results from the LCA model are higher than the result in the ReStore model. The similarity also becomes obvious in terms of order of impact. Both models reveal that bio-digestion and composting show worse environmental performance in contrast to WtE. This similarity can be expected because both models have been adjusted to have the same system boundary. Despite the close outcome, few differences were spotted, showing that it is most likely that each model cannot yield the exact same results. Further reasoning on possible factors to cause the difference in results will be addressed in Chapter 6.

Table 4.4 Climate change scores between LCA model and ReStore model for three options of managing organic waste in the Amsterdam neighbourhood for a year

Alternatives	**Climate Change Score (kg CO_2-eq)**	
	ReStore model	**LCA model**
WtE	35.56E+03	36.35E+03
Bio-digestion	55.39E+03	57.15E+03
Composting	51.84E+03	51.03E+03

4.3.4 Normalisation Results

In this stage, the magnitude of impact indicator results is calculated relative to a certain reference value in year units. This is done by dividing the values over the total known yearly worldwide value based on CML2001 normalization. This gives an indication of the contribution of the characterization result to the total global problem. Therefore, the score from each impact category which initially has different units can then be compared with the result from different impact categories in the same unit. As this study only considers the impact of the climate change category, it is not necessary to do result normalization.

4.3.5 Interventions for which Characterisation Factor is Lacking

On account of the scope of this study to only research the equivalent CO_2 emissions, there is no missing characterisation factor found in this context. However, it is important to note that there are some environmental extensions that cannot be sub-divided to a certain environmental impact, and thus, affects the completeness of the reporting of an LCA study. Out of the total of 1,910 environmental interventions, 1,236 of them do not have characterization factors, reflecting that almost 65% of the inventory result is not included in the characterization result. This becomes the major constraint of an LCA study as this 65% of the environmental interventions are deemed to have a neutral environmental impact.

4.3.6 Economic Flows not Followed System Boundary

While it is preferred to include economic flows as complete as possible, this, unfortunately, is not always feasible. This is why some cut-offs were applied to certain economic flows on the original ReStore model. Subsequently, based on the adjusted system boundary of ReStore, an LCA model was then developed by trying to resemble the same state as defined in ReStore as close as possible.

Firstly, the upchain processes in which organic waste is generated is excluded. Next to this, the chain in which the capital good is produced is a cut-off. As explicated in the literature review section, each organic waste management option is specific, and thus, requires different equipment accordingly. The energy that these equipment used during the waste treatment process is included. However, the materials and energy needed to construct or dispose this equipment are neglected. In addition, the utilisation of products obtained from each waste treatment process is also omitted since applying these products may involve another life cycle of production, use, and final disposal of additional products. This goes beyond the scope of this study.

4.4 Interpretation

In this last sequence of the LCA process, the previous results from inventory analysis and impact assessment are examined with respect to its consistency, completeness, and robustness. This information is then translated to report the results transparently, formulate conclusions, and draw recommendations.

4.4.1 Consistency Check

Since this study was built on several assumptions, it is recognized that several inconsistencies might occur. It is then important to conduct a consistency check to ensure that assumptions, methods, models, and data are consistent and relevant to the initial goal and scope of this study. The consistency check shall be grounded in several aspects, which are data sources, data accuracy, technical level, temporal aspects, geographical representativeness, and functions (Guineé et al. 2002).

In terms of *data source*, the foreground process data was sourced from ReStore for both models. Next to this, the background process data was acquired from the Ecoinvent v3.4 database for the LCA model while ReStore sourced their background data from external literature. It is then noted that there are some inconsistencies present with regard to the *data accuracy* for background processes. There is no particular difference in the *technical level* between the ReStore model and the LCA model since the LCA model reflects the technical framework of ReStore. Moreover, since WtE, bio-digestion, and composting have been commonly applied as organic waste treatment, there is no technical differentiation in this case. Concerning the *temporal aspects*, it is known that the data obtained from ReStore was within the year of 2019, which is fairly recent. Data sourced from Ecoinvent also lies between 2009-2020, as what has been defined in section 4.1.2 for temporal scope. In terms of *geographical representativeness*, all data for foreground processes is the raw data from ReStore. Background data are stemmed from Ecoinvent v3.4 although it is not possible to gather all data from the same geographical area since some products are manufactured outside the Netherlands. With regard to the *functions*, all alternatives stated in both models fulfil the same function, namely managing organic municipal waste in the Amsterdam neighbourhood within a year.

4.4.2 Completeness Check

In this phase, any missing or incomplete information is checked. Reflecting upon the goal of this study which aims to perform a comparative analysis, it is important to ensure that the ReStore model and the LCA model are being compared on the same level of completeness. To make this feasible, the original ReStore model is adapted towards several conditions. The first adjustment was made on the scope of the organic waste management system. While decentralised processing was initially included in the ReStore model, this is no longer becomes part of the studied system. The next one is the exclusion of the application phase of the produced goods. Lastly, the original ReStore model considered the impacts avoided by incineration, bio-digestion, and composting. However, in the adjusted model there is no substitution applied. Because the setup of the LCA model is drawn on the adjusted ReStore model, both models are then estimated to have the same completeness level.

One of the guidelines for completeness check is to ground it on the results of the study and compare them with the results of previous studies on related subjects (Guineé et al. 2002). There are abundance of research which investigate the environmental impact of municipal solid waste treatments in general but less was found in respect of organic fraction of municipal waste, especially in the Netherlands. One similar study was performed by Mondello et al. (2017) which compared various scenarios for food waste management in Italy. In their study, they classified impacts occurring throughout the system into three stages: collection, pre-treatment, and final treatment. These categories are pretty similar to what are being observed in this LCA study. The research from Mondello et al. (2017) supported the finding from this study which highlighted the treatment process as the highest CO_2 contributor. Results from Mondello et al. (2017) addressed that incineration has the largest impact while in this LCA study, the highest impact is associated with bio-digestion. On the contrary, the paper surveyed bio-digestion to be the least GHG emitter, while in this LCA study this belongs to composting. This is reasonable because both studies have different inventory data. Moreover, the result gained in this LCA study is much larger than those obtained from the paper of Mondello et al. (2017). It was pointed out that the latter study observed the impact of waste treatment per one tonne of food waste while the functional basis for this LCA study is related to the total amount of organic waste generated per year. Nevertheless, several discussion sessions with supervisors and commissioner have been held throughout the project to ensure the completeness of this study, though it is possible that this study might fail to notice several aspects.

4.4.3 Contribution Analysis

Given that one of the goals of this study is to determine the environmental impact of three different organic waste management options and to compare the results with the model developed by ReStore, finding hotspots is of a great importance. Contribution analysis allows an impact evaluation from each stage of every scenario to a given environmental score. The result of contribution analysis is usually expressed as a percentage of contribution of the specific process of the total environmental impact generated per impact category. The data that was used to develop the contribution graph along with its calculation in this section is shown in Appendix D. The graphical representation of the percentage contribution from the LCA model and ReStore model is shown in Figure 4.7 and Figure 4.8 respectively.

When examining the whole system more closely, it can be seen that both models possess similar behaviour in terms of emission contributor, where processing gains the most salient impact for all alternatives, amounting to 79%-86% of the total emission in the LCA model, as shown in Figure 4.7. In line with the result from the LCA model, the result obtained from ReStore also highlights processing as the most CO_2 contributor, pertains to 84%-87% of the total emission, as seen in Figure 4.8. It can also be noticed that the contribution in absolute terms for other hotspots seem to be more or less the same between the ReStore and the LCA model. This is defined by the impact distribution from WtE, where collection takes up around 16% of the impact in both models, while the impact for transport is hardly recognised. Following this, the impact associated to collection in bio-digestion consistently shows 9% of contribution for both models, while the impact for transport reaches 11% for the LCA model and 7% for the ReStore model. In the case of composting, collection gains 8% of the impact in both models and followed by transport where it is associated with 5% of the total impact from both models. In this regard, the impact configuration from each alternative in both models are seen to be nearly alike.

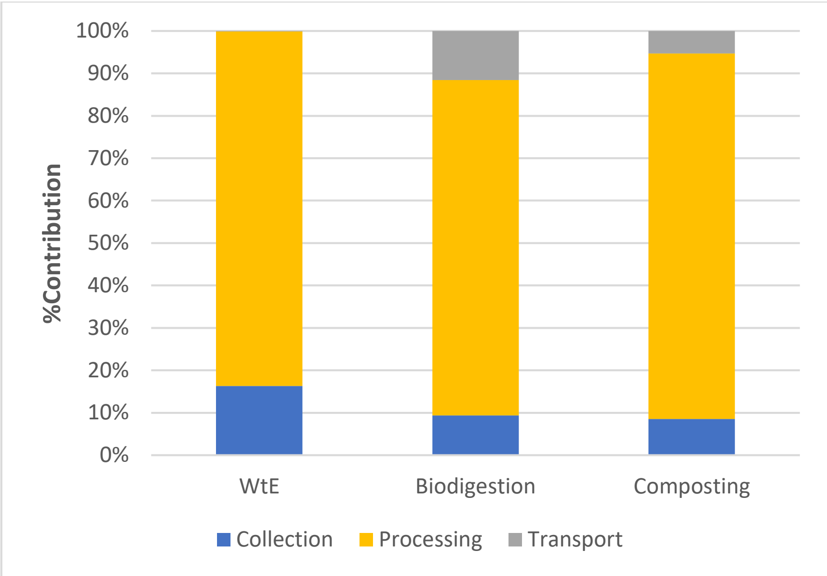

Figure 4.7 Percentage contribution per each phase for each alternative in the LCA model

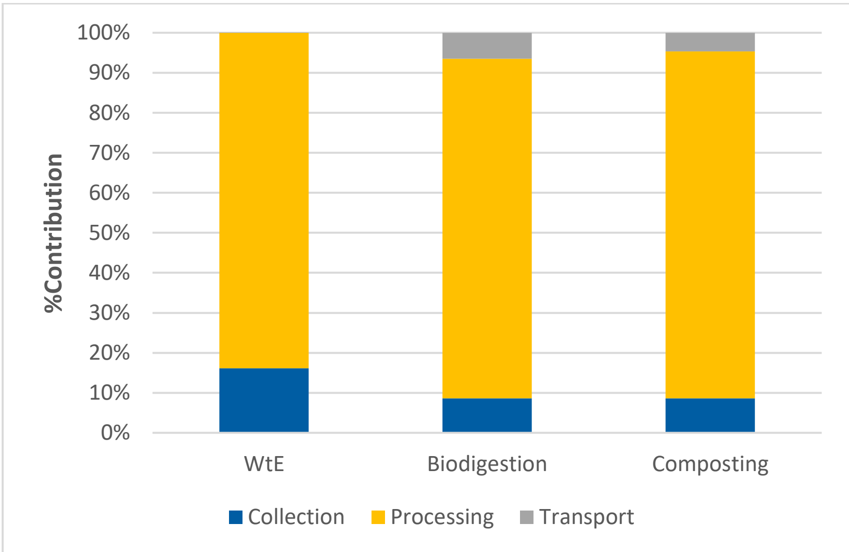

Figure 4.8 Percentage contribution per each phase for each alternative in the ReStore model

4.5 Chapter Summary and Conclusion

After having analysed the current state of ReStore model, this chapter assesses the environmental impact by means of different organic waste management options by applying the LCA methodology to the ReStore case study. The result from this chapter provides the answer to the second sub-research question of "*Taking the model developed by ReStore as a starting point, what is the carbon footprint of bio-digestion, composting, and WtE within the LCA perspective?*". It was found that WtE has a carbon footprint of 36,350 kg CO_2-eq, bio-digestion has a carbon footprint of 57,152 kg CO_2-eq and composting has a carbon footprint of 51,026 kg CO_2-eq. These results were obtained in the context of the baseline setting, when system expansion was used to solve multi-functionality issue. However, the influence of different methods in solving multifunctionality towards the final result was examined on the sensitivity analysis that is detailed in the next chapter. Nonetheless, the contribution analysis denotes that both models gain the same behaviour per each alternative. This is explained by the same impact contributor which is directed to processing stage as well as by the identical impact dispersion of other stages.

Chapter 5
Sensitivity Analysis

This chapter intends to evaluate several assumptions addressed in this study in order to find out the key influencing factors from both models through sensitivity analysis. This analysis serves as an additional check to see how stable the results are against changes in some parameters. The sensitivity analysis was carried out in several aspects. First of all, it was performed on different methods to solve multifunctional process. Next, the sensitivity analysis was conducted on the assumptions made on the process data, such as the assumption on the chosen equivalent products. Finally, this chapter ends with a summary of sensitive variables in both models.

5.1 Sensitivity towards Changes in Method for Solving Multifunctional Problems

According to Guineé et al. (2002), there is no an objectively correct way of solving multi-functionality problem, not even in theory. Thus, Guineé et al. (2002) addressed the importance to analyse the influence of different allocation methods on the outcome as a sensitivity analysis. Hence, this study choose substitution and economic allocation as sensitivity analysis towards system expansion which is used as a default setting to solve multifunctional processes in this study. The data used to develop the result of this sensitivity analysis is displayed in Appendix F.

5.1.1 Using Substitution to Solve Multifunctional Process

The first attempt is to use substitution to solve multifunctionality. In contrast to system expansion, in substitution, the recovered materials and energy from the organic waste management system substitute items with similar features. Therefore, the demand for the replaced items decreases, which, in turn, causes the avoidance production of these items and their associated environmental impacts that could have been emitted otherwise (Brander et al. 2012). The avoided impact from the avoided products is then subtracted from the impact generated in the multifunctional process, as shown in Figure 5.1. It has long been misunderstood that substitution is perceived to be equal with system expansion, in the sense that both models will give the same outcome. This way, it has often been incorrectly cited that ISO recommends the use of substitution as a prioritized way to avoid allocation (Brander & Wylie, 2015; Heijungs, 2014; Wardenaar et al. 2012). Yet, both methods are merely conceptually equivalent, where both provide results that are compatible (Wardenaar et al. 2012; Guineé et al. 2018). Thus, along with system expansion, using substitution will increase the level of complexity of the system since now the system is also enlarged, but with the avoided process.

However, the choice of replaced items is really influential in determining the LCA result, causing the result to be largely diverge (Heijungs & Guineé, 2007). In the case of recycling scenario, especially for open-loop recycling where wastes are recycled into products used by another system, the recycled materials can either replace virgin material from the product of the same type, or substitute recycled materials from other products, or even displace completely different product. It is hard to predict to which group do the recycled products belong and what processes are affected if changes in recycling flows take place, which makes this method to be questioned on its clarity (Nakatanai, 2014). Moreover, another conceptual problem raised by substitution is that it involves a credit for emissions that have not happened because its function is fulfilled by the co-products produced by the system.

This means that the result of the assessment will not reflect a true inventory of the actual physical emissions (Brander et al. 2012).

Since the avoided product is subtracted from the impact of the multifunctional system, assumptions are made on the replacement rate. In substitution, the same assumption on the alternative product as in the system expansion is used. It is important to note that alternative products have the same feature as the products that are being replaced, so that both systems provide comparable services (Brancoli & Bolton, 2019). The adapted system boundary when substitution is used to solve multifunctional process is shown in Figure 5.2.

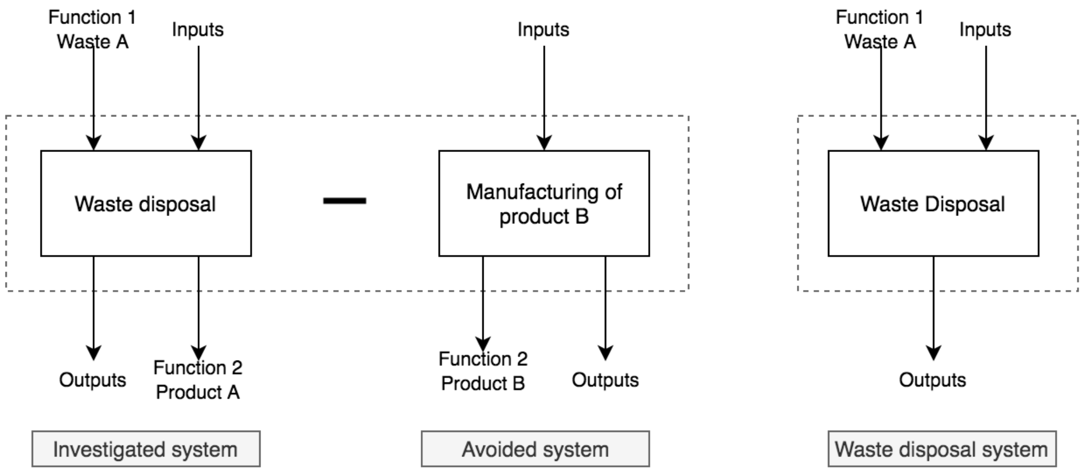

Figure 5.1 Hypothetical representation of solving multifunctional problem with substitution

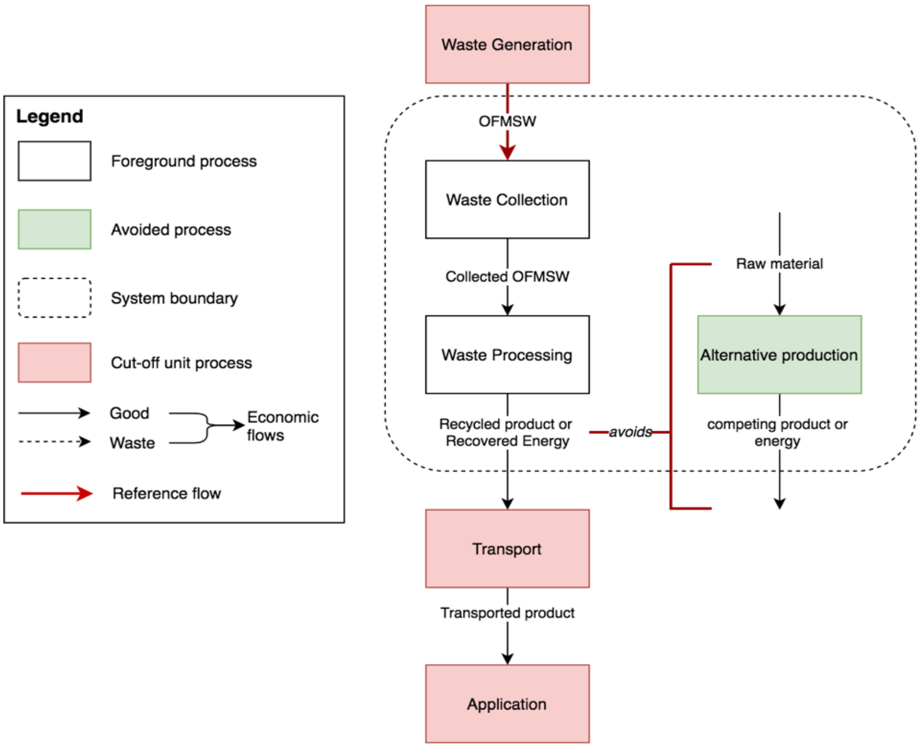

Figure 5.2 Illustration on the system boundary when substitution is performed

The details of the substitution method is shown in Table 5.1, where it elaborates the assumed products or functions that are replaced by products obtained from the investigated process. The electricity generated from the incineration process replaces the electricity from the Dutch electricity mix. The data for electricity from the Netherlands grid was sourced from Ecoinvent, which represents the production mix of Dutch power supply in 2016 with composition percentage as shown in Table 5.2. The produced heat replaces the district heating from natural gas. The bottom ash as by-product from incineration replaces the virgin construction material in the form of sand.

Table 5.1 Details of substituted product due to applying substitution to solve multifunctional processes

Unit Process	Functional Flow	Amount	Unit	Assumed Competing Product	Location	Amount	Unit
Incineration	Electricity	48,548	kWh	Electricity from the Dutch electricity mix	NL[1]	48,548	kWh
	Heat	116,499	MJ	Heat from natural gas co-generation	NL[1]	116,499	MJ
	Bottom ash	1.75	ton	Sand	RoW[2]	1.75	ton
Digestion	Biogas	15,138	m^3	Natural gas	RoW[2]	15,138	m^3
Post-compost	HN Compost	123.4	ton	Potassium fertiliser	GLO[3]	1.78	ton
Co-generation	Electricity	2,246	kWh	Electricity from natural gas co-generation	NL[1]	2,246	kWh
	Heat	9,704.36	MJ	Heat from natural gas co-generation	NL[1]	9,704.36	MJ
Composting	HN Compost	113.4	ton	Potassium fertilizer as K_2O	GLO[3]	0.72	ton

NL Location within the Netherlands[1]
RoW Location within the Rest of the World[2]
GLO Location within the global scale[3]

Table 5.2 Dutch electricity mix composition in 2016 (Ecoinvent, 2017)

Power Source	Share (%)
Coal	26.11
Oil	55.68
Natural gas	4.35
Wind	9.50
Nuclear	3.55
Biomass	0.81
Total	100%

The result of using substitution for solving multifunctional problem is shown in Table 5.3. The results from the LCA model are also found to be in a close range with those obtained from ReStore. As become obvious, WtE is still associated with the least climate change score but now represented with negative results, which makes the result from substitution stands out in this case. This indicates GHG emission savings because the impact of the substituted energy on the market is larger than the impact generated from the treatment process. This is followed by composting and eventually bio-digestion as the largest CO_2 emitter. The order between bio-digestion and composting is in a complete flip with results obtained when system expansion is used. This might be due to the impact of downstream processing that are not counted in when using substitution. While most of the impact of bio-digestion is directed from post-compost process and transport process under the system expansion method, these impacts are excluded in substitution, causing the impact from bio-digestion to be less than the impact from composting.

Table 5.3 Climate change scores on LCA and ReStore model on three options of managing organic waste in the Amsterdam neighbourhood for a year when using substitution to solve multi-functionality issue

Alternatives	Climate Change Score (kg CO_2-eq)	
	ReStore model	LCA model
WtE	-19.81E+03	-18.94E+03
Bio-digestion	7.41E+03	9.32E+03
Composting	20.55E+03	18.20E+03

5.1.2 Using Economic Allocation to Solve Multifunctional Process

Next to substitution, the second option is to perform an allocation. The basic principle of allocation is to partition the multifunctional process into several monofunctional processes where non-functional flows are allocated to the functional flows according to certain allocation principles (Mackenzie et al. 2017). One of the most common allocations is economic allocation (Ardente & Cellura, 2012). When working with economic allocation, the flows will be allocated to the identified functional flow based on their share in the total proceeds (Guineé et al. 2004). Proceeds are price-based that can be expressed in any monetary unit. Proceeds are calculated by multiplying the price per unit with the product's quantity. The allocation factor is quantified as the share of each proceed for each product to the total proceed (Guineé et al. 2002). The emission of a certain process is then determined based on its associated allocation. The hypothetical example of economic allocation is shown in Figure 5.3. It can be seen that partitioning envisions multifunctional process itself as the cause of problem and the start of a solution, whereas system expansion and substitution take the system of processes serving a function as a whole (Guineé et al. 2018).

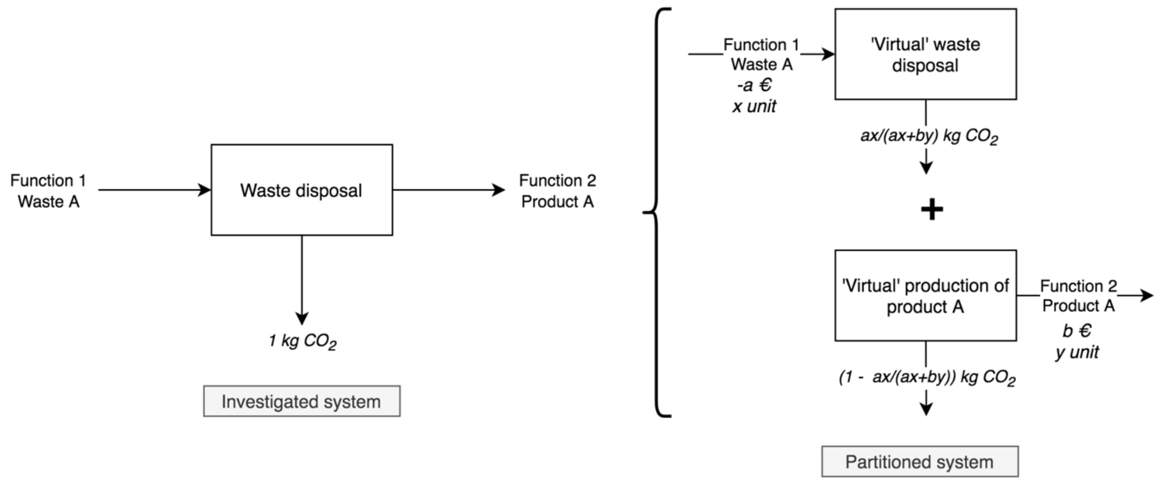

Figure 5.3 Hypothetical representation of solving multifunctional problem with economic allocation

Next to this, it is possible to perform allocation on other parameters, where allocation factor is determined on the basis of mass or the energy content. To this matter, the choice of allocation is rather arbitrary. Furthermore, some issues such as the unknown market prices, inflation, as well as price fluctuation may add complexities and limit the implementation of this method (Guineé et al. 2004; Werner & Richter, 2000). Moreover, in economic allocation, much of the down-chain processes of waste management service are not taken into account, leaving the system to calculate the impact until the waste treatment service only, as represented in Figure 5.4. Despite these limitations, this allocation type is quite simple and straightforward. By having a fixed allocation factor, this approach offers a consistent solution with no specific theoretical problem, and therefore, ambiguous results as what could have occurred in substitution and system expansion can be avoided.

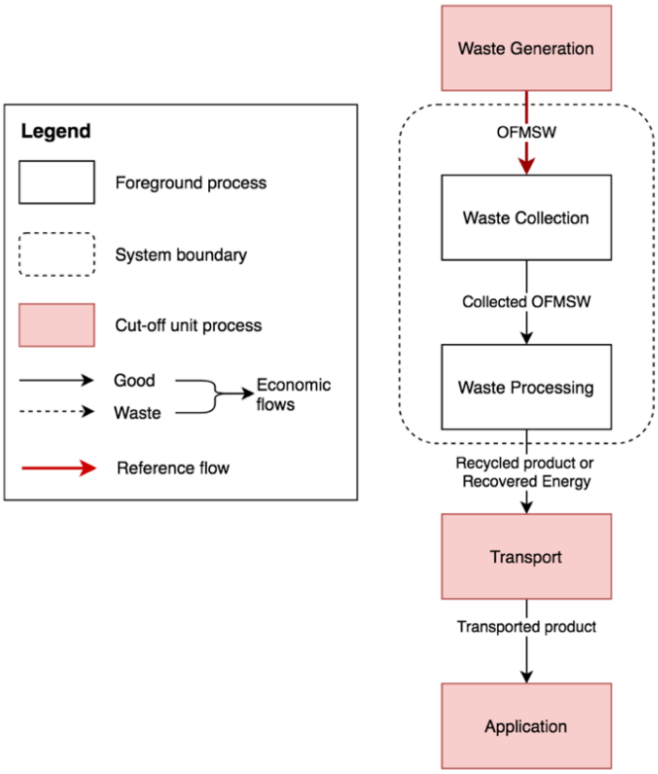

Figure 5.4 Illustration on the system boundary when economic allocation is performed

The details of economic allocation are shown in Table 5.4. It can be seen from the table how functional flows are partitioned in proportion to their economic value. Furthermore, the characterisation result from applying economic allocation is shown in Table 5.5. The impact now becomes smaller when economic allocation is performed, mainly because the downstream processes are not counted in, as what has been explained previously. Additionally, the order of impact stays the same as in substitution, where WtE remains to be the most-favourable option and composting the least. This means that there is also a switch in the order of impact from system expansion for bio-digestion and composting in economic allocation, as what was observed in substitution. This is also probably take place under the same reason, that is due to the consequences of having down-chain processes being neglected. Nonetheless, the economic allocation also bears similar results per each alternative for both models.

Table 5.4 Allocation factor for economic allocation

Unit Process	Functional Flow	Quantity	Price (€/unit)	Proceeds (€)	Allocation Factor
Incineration	Collected OFMSW	0.27E+03 ton	-54[1]	14.41E+03	0.52
	Electricity	48.55E+03 kWh	0.22[2]	10.68E+03	0.38
	Heat	116.49E+03 MJ	0.024[3]	2.79E+03	0.10
	Bottom ash	1.75 ton	7.35[4]	0.012E+03	4.61E-4
Total				27.89E+03	1
Digestion	Collected OFMSW	0.12E+03 ton	-54[1]	6.67E+03	0.35
	Biogas	15.14E+03 m^3	0.83[5]	12.56E+03	0.65
Total				19.23E+03	1
Post-composting	Collected OFMSW	0.12E+03 ton	-54[1]	6.67E+03	0.24
	Digestate	0.10E+03 ton	-5.93[6]	0.63E+03	0.02
	HN compost	0.28E+03 ton	121[7]	33.59E+03	0.74
Total				40.88E+03	1
Co-generation	Electricity	2.25E+03 kWh	0.22[2]	0.49E+03	0.68
	Heat	9.70E+03 MJ	0.024[3]	0.23E+03	0.32
Total				0.72E+03	1
Composting	Collected OFMSW	0.23 ton	-54[1]	12.24E+03	0.47
	HN compost	0.11E+03	121[6]	13.72E+03	0.53
Total				25.96E+03	1

[1]WRAP, 2018
[2]Global Petrol Prices, 2019
[3]ACM, 2018
[4]Kamal et al. 2017
[5]Timonen et al. 2019
[6]Environment Agency, 2009
[7]Chen, 2016

Table 5.5 Climate change scores for the ReStore and LCA model on three options of managing organic waste in the Amsterdam neighbourhood for a year when using economic allocation to solve multi-functionality issue

Alternatives	Climate Change Score (kg CO_2-eq)	
	ReStore model	LCA model
WtE	6.22E+03	6.71E+03
Bio-digestion	10.83E+03	8.75E+03
Composting	12.12E+03	11.30E+03

5.2 Sensitivity towards Changes in Types of Electricity

It is known that choices made on the replaced product have a decisive impact on the LCI results. In this study, a 1:1 replacement ratio for electricity is used, where 1 kWh of electricity produced from WtE and CHP substitutes 1 kWh electricity from the Dutch electricity mix. This type of electricity was chosen as it is the type of electricity that is most likely to be replaced so that the results are more relatable to the Netherlands situation. However, there are numerous other potential sources of power generation that can be harnessed. It is then interesting to know whether different types of electricity with different composition will affect the total impact generated by the system. Nevertheless, it is rather impractical to assess each and all of these options in this analysis. Moreover, the fact that the national market for power supply will continue to develop as a result of changes in energy policy, ongoing sustainability issues, and energy security planning will lead to further uncertainties. Therefore, this sensitivity analysis will only consider two scenarios options.

The first scenario takes electricity generated from the combined-cycle gas power plant while the second scenario considers the power supply from the coal-fired power plant as an approach. In these cases, the electricity generated from the system understudied corresponds with the electricity sourced from natural gas and coal. The analysis was done when system expansion and substitution are used to solve the multifunctional problem. Figure 5.5 shows the result for both models by solving multi-functionality through system expansion, while Figure 5.6 presents the result when multifunctional processes were solved using substitution.

It can be seen that the change in replacement rate clearly affects the climate change score of three alternatives on both models and allocation methods. In fact, when system expansion is used, this leads to lower climate change scores for both models. As shown in Figure 5.5, the total CO_2 emission equivalent for each alternative modelled in ReStore is decreased by 8%, 9%, and 14% for WtE, bio-digestion, and composting in the first scenario. In the LCA model, the impact from WtE, bio-digestion, and composting is reduced by 15%, 10%, and 11% respectively. Meanwhile, when types of electricity is switched to coal, the impact is increased largely in both models. In the ReStore model, the impact goes up by 77% , 47%, and 42% for WtE, bio-digestion, and composting, while in LCA, the enhancement for each alternative in respective order are 86%, 44%, and 51%. This is because the Dutch electricity mix gains more emission compared to natural gas alone, but is presumed to be cleaner enough compared to electricity produced from coal. Although the Netherlands has incorporated the use of renewables, the country is still in continuous reliance on fossil-based electricity. Thus, the inclusion of renewables does not seem sufficient to offset the impact generated from the production of electricity from fossil fuels (Salemdeeb et al. 2018; Shonfield, 2008). Nevertheless, based on the outcome of this sensitivity analysis, both models show an interrelated tendency on impact reduction and increment for every scenario.

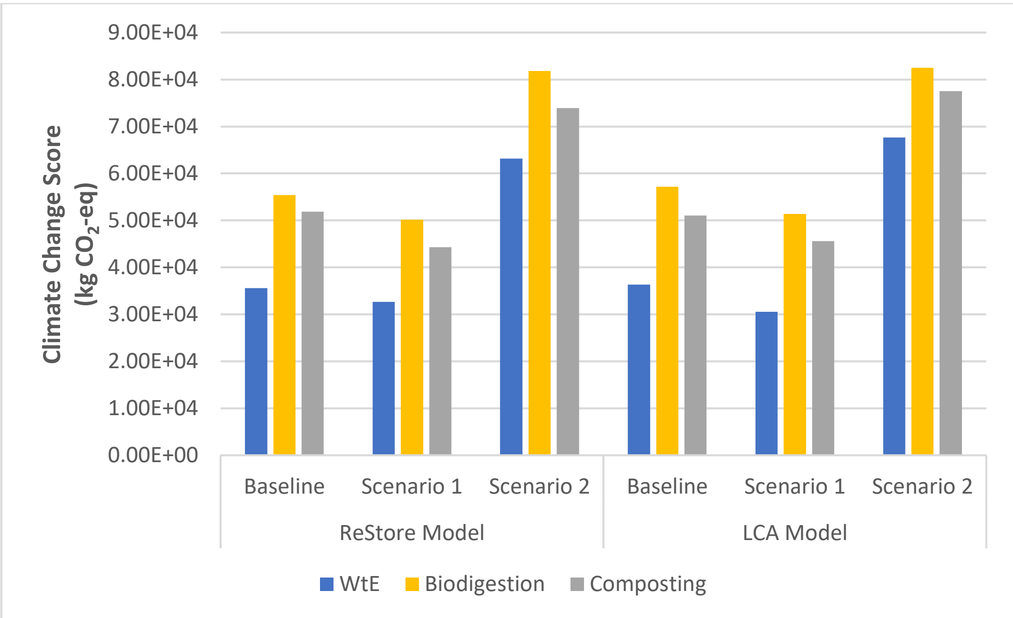

Figure 5.5 Climate change score for the Restore model and the LCA model when assumed equivalent product for electricity and is changed, using system expansion to solve multifunctional issue

On the other side, when substitution is chosen, the impact also fluctuates per scenario. As seen in Figure 5.6, generally, the impact is increased in the first scenario and decreased in the second scenario. it can be seen that the effect on bio-digestion is minimal while the change in emission for WtE is quite prominent. In the first scenario, the climate change score of WtE is reduced by 26% and 3% for bio-digestion for the ReStore model. A similar result was obtained in the case of LCA model, where the impact is decreased by 27% for WtE and 2% for bio-digestion. A huge decline in the climate change score is observed when the generation of electricity is shifted to coal. The combustion of coal results in higher CO_2 emission and consequently, leads to greater environmental savings. This becomes noticeable as the impact from WtE in the ReStore model decreases by a factor of two while the bio-digestion shows 15% of impact reduction. The nearly similar results are observed in the LCA model for WtE, while the impact reduction in bio-digestion is achieved at 7%. In both cases for modelling options, the impact of composting does not change because there is no relevant equivalent product taking place on this process. The results conclude that for both models and solutions for solving multifunctionality, switching electricity from the Dutch electricity mix to natural gas is less sensitive than when electricity is assumed to be supplied by coal-fired power stations.

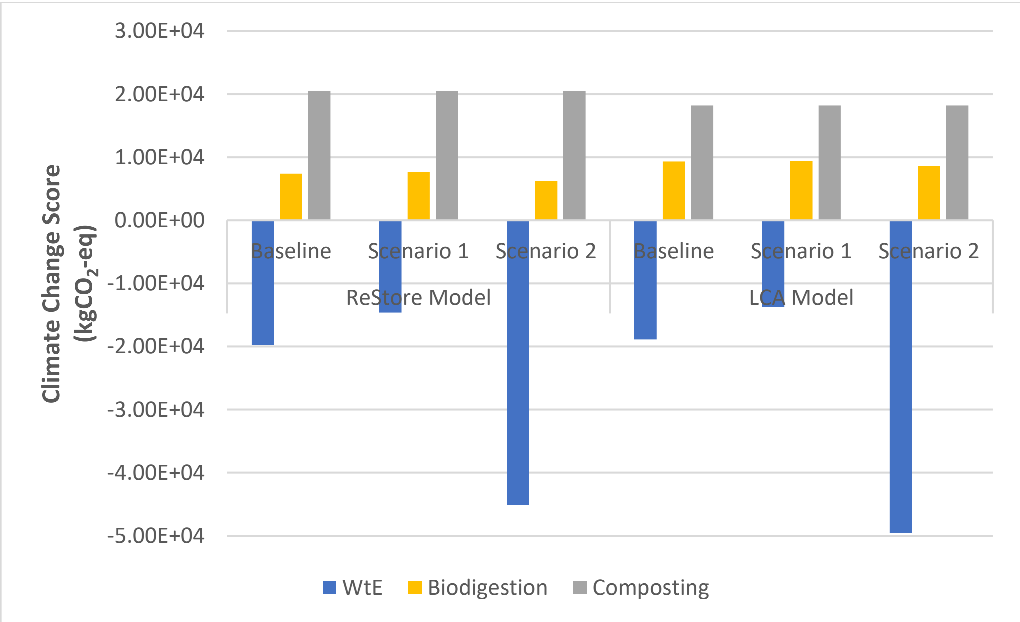

Figure 5.6 Climate change score for the Restore model and LCA model when assumed equivalent product for electricity is changed, using substitution to solve multifunctional issue

5.3 Sensitivity of the Selected Equivalent Product of Compost

5.3.1 Mineral-based Fertiliser

As shown above, the chosen electricity source to substitute the electricity generated by the system greatly affect the final result of the study. As organic waste is primarily consists of food by-products that are an excellent source of potassium, the produced compost from the bio-digestion and the composting process is assumed to be equivalent to mineral-based fertilizer in the form of potassium fertiliser. However, there are various other types of fertiliser which the produced compost from bio-digestion and composting could substitute for. In order to evaluate this assumption, the compost is then assumed to be equivalent to other types of fertiliser which is nitrogen fertiliser in the form of urea as the first scenario and phosphorous fertiliser as the second scenario. The result is shown in

Figure 5.7 for both models when system expansion is selected to solve multifunctional problem and in Figure 5.8 for both models when substitution is selected to solve multifunctional problem.

Under the system expansion method, the result depicts a subtle increment in almost all scenarios. In scenario 1, the impact is increased by 2.2%, 0.6%, and 0.2% for WtE, bio-digestion, and composting for the ReStore model, while the enhancement lies at 5.6%, 1.4%, and 2.4% for the respective alternative in the LCA model. Furthermore, when phosphate fertiliser is used instead of nitrogen fertiliser in the second scenario, both model shows a different trend of outcomes. In the ReStore model, the result decreases by 0.6% for WtE, 0.3% for bio-digestion and 0.1% for composting while for the LCA model the result increases by 3.4% for WtE, 0.8% for bio-digestion and 1.5% for composting. This is because the impact of phosphate fertiliser as defined in Ecoinvent is larger than the impact of potassium fertiliser while this is the opposite case in ReStore where the impact of potassium fertiliser is higher than the impact of phosphate fertiliser. This leads to the gap present on the result between both models.

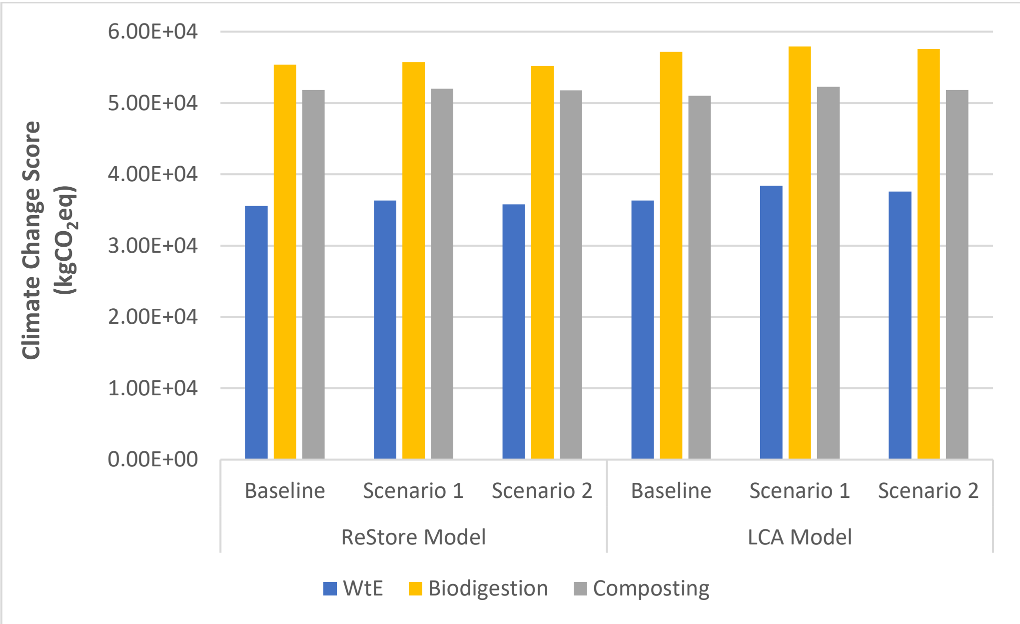

Figure 5.7 Climate change score for the Restore model and the LCA model when assumed equivalent product for compost is changed, using system expansion to solve multifunctional issue

Under the substitution method, generally, the impact is decreased in all scenarios. In the first scenario of the ReStore model, the impact is reduced by 7% in bio-digestion and 0.7% in composting, while for the LCA model, the impact goes down by 21% for bio-digestion and 4% for composting. However, the impact for bio-digestion and composting is increased in the ReStore model on the second scenario while the impact is decreased in the LCA model. Along with the previous explanation, this is due to the influence of different GHG emission factors. As potassium fertiliser is defined to have larger emission in ReStore rather than in Ecoinvent, the impact is already higher in the first place. Shifting to phosphate fertiliser means that less impact can be avoided which leads to a bigger outcome. In both cases for modelling options, the impact of WtE does not change because there is no relevant equivalent product taking place on this process. In summary, the result from this sensitivity analysis shows that the global warming impact of both models is not as particularly sensitive to a shift of certain types of fertilisers as when different types of electricity were selected.

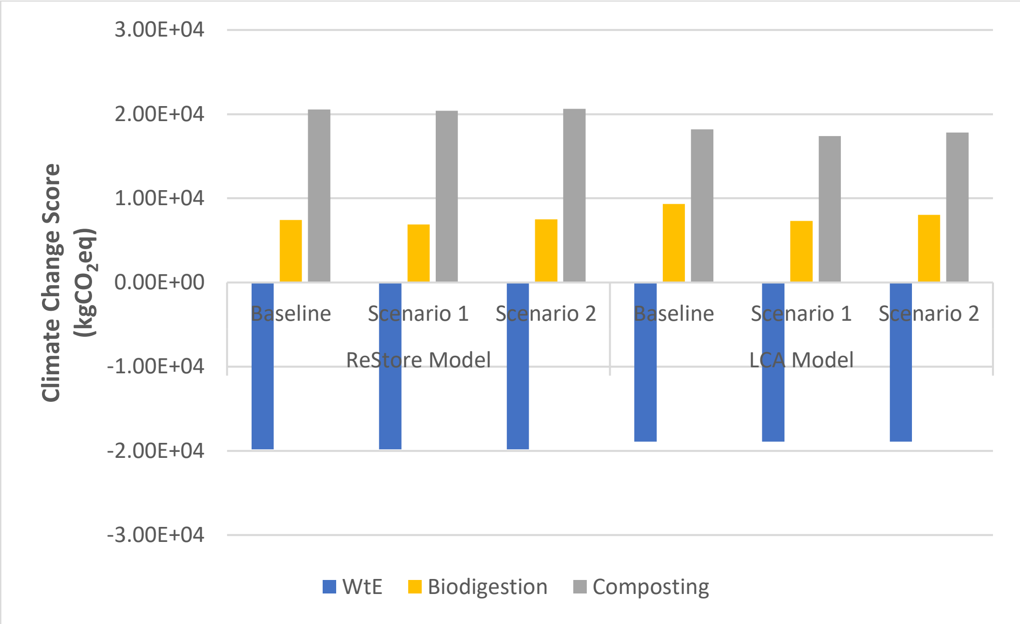

Figure 5.8 Climate change score for Restore model and LCA model when assumed equivalent product for compost is changed, using substitution to solve multifunctional issue

5.3.2 Peat

This study also investigates the effect if a completely different product category is picked, which in this case is peat. This sensitivity analysis was assessed when system expansion and substitution are used to solve multifunctional problems. The result when compost is assumed to be equivalent with peat is shown in Figure 5.9 under the system expansion method and Figure 5.10 under the substitution method to solve multifunctional process.

When system expansion is used, the result in ReStore goes up by 35% for WtE, 21% for bio-digestion and 9% for composting while the result in LCA shows a relatively low increase of 2% for WtE, 3% for bio-digestion, and 1% for composting. The effect on the results of changing the basis equivalence product of compost from potassium fertiliser to peat is more dramatic when substitution is used to solve multifunctional problem. Under the case of substitution as shown in Figure 5.10, the impact from the ReStore model declines by 29% for bio-digestion and 23% for composting, while the reduction in the LCA model is 11% for bio-digestion and only 2% for composting.

As become apparent, the increment and reduction are higher compared to when mineral-based fertilisers were chosen. This is because the replacement rate of compost for peat is higher than the replacement rate of compost for mineral fertiliser, causing the amount of impact being subtracted and added to be larger (Farrell & Jones, 2010). Furthermore, the effect on changing the basis equivalence product of compost from potassium fertiliser to peat is more dramatic in the ReStore model. This variation is influenced by the difference assumption made in the GHG emission factor for peat, where the GHG emission score for peat as defined in the ReStore model is higher than the number in Ecoinvent. In this case, the impact of WtE does not change because there is no replacement taking place on this alternative. Nevertheless, these sensitivity results sum up that switching to peat over potassium fertiliser is a more sensitive parameter for the ReStore model than the LCA model.

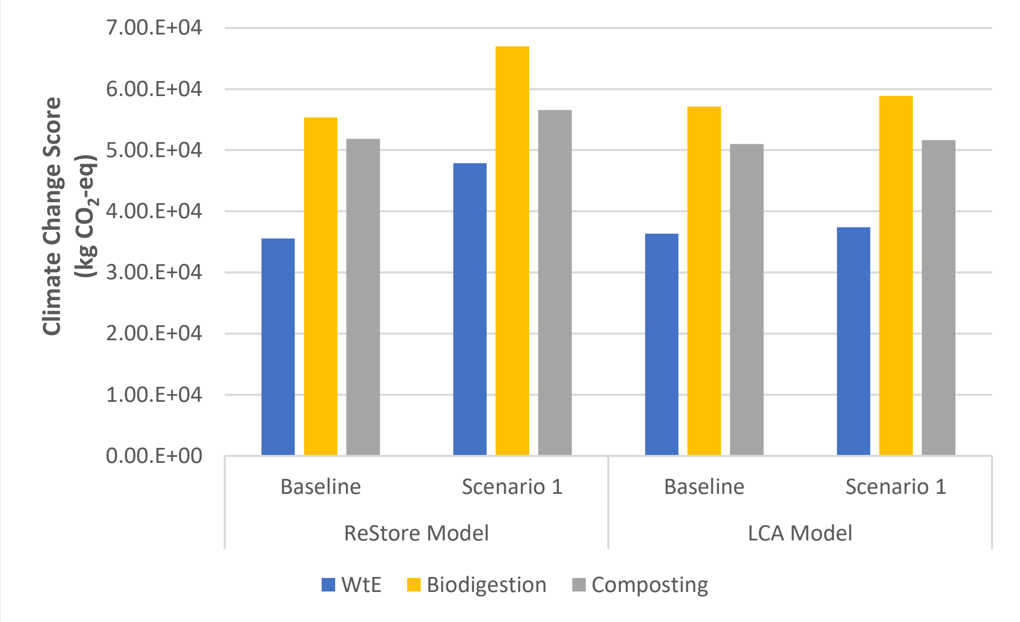

Figure 5.9 Climate change scores for ReStore model where compost replaces peat, using substitution to solve multi-functionality

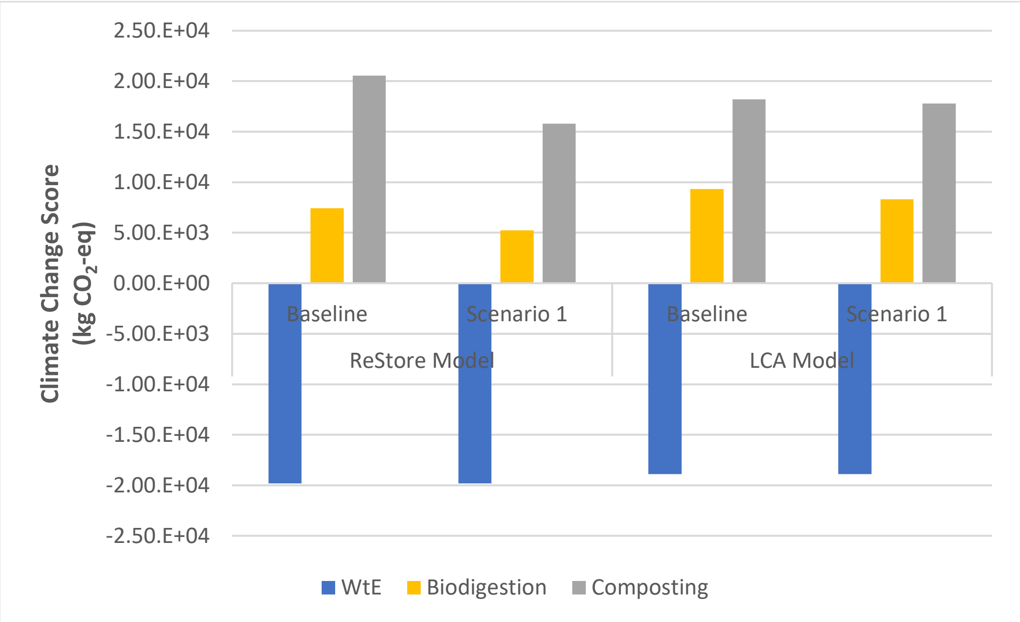

Figure 5.10 Climate change scores for ReStore model where compost replaces peat, using substitution to solve multi-functionality

5.4 Chapter Summary and Conclusion

The information on this chapter becomes the first reference to figure out the answer of the third sub-research question which is "*To what extent does the ReStore model differ with the LCA model in terms of environmental performance for organic waste management options and what are the influencing* *factors?*". The information from this chapter is combined with the discussion elaborated in chapter 6 to determine the complete answer to the third sub-research question.

The characterisation result denotes that results from both models are nearly similar, either from the final climate change score or from the hotspot deployment. Though the results do not hold significant difference, there are several factors which reason the gap present between results. Firstly, the sensitivity analysis made on different types of method to solve multifunctional issues gives the impression that different allocation methods can lead to different outcome. This underscores the importance of the choices made on the selected method as it prescribes considerable impact on the outcome of an LCA study. In all allocation methods assessed in this study, WtE has the least climate change score. However, the subsequent order of impact varies per allocation method where bio-digestion shows the second-highest impact under the system expansion method while this belongs to composting when the allocation method is changed to substitution and economic partitioning.

Secondly, the sensitivity analysis made on different types of equivalent products reveals that each model has a different sensitivity level towards certain parameters. Both models react sensitively when the type of electricity is switched from the Dutch electricity mix to coal rather than when the power supply from natural gas is used. However, in the case of switching to other types of mineral fertiliser such as phosphate and urea, there is no significant difference observed in the result from both models. With respect to the sensitivity over peat, the ReStore model shows a more contrast result while the outcome is more subtle in the LCA model.

Moreover, the sensitivity analysis remarks that differences are discernible in terms of GHG emission factor of several parameters. Among them is the emission factor of mineral fertilisers and peat. The number is found to be higher in ReStore for the case of mineral fertilisers, while peat is affirmed to have larger CO_2-eq value in Ecoinvent. Although the characterisation result for both models are shown to be nearly similar, these factors might explain the minor difference. A more elaborate description on different levels of comparison between both models is given in the next chapter.

Chapter 6
Discussion

This chapter aims to present the discussion by highlighting the comparison between the LCA model and the ReStore model. To achieve this goal, an LCA model was first developed using the data retrieved from ReStore. The result from this model was then compared with the result from ReStore. The comparison is divided into several aspects which are detailed in the separate sub-chapters. By the end of this chapter, a brief conclusion is followed to summarize the main findings and the role and contribution of the LCA model and framework to the ReStore model and vice versa.

6.1 Model Comparison

Having determined the carbon footprint of several organic waste management options by means of LCA, several differences were encountered between the LCA model and the ReStore model on different aspects. This section strives in explaining the differences found between both models based on the result drawn from the characterisation and sensitivity analysis. The comparison is analysed from different levels and perspectives which are discussed in each of the following sub-section, aiming to provide the answer to the third sub-research question: "To what extent does the ReStore model differ with the LCA model in terms of environmental performance for organic waste management options and what are the influencing factors?"

6.1.1 Comparison on the Method

GHG Emission Factor

As can be seen from the characterisation section, the response from both models are almost aligned to each other. This can be expected because both models are being compared on the same state and boundary. Nonetheless, it is most likely that the outcome cannot be exactly the same with one another and this can be grounded on numerous causes. The difference in the result between both models is firstly due to the difference in the method. One of the possible reasoning is due to the different GHG footprints of consumed services defined by ReStore and Ecoinvent background data. This is supported by the result from the sensitivity analysis on the previous chapter which embraces different model behaviour per each introduced variation.

When different scenarios on types electricity were used, both models show corresponding behaviour. Meanwhile, other parameters promote dissimilar response on both models. For instance, when other types of mineral fertiliser were selected, there comes a point when the LCA model shows a decrease in result but the result increases in the ReStore model. Moreover, when peat is chosen over potassium fertiliser, massive changes are observed only in the ReStore model. These results indicate that differences in the assumed GHG emission factor holds a quite prominent role to affect the divergence in the result.

Following this explanation, the GHG emission factor of the consumed services in both model are listed in Table 6.1. It is in clear view that some parameters are indeed have different CO_2 conversion although there are also some parameters with an almost identical conversion value. Among them, the differences are readily perceptible in the case of GHG footprints of mineral fertiliser and peat. It is found that in the LCA model, the conversion number is higher for mineral fertiliser, while the value is lower for peat. These findings explain the different reaction in both models when types of products to be equivalent with compost are modified. The similar behaviour observed in the case of selected types of electricity is due to the fact that the involved economic flows have already exposed a close value of GHG emissions between both models. The result informs that different assumption made on the GHG emission is responsible for the difference in the modeling outcome.

Generally, the determination of the climate change score is derived based on the standardized pre-defined characterisation model (Udo De Haes & Heijungs, 2009). The characterization model for climate change impact category is stemmed from the Intergovernmental Panel on Climate Change (IPCC) (Guinée et al. 2002). The characterisation model provides the basis for the characterisation factor for different greenhouse gases. The characterization factor measures the climate change by translating the radiative forcing into mass-unit of greenhouse gas. The resulted characterisation factor is Global Warming Potential for 100-year time horizon (GWP100) for each GHG emission released to the atmosphere, which has the unit of kg CO_2 equivalent for the final indicator result.

Table 6.1 Comparison on the GHG emission factor between both models

Parameter	**Model**		**Unit**
	ReStore	**LCA**	
Electricity	0.41	0.37	kg CO_2-eq/kWh
Heat	0.036	0.064	kg CO_2-eq/MJ
Diesel	3.88	4.37	kg CO_2-eq/kg
Natural gas	2.11	2.52	kg CO_2-eq/m^3
Potassium fertiliser	0.23	0.46	kg CO_2-eq/kg
Phosphate fertiliser	0.18	1.62	kg CO_2-eq/kg
Nitrogen fertiliser	0.89	3.27	kg CO_2-eq/kg
Peat	0.15	0.023	kg CO_2-eq/kg
Sand	0.012	0.012	kg CO_2-eq/kg

Types of Equivalent Product

Moreover, the type of assumed relevant products to be substituted or expanded appeared to profoundly affect the final result of both models. As the main setting, the generated electricity is assumed to replace 100% of the electricity from the Dutch electricity mix. In order to evaluate the dependency of the outcome on the type of the chosen substituted products, an additional sensitivity analysis was performed. The electricity from WtE and co-generation is changed from fully replacing the Dutch electricity mix to substitute the electricity generated from natural gas and coal.

As shown in the result for system expansion and substitution, a similar trend in results is noticeable for both models in each scenario. The result highlights a massive change which happens to the amount of impact when the type of electricity is switched to coal. This is referred to both models, where the climate change value is almost doubled. In comparison to this, the outcome is less dramatic when natural gas is used. Although variation of types of electricity does affect the GWP results, this is not an extent where relative rankings of alternative change.

Several studies have researched different types of electricity as the equivalent product. Some of them assessed that the generated electricity corresponds with the marginal electricity rates (Nabavi-Pelesaraei et al. 2017; Mondello et al. 2017; Dong et al. 2013) while some researched into the average electricity mix which varies per geographical area (Salemdeeb et al. 2018; Corsten et al. 2013; De Feo & Malvano, 2009). These previous studies support the result obtained from this research, where the results greatly vary according to the type of electricity chosen. Furthermore, the result of this study also goes in line with the findings from Shonfield (2008). In the paper, it was initially assumed that the power generated from municipal incinerators was equivalent to the electricity from the UK grid. Later on, the sensitivity analysis contrast other types of product, which were electricity electricity supplied from natural gas combined-cycle power plants and electricity from coal-fired stations. The results reveal the same trend as observed in this study. The result showed that a switch from natural gas to UK power grid decreased the impact, and the reduction was even larger when the electricity was switched to coal. The paper concluded that switching the gas-powered electricity to UK electricity mix was less sensitive than shifting to coal-based electricity, which fully aligns with the result of this research.

Another sensitivity analysis was carried out on the type of items being replaced by compost. When mineral fertiliser is assumed to be displaced by the produced compost, slight changes are observed in both models regardless of the methods used to solve multifunctional process. However, when peat is selected instead of chemical-based fertiliser, the impact of bio-digestion and composting change more prominently, especially for the ReStore model. As addressed in the previous paragraph and according to the study of Shonfield (2008), changing the basis of the equivalent product brings remarkable consequence to the end result.

6.1.2 Comparison on the Completeness of Process Chain

As previously stated, there are some differences spotted on the GHG footprints of several parameters in both models. Above all other parameters, the disparity is quite large for the GHG value of mineral fertilisers and peat. This is because the dataset used for each model might have different levels of completeness on the included process chain, where in this case, the inclusion of unit process as defined in Ecoinvent might be different with those stated in the external literature used by ReStore. In Ecoinvent, the included processes for mineral fertilisers cover the extraction of raw materials, transport of intermediate products, until transport of fertiliser product from the factory to the regional storehouse (Ecoinvent, 2017). While the CO_2 emission associated to fertiliser in Ecoinvent is defined based on the preceding process chain, the start and endpoint of activities might be different in the literature used by ReStore. The same case also happens to peat. However, the number is now much lower in Ecoinvent compared to what is defined in the ReStore model. For the same reason, this might be because there are some processes that are not taken into account along the cradle-to-gate process chain.

6.1.3 Comparison on the System Definition

Another level of comparison is correlated with the system definition. Looking further on the initial system boundary of ReStore shown in section 4.2.2, it is in high possibility that the model used substitution as the allocation method in the first place. According to the elaboration made in section 4.2.1, some adjustments were made to the original system of ReStore to resemble the system defined in this LCA study. As a default setting, this study goes through system expansion to deal with multifunctional process. Since there is no particular right way on which method should be selected to solve the multifunctional problem, this study also applies substitution and economic allocation method as a sensitivity analysis to investigate the effect of changing the solutions for multifunctional issues towards the final result for all alternatives. The same allocation method has been used in all cases for alternatives in the ReStore model and LCA model.

The sensitivity analysis shows that the choice of methods in solving multi-functionality problems has a remarkable influence on the final outcome, both on the LCA model and the ReStore model. When system expansion is selected, WtE has the best environmental performance due to its relatively low GHG emission while bio-digestion contributes to the highest impact. In the case of substitution, WtE still becomes the most environmentally favourable option, yet it shows a distinctive result for being represented with negative numbers. In this regard, the multifunctional problem is solved by subtracting the avoided burden of products being replaced by WtE, where in this case, the electricity and heat which replaced the production of these goods from the grid. The avoided impact is larger than the impact of the incineration process itself, causing the final result to be negative. This leaves the impact of composting to be the highest because it only produces compost to displace the production of chemical fertilisers, which, if compared to electricity and heat generation, the avoided impact will not be as much.

According to the result, the ranking of each alternative on its climate change score is slightly different when using system expansion compared to when multifunctionality is solved using substitution and economic allocation. All methods convey the same result with regard to the most environmentally friendly option, but the result for the highest CO_2 emission is flipped between system expansion and the other two methods. This can be explained by the procedure of each allocation type. In system expansion, each alternative is expanded to include the co-products that are provided by other alternatives in the defined system, where in this case, when comparing organic waste management service, all possible other co-products produced by other alternatives are taken into account. The impact of the alternative will get larger because now there are more than one function being delivered. However, when doing substitution and economic partitioning, one strives for the same aim, which is making a single functional system out of a multifunctional system. Much of the downstream processes are corrected and the methods only calculate the results for the waste treatment only. Based on this concept, the impact of bio-digestion which is found to be quite large for post-composting and transport are being cancelled out in substitution and economic allocation, which results in a lower climate change score compared to composting.

The results obtained from sensitivity results are in line with those observed in the paper of Nabavi-Pelesarai et al. (2017). This study used the avoided burden approach and negative results were also obtained for the WtE scenario. The study informed that WtE results in the prevention of almost 10% of toxic compounds being released to the atmosphere due to heat and electricity recovery. Moreover, the study indicated the same contributor where most of the global warming impact arose from the incineration process. Along with the research of Parkes et al. (2015) which combined multiple scenarios for handling organic waste, a negative result was also obtained for WtE which was particularly due to the high avoided burdens from the credits of energy production. The negative value indicates environmental benefits and in this regard, Parkes et al. (2015) mentioned that incineration with energy recovery as the most environmentally profitable option compared to other scenarios addressed in the study.

A lot of relevant LCA studies in the field of organic waste applied substitution as the method to solve the multifunctionality issue. On the flip side, only a few studies carried out an environmental evaluation by applying system expansion. Among them are Eriksson et al. (2005) and Mondello et al. (2017). Erikksson et al. (2005) reported that the contribution of waste treatment processing is larger than the contribution of the compensatory system, which supports the findings from this study. The latter study of Mondello et al. (2019) revealed that the main GHG emission was related to the incineration scenario, while the best environmental performance was connected to the composting scenario, which in a complete flip with the results obtained from this study. However, the result from Mondello et al. (2019) underscored that climate change score related to the treatment stage holds the major share towards the total impact, where the similar pattern on the impact contribution is also observed in this study.

Next to this, when economic allocation is performed instead of system expansion and substitution, a rather similar result is obtained as when substitution is used. WtE gains the smallest impact, therefore being the most preferable option. However, in this case, the impact of all alternative is represented by positive value because the impact is partitioned among the functional flows, in which negative result is hardly possible to occur. Right after WtE, bio-digestion is the second preferable option, leaving composting to be the least. When performing economic allocation, the price for wastes and goods is among the most important factor because it determines how the impact will be partitioned among the functional flows. In the case study, the price of produced goods is much higher than the price for collecting the waste, and thus, makes the impact to be mostly allocated to production of co-products from the waste treatment.

The results of applying economic allocation agreed with the result from Sunqvist. (2002). This study analysed the same scenario as addressed in this research. It showed that although composting organic waste was preferable from the welfare and economic parameter, it had higher energy usage and exerted more environmental impact. Thus, for the climate change impact category, composting was deemed as the least favourable options than bio-digestion and incineration. A research performed by Gao et al. (2017) also supported the result from this study where it was informed that composting was considered to contribute most to GWP.

6.1.4 Comparison on the Goal of the Model

Another important aspect to review is the reason of existence and the goal of both models. As the LCA model was developed according to the framework set by ReStore, the purpose-driven in the LCA model complies with the fundamental goal of ReStore, which is to evaluate the environmental impact in terms of climate change value of different waste processing systems for organic municipal waste in the Amsterdam neighbourhood. Thus, both models serve the same end-goal because both models refer to the same function and functional unit.

However, the process goal referring to strategies and procedures to be taken in order to help achieving the desired outcome goals might be different in both models because of the different modelling platform and concepts implemented. Next to the process goal, there is performance goal.

Performance goal set the standards on how the process goals will be performed. In this case, both models are likely to have different performance goals as well, referring to how was the LCA and the ReStore model done. The modelling concepts of LCA implement the generic analysis meant for experts, which takes general approach in evaluating processes and environmental problems. Meanwhile, the performance goal of ReStore is to serve a really detail and specific analysis for practitioners who look for solutions regarding the organic waste treatment. It tries to take into account the dependencies between detailed waste properties, process characteristics, and its consequential emissions. Thus, while the representation of the desired end-state may be equal in both models, the behaviour, strategies, and standards established by both models to accomplish the final purpose are different.

6.2 Degree of Complementary of Both Models

While the previous section has identified the comparison between both models on various levels, this section points out how both models can complement each other. Discussions are then followed on the benefits and limitations of each model which serve as the foundation to answer the last sub-research question of: "*How can the LCA model and the LCA framework contribute to the ReStore model for providing suggestions on modelling the organic waste management and vice versa?*"

6.2.1 The Model *State of the Art*

After knowing to what extent both models differ, the contribution of each model to one another can then be determined. First and foremost, It becomes clear from the case study description that ReStore is an excel-based model where they decompose organic waste on product level and based on its chemical composition. By having the decomposition of organic waste streams on a high level of detail, this allows ReStore to effortlessly handle to which treatment process should a certain organic waste fraction be directed, which makes the model more dynamic. This has become very useful with regard to the fact that not all organic waste is being separated from the source and that not all alternatives can handle the same waste stream. While meat, fish, and dairy products should not be added to composting, almost all organic waste fraction can be included in bio-digestion and WtE (Chen et al. 2011; Trautmann & Olynciw, 2006). ReStore looks at the performance of waste management as a whole system that can be built with various treatment options. ReStore may reflect a closer representation of what the real and actual waste management looks like, which sets ReStore apart from the classic approach of the usual organic waste management.

However, the attention on how organic waste composition can influence the total outcome seems to be lacking in LCA. The Ecoinvent database provides classifications for the rest categories of municipal solid waste, such as paper, glass, and plastic but none is made for organic waste. This is because there is no data available for the distribution of organic waste to different collection strategies. Some municipalities might collect their kitchen and garden waste as mixed biogenic waste, while others might only collect them separately or only collect one of those fractions. The inventory for organic waste is therefore assessed as a mixed fraction of biogenic waste as only data of total amounts of garden and kitchen waste are available (Haupt et al. 2018).

Despite of this, it is still feasible to manually defined different processes for different compositions of organic waste. This means that for certain types of organic waste, different processing routes can be developed in Ecoinvent. However, the extent to which this can be altered in LCA is not as detailed as what is facilitated in ReStore. For instance, it is not possible to directly adjust the protein, carbohydrate, and fat content of certain types of food waste in Ecoinvent. Therefore, it can be inferred that at some point, some parameters in the LCA model are becoming less flexible to adjust than in ReStore model.

By this, ReStore can be considered as a technological model that is more detail and flexible when it comes to the analysis of organic waste stream. It takes specific properties and characteristics of organic waste and assess the impact based on the GHG emission. On the other hand, the LCA model is a rather general one, both in type of processes and type of environmental damages. Besides, the ReStore model has inputs of organic waste with its certain properties and with this, the model can calculate the amount of energy usage and the amount of material consumption. While these input values can be calculated in the ReStore model, this is another feature that cannot be done in the LCA because the process data must be given in. In that sense, the ReStore model may calculate some of the inputs, while in the LCA, the parameter needs to be directly given in as inputs. In this context, the ReStore model excel the LCA model in terms of its accessibility.

6.2.2 Framework and Conceptualisation

Based on Figure 4.1, there are four main stages of managing organic municipal waste within the initial system boundary of ReStore, which are collection, processing, transport, and application. However, it was found that the modelling in ReStore stops at determining the replacement rate of the product from the investigated system instead of taking into account the direct impact of its utilization. For example, in the composting scenario where compost was produced and then transported, the model found the amount of mineral fertilizer that can be substituted with the corresponds amount of the produced HN compost, causing the impact of producing mineral fertilizer to be avoided. The same case also applies to bio-digestion and WtE scenario, where the recycled products and recovered energy displace the competing products or energy from the market. This emission that would, in other cases, have been emitted are avoided and subtracted from the total impact of the system. This shows some contrasts with respect to the LCA methodological framework where this is defined as substitution method in LCA, referring to one of the solutions to solve multifunctional process.

The ReStore model has the input of certain waste quality, energy usage, and other additional inflows to calculate the associated direct emission. On the other hand, all inputs and outputs need to be inserted as inflows and outflows to and from a new process in the LCA model. By this, the ReStore model might overlook that their system actually delivers two functions at once instead of only serving one function, which is normally recognized as solely treating the organic waste. In the processing stage, for example, collected organic waste goes in as an input and converted into certain products. In this case, such process is ascribed to have two functions, where organic waste treatment serves as the first function and the production of relevant goods as the second function, thereby making the system to be multifunctional.

In LCA, multi-functionality is seen as an essential issue. These multifunctional processes need a solution to know exactly how should the environmental impact of these functional flows be allocated to different product systems involved. Some possible solutions include expanding the system boundary, performing substitution, and the partition the impact of a process, as what has been detailed in section 4.2.4, section 5.1.1, and section 5.1.2. By this, ReStore might not recognise the state that multifunctional problem is present in their system and presume the processing phase as a system serving the waste treatment function only. As a consequence, ReStore also does not take into account the procedure on how to deal with multi-functionality issue. In this way, the LCA framework contributes to refine the model representation in a scientifically robust and accurate manner. The holistic approach of LCA is beneficial for ReStore to think more critically about comparable system boundaries between different alternative. It will also help ReStore to be more aware about the multifunctional systems and to address it more consistently.

6.2.3 Approach and Interpretation

Taking along the ReStore model within the LCA method will provide opportunities for ReStore to embrace how the LCA approach and theory works. The coherent stages of LCA are a great fit to conduct a systematic analysis with a high level of accuracy. More specifically, the goal and scope phase will shape the research objective and help in describing a clearer system boundary. The inventory analysis and the impact assessment phase might seem to be rather universal but has an important role in translating the result into certain impact classification transparently and extensively. The interpretation phase serves distinctive investigation by providing the model with in-depth evaluation from diverse perspectives. It evaluates the completeness, consistency, and robustness of the study which adds to a valuable complementary. The sensitivity analysis denotes several parameters to be more sensitive over others such as the types of methods to solve the multifunctional process, the emission factor definition, and the forms of equivalent products. This whole package provides a thorough evaluation of the study that promotes a systematic result interpretation and thus, which helps in defining well-substantiated conclusions.

Other than that, based on the complete characterization result in Appendix C, it can be seen that the result for each alternative varies per impact category. Though WtE appears to always become the least polluting alternative, the outcome on which option is associated with the most emission is often shifted between bio-digestion and composting. Thus, it is wise to include other impact categories to frame the result from a bigger picture. However, to include impact categories other than climate change will be less handy in ReStore because the measurement unit for each impact category still needs to be defined separately. On the contrary, this can be done straightforwardly in the LCA model due to the previous elaboration on the built-in feature of the characterisation model. Due to this characteristic, the LCA model will add to a more complete overview in providing information as well as interpreting the result from different impact perspectives.

6.3 Chapter Summary and Conclusion

This chapter starts with a reflection on the results where the elaboration on models comparison are discussed. It explains the differences in results between both models while giving the answer to the third research question of "*To what extent does the ReStore model differ with the LCA model in terms of environmental performance for organic waste management options and what are the influencing factors?*"

Both models show similarities on how certain aspects are framed. This is reflected on the overall trend for the total emission of organic waste management system from both model that is align to one another. The lowest carbon footprint is correlated to WtE. The trend is peaked in bio-digestion and levelling down slightly towards composting, indicating bio-digestion with the topmost environmental burden. The fact that the result from both models are pretty close is because both models have the same system boundary, with the same cut-offs and same allocation method applied. Nonetheless, minor result gaps were observed between the results of both models which can be ascribed to several factors.

The first line of reasoning deals with the difference in the method and tool. ReStore built their model in Excel and uses the GHG emission factor compiled from external sources for their process data. The LCA model was constructed in CMLCA in which it is incorporated with background processes from Ecoinvent v3.4 database. Therefore, the LCA model includes the impact assessments as drafted by Ecoinvent. As becomes clear from Table 6.1, some parameters used in both models have different CO_2 equivalent value. The presumption on what this may cause becomes even more visible from the sensitivity analysis. A different behaviour was observed in both models when types of product to be equivalent with compost is shifted from potassium fertiliser to urea, phosphate fertiliser, and peat respectively, which is attributed to the large discrepancies found in the GHG emission of these products. This explains one of the main factors to cause the difference in the result. Furthermore, it was observed that both models serve different process goals and performance goals, although both aim for the same final purpose. The generic approach of LCA sets this method to make the analysis more universal. Meanwhile, the modelling in ReStore was done in a more specific manner, resulting in a more specialized analysis.

Furthermore, this chapter provides insight from the point of view on what can be done in the LCA model that cannot be done in the ReStore model and vice versa. It is noted that the framework of LCA helps ReStore to define their model in a more structural and systematic way which can be explained through several reasoning. The explanation is oriented to formulate the answer to the last sub-research question which is "*How can the LCA model and the concept of LCA contribute to the ReStore model for providing suggestions on modelling the organic waste management and vice versa?*"

Firstly, the LCA framework helps ReStore to distinguish between input, output, and process more clearly. Input is an economic flow that goes into a process through which another economic flow leaves as an output. By defining this in a clearer way, the model is able to determine which flows are the functional flow.

Secondly, based on the previous feature, the model can set a process with more than one function apart since this will lead to another prominent concern, which is the multifunctional system. The holistic approach of LCA helps ReStore to be more conscious with regard to this matter that was originally overlooked in the ReStore system. Multifunctional process is a process that possesses two functions at the same time and this is an issue in LCA that needs a solution. This is important because the impact needs to be allocated to the right functional flow.

Thirdly, a clear boundary is given on which processes belong to foreground process and which processes are associated with background processes in the LCA model, while ReStore does not distinguish this context. This will help in giving a clear overview and boundary on how complex and extensive the system is going to be modelled.

Fourthly, by realising the existence of multifunctional issue as well as the clear system boundary differentiation will help ReStore to differentiate these concepts better. In their initial system boundary, avoided products are still included in the system while this is actually one of the methods in solving multifunctionality and is not part of the process chain. Therefore, it is important for ReStore to be consistent and aware in the first place on which method they want to base their analysis on.

Fifthly, as become apparent from the full characterisation result, the LCA concept is able to derive the whole overview of a certain alternative because it includes the complete impact category from a certain impact family. This will also add as an essential benefit for ReStore to include other groups of impact to make the result elaboration more extensive.

Sixthly, the LCA framework gives the opportunity to evaluate the completeness and robustness of the system and determine the sensitivity of certain parameters. This will contribute to a more detail analysis while examining the model's consistency level and make the analysis more conclusive where a more coherent conclusion can be derived.

While the LCA model and its concept shares imperative roles to the ReStore model, the LCA model model could also learn from the ReStore model in some ways. *Firstly*, the ReStore model is able to handle changes in organic waste composition more flexibly rather than the LCA model. *Secondly*, ReStore contributes to a very detail and specific analysis, that it is capable of taking into account typical waste properties and process characteristics. The LCA model can learn from this characteristic to make its analysis more specific. *Lastly*, the ReStore model is accounted for its accessibility, that it is simple enough to be familiarly used by non-experts, but detailed enough to describe specific situations. This is something that is not attributable to LCA as it is a complex tool and its practice is often a lengthy process.

Chapter 7

Conclusions and Recommendations

This chapter entails to reflect back on the results and summarize the findings and lesson-learned throughout this study. In the first section of this chapter, each sub-research question is reiterated and a conclusion to answer the main research question is drawn. Next to this, the study limitations are provided in section 7.2 to list down some possible constraints. In section 7.3, the implications of this study in terms of its contribution to academic and society are explicated. Lastly, propositions for the ReStore model and possible future research are elaborated in section 7.4.

7.1 Conclusions

This study aims to conduct an LCA of managing organic municipal waste in the Amsterdam neighbourhood for a year and to compare the results between the LCA model and the ReStore model. Considering this, the following main research question was proposed: *What is the carbon footprint of bio-digestion and composting as organic waste management alternatives in the Amsterdam neighbourhood towards the current practice of Waste to Energy (WtE) based on the LCA methodology compared to the model developed by ReStore?* In order to answer this main research question, four sub-questions have been developed as detailed in section 1.4. In this chapter, the pre-defined sub-questions are answered individually to subsequently provide the answer to the main research question.

1st sub-question: What are the characteristics of the ReStore model in evaluating the municipal waste management in the Amsterdam neighbourhood?

ReStore is an excel-based model that assesses the impact of different options for managing organic waste based on the environmental, economic, and social perspective. The data on organic waste was collected from the public data that provides waste decomposition on the product level. The model then differentiates this waste input to cover protein, fat, carbohydrate, water, and ash content. In the model, different scenarios were developed and compared with WtE as the current measure of treating organic waste, which serves as the baseline scheme. As stated in their initial system definition in section 4.2.2, organic waste is being processed to bio-digestion, composting, and vermicomposting. The composting and bio-digestion option can be modelled in a centralised and decentralised manner within the model.

In addition to the environmental assessment, the economic impact was estimated by measuring the operational costs, investment costs, and financial benefits for each processing step. The social impact surveyed the social added value of organic waste processing. This impression was approached through the social cohesion, cooperative participation, and educational development as the represented indicators. ReStore took into account the organic waste management scheme starting from the waste collection process all the way until the products are transported to end users. The application of the products by end users was the last process to be described. The outline and structure of the ReStore model serves as the reference to construct the LCA model.

2nd sub-question: Taking the model developed by ReStore as a starting point, what is the carbon footprint of WtE, bio-digestion, and composting within the LCA perspective?

The climate change scores based on the result from ReStore are 35,557 kg CO_2 for WtE, 55,386 kg CO_2 for bio-digestion and 51,184 kg CO_2 for composting. Meanwhile, the LCA on organic waste management for WtE, bio-digestion, and composting shows a total annual emission of 36,350 kg CO_2, 57,152 kg CO_2, and 51,026 kg CO_2 respectively. It is important to note that these are the results based on system expansion which was used as the baseline setting to solve multifunctionality issue. The largest contributor to the overall impact for all three alternatives comes from the processing stage, where it contributes to more to around 79-86% of the total CO_2 emission in the LCA model and 84-87% of the total CO_2 emission in the ReStore model. The contribution of collection and transport are seen to have the same pattern of contribution per each alternative for both models.

3rd sub-question: To what extent does the ReStore model differ with the LCA model in terms of environmental performance for organic waste management options and what are the influencing factors?

It becomes clear from the characterisation result that both studies yield quite similar outcomes, either on the final result, order of impact, or on the hotspot deployment. In both models, bio-digestion and composting are less environmentally favourable than WtE because of its higher climate change score. Another similarity is emphasized from the contribution analysis. In both models, processing consistently represents most of the CO_2 emission, while the impact of transport and collection varies per alternative and follow the same trend. By this, it can be concluded that both models seem to follow an identical behaviour, which can be expected because both models have been adapted to resemble the same system definition and because the same allocation method has been performed.

Nevertheless, there comes a point where some differences were discovered. This can be explained through the following influencing factors. First is the difference in the GHG emission addressed in Ecoinvent and ReStore, especially for mineral fertilisers and peat. This is then related to the second reason, which is the difference in the completeness of process chain of these goods. Furthermore, it was found that both models serve different goals, in terms of its process and performance. The LCA model is meant to provide a rather general analysis for experts while the ReStore model is built to comprehend a specific evaluation intended for non-experts and practitioners.

4th sub-question: How can the LCA model and LCA framework contribute to the ReStore model for providing suggestions on modelling the organic waste management and vice versa?

As become apparent now, differences found between both models are quite tangible which may be due to several factors explained beforehand. With these being said, it can be analysed how the LCA model and the LCA perspective might help in offering recommendations for ReStore to find some areas of improvement. First, the concept of LCA will guide ReStore to clarify their system definition. ReStore might want to define their system boundary more transparently on the extent to which scope they want their model to handle and not to mix up between the included unit process and the method use to solve multifunctional process. Next, a more extensive representation of results can be achieved because LCA helps to quantify the environmental impacts from wide-range impact categories. This will help ReStore to assess each organic waste scenario from a complete perspective and thus, aids to draw a more profound and extensive conclusion. Moreover, taking the ReStore model along the systematic approach of LCA has helped ReStore to understand the iterative stages of LCA, opening the path for ReStore to make the modelling more structured, complete, consistent, and robust, which will be a solid foundation to provide responses to actions.

Furthermore, the knowledge from ReStore has contributed to inspire the LCA model to be more specific with regard to the modelling and analysis. Secondly, the LCA model may learn about flexibility from the ReStore model in terms of handling changes in the waste composition. Finally, the ReStore model is able to calculate some of the required inputs, whereas this needs to be readily inserted in the LCA. Hence, this accessibility enclosed in the ReStore model adds as another learning point for the LCA model.

Main research question: What is the carbon footprint of bio-digestion and composting as organic waste management alternatives in the Amsterdam neighbourhood towards the current practice of Waste to Energy (WtE) based on the LCA methodology compared to the model developed by ReStore?

The answer to this main research question is built upon the answer from previous sub-research questions. According to the evaluation through the LCA methodology, the carbon footprint of bio-digestion and composting are 55,386 kg CO_2-eq and 51,184 kg CO_2-eq in contrast to the existing scheme of WtE which has the carbon footprint of 35,557 kg CO_2-eq. This results in a close outcome compared to those obtained from the model developed by ReStore which has the carbon footprint of bio-digestion and composting of 57,152 kg CO_2-eq and 51,026 kg CO_2-eq towards WtE with the value of 36,350 kg CO_2-eq.

This research has shown that the modelling results have a strong reliance on the types of methods used to solve the multifunctional process and the assumptions addressed in the study. The initial characterisation result shows that WtE is the most environmentally favourable option in contrast to the other two options. The second-largest climate change score is composting and leave composting to be the highest CO_2 emitter. In further evaluation of these results through sensitivity analysis, the results vary for every adjustment introduced. After all, despite all these modifications, the results confirm that neither bio-digestion nor composting are seen as the preferably option towards WtE.

7.2 Study Limitations

Some limitations have been encountered during this study which could be considered crucial in the light of future research. First of all, it is quite difficult to obtain data for background processes within the Netherlands. Therefore, most of the data used to model the system under-studied were sourced from Europe globally. However, using the data for other countries as a proxy does not seem sufficient to realistically interpret the organic waste management characteristics in the Netherlands specifically and to accurately represent its emission.

Furthermore, this study used the Ecoinvent v3.4 database to provide data for background processes. The economic flows from Ecoinvent v3.4 are a result of accumulated data of different resources that in some cases do not reflect the Netherlands context. Some examples of these processes are consumables production and production of equivalent product such as fertiliser, where most of them are adapted to the circumstances of the European Union. However, it is beyond the scope of this study to adjust these data to the Netherlands context. Therefore, by assuming that these data are also suitable to be implemented in the Netherlands could possibly make the characterization result to be underestimated.

LCA is an environmental assessment tool and thus, it does not encompass the economic and social aspect. Therefore, the assessment made in this study did not include the economic and social impact of the proposed organic waste management alternative. In fact, to define the whole sustainable performance of a certain system, it is best to incorporate all pillars of sustainability. Hence it is important to also include the economic and social aspects with regard to the cost and revenue of managing organic municipal waste and measuring the awareness of residents in a given area to separate their organic waste.

As explained in the definition of the system boundary, this study only models three ways of managing organic municipal waste, namely WtE, bio-digestion, and composting, where all of them are assumed to be performed centrally. However, there are more various treatments for managing organic waste, such as vermicomposting, composting through the presence of insects, heat-moisture reaction, and dry-heat treatment. Next to this, the decentralised option where organic waste is treated within the households is also considered important to assess. Several treatments as selected in this study can also be examined from the decentralised perspective, such as decentralised composting, decentralised bio-digestion, and another possible option such as the use of food waste processor under the kitchen sink.

Furthermore, another limitation is related to assumptions made on the replacement rate of avoided products, type of substituted products, transport distance, energy consumption, and conversion efficiency which can lead to several uncertainties. This shows that either the LCA model or the ReStore model is pertaining to a lot of assumptions, which makes it rather subjective to derive valid recommendations.

After all, due to the inherent holistic approach of LCA, this study attempts to encompass all economic and environmental flows associated with the functional unit of managing organic fraction municipal solid waste in the Amsterdam neighbourhood for a year. While this is done to the best effort, it is possible that some details and background processes are still overlooked.

7.3 Scientific and Societal Contribution

7.3.1 Scientific Contribution

This research demonstrates its contribution towards the academic field. Several studies informed that the environmental impact in the context of organic waste management is genuinely specific as it differs largely per country as well as per processing plant (Lou 2008; Parkes et al. 2015; Nabavi-Pelesarai et al. 2015). These studies recommended undertaking further research to investigate a specific geographical location for its methods in handling organic waste. Numerous studies have been incorporated the LCA framework in the research of organic waste management practice that mostly lies in the Northern or Southern European region (Costa et al. 2019; Oliveira et al. 2016; Bernstad & Jansen, 2012; De Feo & Malvano, 2009), while the research in the spatial context of the Netherlands remains underexplored. The focus of this study, therefore, conducts a further evaluation to contribute to the existing scientific knowledge gap, which adds to the academic relevance of this study.

This research aims to reproduce the model developed by ReStore by means of LCA where subsequently, both models are compared in terms of the data, modelling concept, system definitions, and used assumptions. The comparison, which has been successfully performed, is correlated to the strict framework applied in the first place. Both models were carefully aligned and structured by investigating the involved components, characteristics, interactions, and mechanisms. The initial system definition of ReStore was adjusted and this new model structure was applied to the LCA model, resulting in two models with the same structure and system boundary that are comparable. Thus, when taking both models on one-on-one comparison, it is possible to track back on what has been changed and what remains the same. Hence, when differences were spotted on the behaviour or result from both models, the causal factor can be straightforwardly detected. All of this elaboration made on the procedure of executing the comparison on both models amplifies the additional scientific contribution of the study.

7.3.2 Societal Contribution

As regard to the societal relevance, this research carried out the life cycle thinking analysis that is important from the macro and the meso level of analysis. At the macro level, the results of the research could benefit the municipality to integrate the life cycle approach into their decision-making procedure in pursue of the appropriate organic waste treatment from the ecological point of view. Speaking of the meso level, the outcome of this research will benefit waste management industries as this will enable companies to introduce several process improvements that may increase their sustainability performance. The evaluation through the LCA perspective is expected to facilitate waste management companies in their operational processes as well as their strategic planning in measuring and identifying the environmental sustainability of their business. Since this study focuses on the case of the Amsterdam neighbourhood, the social contribution particularly relates to stakeholders and waste management industries within this context.

7.4 Recommendations

7.4.1 Recommendations for ReStore

From this research, it has become clear that the preferred way to manage organic waste is heavily affected by the types of methods selected to deal with the multifunctional issue. The most environmentally favourable option is settled to WtE for all allocation methods, yet, the decision cannot be forthrightly made on which option yields the highest CO_2 emission between bio-digestion and composting. As become apparent, when choosing system expansion, bio-digestion is the least preferred way of managing organic waste in the Amsterdam neighbourhood while when using substitution and economic allocation, composting turns out to be the least favourable option. It is therefore recommended for ReStore to take this knowledge into account when deciding on how they will proceed with the system evaluation of the overall performance of organic waste management.

In accordance to this, ReStore might want to define their system boundary more clearly. ReStore needs to be more consistent and not to mix up the concept of solving multifunctional process with the included unit process. Moreover, in attempting to a more in-depth conclusion, ReStore might want to consider the inclusion of several other impact categories aside from climate change. This study also shows the importance of assessing several parameters since it brings distinguished effects to the final outcome. For instance, the type of electricity and fertiliser substituted could vary according to the adopted assumption and ReStore needs to be aware of its consequences to the result interpretation. To this, ReStore might want to carry out extra analysis to have these parameters evaluated further through sensitivity analysis. Furthermore, as can be seen that most gains lie in the processing stage, this can also be assessed through additional sensitivity analysis by changing several related variables.

7.4.2 Recommendations for Future Research

It is important to notice that the above-mentioned findings and conclusions derived from this study were grounded on a number of assumptions as explained in section 4.2.3.1. Therefore, it would be a good starting point to refine and reproduce this study to see whether the same results and conclusions prevail. This can firstly be done through a more refined and accurate data collection in order to avoid using data from other regions as an estimation. Another option for further research is to include more options for organic waste management by investigating the potential of other alternatives stated beyond this study. Furthermore, it is then interesting to know the possibility of managing organic waste in a decentralised manner and whether this option is opted to be more environmentally friendly because no transport is needed to transfer the waste to the central collection since waste is being treated on-site.

The next point to research further is to include the social and economic impact to complement the results and conclusions from this study as well as to appraise the whole system of organic waste management from the lens of all sustainability pillars. Construction, demolition, and final disposal of capital goods are not included for their emission in this study. However, this is an important aspect to the affect the total costs of the system which needs to be included in the part of the financial assessment. For the social aspect, this relates to the evaluation of the awareness activities about organic household waste separation, the involvement and integration of all professional sectors and the communication mechanisms between them, the number of participations and initiatives arose locally, etc. By this, the overall impacts and benefits of all environmental, social, and economic aspects can be evaluated and used as a guideline in the decision making process towards a more sustainable organic waste management.

The study shows that some parameters are rather sensitive and therefore, it is necessary to further analyse several parameters that might be influential to the result. One potential opportunity is the analysis on the robustness based on the contribution analysis result. It justifies that a high share of the impact comes from the processing stage, indicating that this parameter is important to be analysed further. Therefore, it would be interesting to further examine some relevant parameters involved in this process and to what extent are these parameters have the role in influencing the result. This will bring the result interpretation to one level higher where suggestions for improvement in the organic waste management sector can be provided for a better organic waste management option on a city level or even on the global level.

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Appendix

Appendix A. Inventory Data

A.1 Inventory Data for WtE

Process = [P14890] Collection to WtE			
Economic inflows			
Label	Name	Value	Unit
[G7419]	transport, freight, lorry 16-32 metric ton, EURO6_transport, freight, lorry 16-32 metric ton, EURO6[RER]	4.04E+04	ton kilometer
[W14907]	OFMSW to WtE	2.47E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[W14890]	Collected OFMSW to WtE	2.47E+05	kilogram

Process = [P14891] Processing to WtE			
Economic inflows			
Label	Name	Value	Unit
[G456]	heat, district or industrial, natural gas_heat production, natural gas, at boiler condensing modulating >100kW[Europe without Switzerland]	12.2	megajoule
[G2907]	electricity, low voltage_market for electricity, low voltage[NL]	0.73	kilowatt hour
[G5827]	ammonia, liquid_market for ammonia, liquid[RER]	8.08	kilogram
[G6507]	sodium hydroxide, without water, in 50% solution state_market for sodium hydroxide, without water, in 50% solution state[GLO]	354	kilogram
[W14890]	Collected OFMSW to WtE	2.47E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[G14891]	Electricity from WtE	4.85E+04	kilowatt hour
[G14892]	Heat from WtE	1.17E+05	megajoule
[W14893]	Fly ash from WtE	140	kilogram
[W14894]	Bottom ash from WtE	1.75E+03	kilogram

Process = [P14892] Transport for fly ash			
Economic inflows			
Label	Name	Value	Unit
[G11048]	transport, freight, lorry 7.5-16 metric ton, EURO6_transport, freight, lorry 7.5-16 metric ton, EURO6[RER]	51.93	ton kilometer
[W14893]	Fly ash from WtE	140	kilogram

Process = [P14893] Transport for bottom ash			
Economic inflows			
Label	Name	Value	Unit
[G11048]	transport, freight, lorry 7.5-16 metric ton, EURO6_transport, freight, lorry 7.5-16 metric ton, EURO6[RER]	167.49	ton kilometer
[W14894]	Bottom ash from WtE	1.75E+03	kilogram
Economic outflows			
Label	Name	Value	Unit
[G14904]	Transported bottom ash	1.75E+03	kilogram

A.2 Inventory Data for Bio-Digestion

Process = [P14894] Collection to Centralised AD			
Economic inflows			
Label	Name	Value	Unit
[G7419]	transport, freight, lorry 16-32 metric ton, EURO6_transport, freight, lorry 16-32 metric ton, EURO6[RER]	3.35E+04	ton kilometer
[W14895]	OFMSW to Centralised AD	2.47E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[W14896]	Collected OFMSW to digester	1.23E+05	kilogram
[W14908]	Collected OFMSW to post-compost	1.23E+05	kilogram

Process = [P14895] Processing to Digester (Biogas)			
Economic inflows			
Label	Name	Value	Unit
[G456]	heat, district or industrial, natural gas_heat production, natural gas, at boiler condensing modulating >100kW[Europe without Switzerland]	8.44E+03	megajoule
[G2907]	electricity, low voltage_market for electricity, low voltage[NL]	1.60E+03	kilowatt hour
[G6092]	diesel_petroleum refinery operation[Europe without Switzerland]	123	litre
[W14896]	Collected OFMSW to digester	1.23E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[G14897]	Biogas (CAD)	1.51E+04	cubic meter
[W14910]	Digestate	1.06E+05	kilogram

Process = [P14902] Processing to Post-Composting			
Economic inflows			
Label	Name	Value	Unit
[G2907]	electricity, low voltage_market for electricity, low voltage[NL]	8.14E+03	kilowatt hour
[G6092]	diesel_petroleum refinery operation[Europe without Switzerland]	333	litre
[W14908]	Collected OFMSW to post-compost	1.23E+05	kilogram
[W14910]	Digestate	1.06E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[G14898]	HN Compost (AD)	2.78E+05	kilogram

Process = [P14900] Biogas Cogeneration			
Economic inflows			
Label	Name	Value	Unit
[G14897]	Biogas (CAD)	1.51E+03	cubic meter
Economic outflows			
Label	Name	Value	Unit
[G14904]	Electricity from CHP	2.25E+03	kilowatt hour
[G14905]	Heat from CHP	9.70E+03	megajoule

Process = [P14901] Biogas Scrubbing			
Economic inflows			
Label	Name	Value	Unit
[G2907]	electricity, low voltage_market for electricity, low voltage[NL]	4.36E+03	kilowatt hour
[G14897]	Biogas (CAD)	1.36E+04	cubic meter
Economic outflows			
Label	Name	Value	Unit
[G14906]	Purified Biogas	7.32E+03	cubic meter

Process = [P14896] Transport of HN Compost (AD)			
Economic inflows			
Label	Name	Value	Unit
[G7419]	transport, freight, lorry 16-32 metric ton, EURO6_transport, freight, lorry 16-32 metric ton, EURO6[RER]	4.14E+04	ton kilometer
[G14898]	HN Compost (AD)	2.78E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[G14899]	Transported HN Compost (AD)	2.78E+05	kilogram

A.3 Inventory Data for Composting

Process = [P14897] Collection to Centralised Composting			
Economic inflows			
Label	Name	Value	Unit
[G7419]	transport, freight, lorry 16-32 metric ton, EURO6_transport, freight, lorry 16-32 metric ton, EURO6[RER]	2.73E+04	ton kilometer
[W14900]	OFMSW to Centralised Composting	2.47E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[W14901]	Collected OFMSW to centralised composting	2.47E+05	kilogram

Process = [P14898] Processing Centralised Composting			
Economic inflows			
Label	Name	Value	Unit
[G2907]	electricity, low voltage_market for electricity, low voltage[NL]	1.50E+04	kilowatt hour
[G6092]	diesel_petroleum refinery operation[Europe without Switzerland]	227	litre
[W14901]	Collected OFMSW to centralised composting	2.47E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[G14902]	HN Compost (C)	1.13E+05	kilogram

Process = [P14899] Transport of HN Compost (C)			
Economic inflows			
Label	Name	Value	Unit
[G7419]	transport, freight, lorry 16-32 metric ton, EURO6_transport, freight, lorry 16-32 metric ton, EURO6[RER]	1.69E+04	ton kilometer
[G14902]	HN Compost (C)	1.13E+05	kilogram
Economic outflows			
Label	Name	Value	Unit
[G14903]	Transported HN Compost (C)	1.13E+05	kilogram

Appendix B. Inventory Result

The result of inventory table is presented on the supplementary appendices excel file.

Appendix C. Characterization Result

Please note that throughout this study only the climate change impact category is evaluated. Thus, no normalisation is needed since this study do not compare one impact category with the others. The complete characterisation result for the rest impact categories is shown in Table C1.

Table C1. Complete characterisation result per alternative per given functional unit

Impact Category	WtE	Bio-digestion	Composting	Unit
Acidification	6.23.E+01	4.43.E+02	4.78.E+02	kg SO2-Eq
Climate change	***3.64.E+04***	***5.72.E+04***	***5.10.E+04***	kg CO2-Eq
Eutrophication	1.66.E+01	1.09.E+02	1.17.E+02	kg PO4-Eq
Freshwater aquatic ecotoxicity	4.17.E+03	7.67.E+03	7.17.E+03	kg 1,4-DCB-Eq
Human toxicity	1.17.E+04	1.67.E+04	1.39.E+04	kg 1,4-DCB-Eq
Photochemical oxidation	4.18.E+00	5.86.E+00	4.64.E+00	kg ethylene-Eq
Stratospheric ozone depletion	3.23.E-03	5.47.E-03	4.35.E-03	kg CFC-11-Eq
Terrestrial ecotoxicity	4.63.E+01	9.24.E+01	8.18.E+01	kg 1,4-DCB-Eq
ADP minerals	7.91.E-01	1.26.E+00	8.80.E-01	kg Sb-Eq
ADP fossils	9.34.E+05	1.14.E+06	1.05.E+06	megajoule

Appendix D. Contribution Analysis

D.1 Contribution Analysis for WtE

D.1.1 WtE alternative

Label	Impact Category	[A44] Collection	[A48] Processing WtE	[A46] Transport of bottom ash	[A47] Transport of fly ash	Total	Unit
[C41]	Acidification	1.38.E+01	8.38.E-02	8.38.E-02	2.60.E-02	4.43.E+01	kg SO2-Eq
[C43]	***Climate change***	***5.94.E+03***	***3.53.E+01***	***3.53.E+01***	***1.10.E+01***	***3.24.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	2.89.E+00	1.85.E-02	1.85.E-02	5.74.E-03	1.43.E+01	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	5.86.E+02	3.93.E+00	3.93.E+00	1.22.E+00	2.71.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	2.67.E+03	1.54.E+01	1.54.E+01	4.76.E+00	7.66.E+03	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	8.91.E-01	5.39.E-03	5.39.E-03	1.67.E-03	2.86.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	1.09.E-03	6.34.E-06	6.34.E-06	1.96.E-06	2.99.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	1.30.E+01	7.75.E-02	7.75.E-02	2.40.E-02	4.01.E+01	kg 1,4-DCB-Eq
[C720]	ADP minerals	3.19.E-01	2.48.E-03	2.48.E-03	7.70.E-04	4.68.E-01	kg Sb-Eq
[C729]	ADP fossils	8.99.E+04	5.28.E+02	5.28.E+02	1.64.E+02	5.70.E+05	megajoule

D.1.2 Expanded conventional system, including the conventional variants of services that are delivered by the other two alternatives (AD and CC)

Label	Impact Category	[A75] Potassium Fertiliser (CC)	[A79] Natural gas (AD)	[A80] Potassium Fertiliser (AD)	[A81] Electricity (AD)	Total	Unit
[C41]	Acidification	1.30.E+00	1.42.E+01	1.96.E+00	5.38.E-01	1.80.E+01	kg SO2-Eq
[C43]	***Climate change***	***3.35.E+02***	***2.05.E+03***	***5.05.E+02***	***1.07.E+03***	***3.96.E+03***	***kg CO2-Eq***
[C49]	Eutrophication	5.67.E-01	7.86.E-01	8.56.E-01	1.03.E-01	2.31.E+00	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	1.76.E+02	1.01.E+03	2.65.E+02	9.33.E+00	1.46.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	5.47.E+02	2.49.E+03	8.25.E+02	1.42.E+02	4.00.E+03	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	7.90.E-02	1.07.E+00	1.19.E-01	5.05.E-02	1.32.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	3.70.E-05	5.72.E-05	5.58.E-05	8.81.E-05	2.38.E-04	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	1.39.E+00	2.56.E+00	2.10.E+00	1.64.E-01	6.21.E+00	kg 1,4-DCB-Eq
[C720]	ADP minerals	1.27.E-01	3.78.E-03	1.91.E-01	9.50.E-04	3.23.E-01	kg Sb-Eq
[C729]	ADP fossils	5.60.E+03	3.34.E+05	8.45.E+03	1.67.E+04	5.70.E+05	megajoule

D.1.3 Total Impact from WtE

Label	Impact Category	Total Impact	Unit
[C41]	Acidification	6.23.E+01	kg SO2-Eq
[C43]	***Climate change***	***3.64.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	1.66.E+01	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	4.17.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	1.17.E+04	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	4.18.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	3.23.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	4.63.E+01	kg 1,4-DCB-Eq
[C720]	ADP minerals	7.91.E-01	kg Sb-Eq
[C729]	ADP fossils	9.34.E+05	megajoule

D.1.4 Percentage Contribution Result for WtE

Label	Impact Category	Collection	Processing	Transport	Total
[C41]	Acidification	22.15%	77.68%	0.18%	100.00%
[C43]	***Climate change***	***16.34%***	***83.53%***	***0.13%***	***100.00%***
[C49]	Eutrophication	17.38%	82.47%	0.15%	100.00%
[C53]	Freshwater aquatic ecotoxicity	14.05%	85.83%	0.12%	100.00%
[C61]	Human toxicity	22.89%	76.94%	0.17%	100.00%
[C76]	Photochemical oxidation	21.33%	78.50%	0.17%	100.00%
[C86]	Stratospheric ozone depletion	33.78%	65.96%	0.26%	100.00%
[C90]	Terrestrial ecotoxicity	28.07%	71.71%	0.22%	100.00%
[C720]	ADP minerals	40.33%	59.26%	0.41%	100.00%
[C729]	ADP fossils	9.62%	90.30%	0.07%	100.00%

D.2 Contribution Result for Bio-Digestion

D.2.1 Bio-digestion alternative

Label	Name	[A49] Collection	[A55] Digestion	[A56] Post-compost	[A57] Co-generation	[A58] Scrubbing	[A59] Transport of Compost	Total	Unit
[C41]	Acidification	1.25.E+01	1.69.E+01	3.77.E+02	1.18.E+00	4.57.E+00	1.55.E+01	4.28.E+02	kg SO2-Eq
[C43]	***Climate change***	***5.35.E+03***	***5.27.E+03***	***1.00.E+04***	***1.08.E+03***	***2.66.E+03***	***6.62.E+03***	***3.10.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	2.66.E+00	2.48.E+00	9.23.E+01	4.56.E-01	4.21.E+00	3.28.E+00	1.05.E+02	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	5.40.E+02	1.53.E+03	3.02.E+03	8.49.E+01	1.37.E+03	6.67.E+02	7.21.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	2.42.E+03	2.95.E+03	3.12.E+03	1.89.E+02	8.87.E+02	2.99.E+03	1.26.E+04	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	8.05.E-01	1.61.E+00	7.92.E-01	7.66.E-02	2.05.E-01	9.95.E-01	4.48.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	9.93.E-04	2.62.E-04	5.83.E-04	6.30.E-05	1.42.E-04	1.23.E-03	3.27.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	1.19.E+01	8.82.E+00	3.38.E+01	1.04.E+00	1.58.E+01	1.47.E+01	8.61.E+01	kg 1,4-DCB-Eq
[C720]	ADP minerals	2.89.E-01	2.02.E-02	3.92.E-01	4.14.E-03	4.22.E-02	3.58.E-01	1.11.E+00	kg Sb-Eq
[C729]	ADP fossils	8.11.E+04	3.67.E+05	1.16.E+05	1.95.E+04	4.54.E+04	1.00.E+05	7.29.E+05	megajoule

D.2.2 Expanded conventional system, including the conventional variants of services that are delivered by the other two alternatives (WtE and CC)

Label	Impact Category	[A75] Potassium Fertiliser (CC)	[A76] Heat (WtE)	[A80] Electricity (WtE)	[A81] Sand (WtE)	Total	Unit
[C41]	Acidification	1.30.E+00	1.50.E+00	1.16.E+01	9.07.E-01	1.53.E+01	kg SO2-Eq
[C43]	***Climate change***	***3.35.E+02***	***2.33.E+03***	***2.32.E+04***	***2.95.E+02***	***2.62.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	5.67.E-01	2.87.E-01	2.22.E+00	2.15.E-01	3.29.E+00	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	1.76.E+02	2.61.E+01	2.02.E+02	5.10.E+01	4.55.E+02	kg 1,4-DCB-Eq
[C61]	Human toxicity	5.47.E+02	3.98.E+02	3.08.E+03	1.26.E+02	4.15.E+03	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	7.90.E-02	1.41.E-01	1.09.E+00	6.42.E-02	1.37.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	3.70.E-05	2.46.E-04	1.90.E-03	1.69.E-05	2.20.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	1.39.E+00	4.60.E-01	3.55.E+00	9.75.E-01	6.38.E+00	kg 1,4-DCB-Eq
[C720]	ADP minerals	1.27.E-01	2.65.E-03	2.05.E-02	7.39.E-03	1.58.E-01	kg Sb-Eq
[C729]	ADP fossils	5.60.E+03	3.34.E+05	8.45.E+03	1.67.E+04	5.70.E+05	megajoule

D.2.3 Total Impact from Bio-digestion

Label	Impact Category	Total Impact	Unit
[C41]	Acidification	4.43.E+02	kg SO2-Eq
[C43]	***Climate change***	***5.72.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	1.09.E+02	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	7.67.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	1.67.E+04	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	5.86.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	5.47.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	9.24.E+01	kg 1,4-DCB-Eq
[C720]	ADP minerals	1.26.E+00	kg Sb-Eq
[C729]	ADP fossils	1.14.E+06	megajoule

D.2.4 Percentage Contribution Result for Bio-digestion

Label	Impact Category	Collection	Processing	Transport	Total
[C41]	Acidification	2.82%	93.68%	3.50%	100.00%
[C43]	***Climate change***	***9.36%***	***79.06%***	***11.58%***	100.00%
[C49]	Eutrophication	2.45%	94.53%	3.02%	100.00%
[C53]	Freshwater aquatic ecotoxicity	7.04%	84.26%	8.70%	100.00%
[C61]	Human toxicity	14.48%	67.62%	17.90%	100.00%
[C76]	Photochemical oxidation	13.74%	69.27%	16.99%	100.00%
[C86]	Stratospheric ozone depletion	18.14%	59.38%	22.47%	100.00%
[C90]	Terrestrial ecotoxicity	12.87%	71.22%	15.90%	100.00%
[C720]	ADP minerals	22.88%	48.78%	28.34%	100.00%
[C729]	ADP fossils	7.09%	84.16%	8.74%	100.00%

D.3 Contribution Result for Composting

D.3.1 Composting alternative

Label	Name	Collection	Processing	Transport	Total	Unit
[C41]	Acidification	1.02.E+01	4.31.E+02	6.33.E+00	4.48.E+02	kg SO2-Eq
[C43]	***Climate change***	***4.36.E+03***	***1.45.E+04***	***2.70.E+03***	***2.16.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	2.16.E+00	1.09.E+02	1.34.E+00	1.13.E+02	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	4.39.E+02	4.90.E+03	2.72.E+02	5.61.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	1.97.E+03	3.68.E+03	1.22.E+03	6.87.E+03	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	6.55.E-01	1.04.E+00	4.06.E-01	2.10.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	8.08.E-04	6.79.E-04	5.01.E-04	1.99.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	9.66.E+00	5.63.E+01	5.99.E+00	7.20.E+01	kg 1,4-DCB-Eq
[C720]	ADP minerals	2.36.E-01	2.72.E-01	1.46.E-01	6.54.E-01	kg Sb-Eq
[C729]	ADP fossils	6.60.E+04	1.73.E+05	4.09.E+04	2.80.E+05	megajoule

D.3.2 Expanded conventional system, including the conventional variants of services that are delivered by the other two alternatives (WtE and AD)

Label	Impact Category	[A76] Heat (WtE)	[A80] Electricity (WtE)	[A81] Sand (WtE)	[A79] Natural gas (AD)	[A80] Potassium Fertiliser (AD)	[A81] Electricity (AD)	Total	Unit
[C41]	Acidification	1.50.E+00	1.16.E+01	9.07.E-01	1.42.E+01	1.96.E+00	5.38.E-01	3.07.E+01	kg SO2-Eq
[C43]	***Climate change***	***2.33.E+03***	***2.32.E+04***	***2.95.E+02***	***2.05.E+03***	***5.05.E+02***	***1.07.E+03***	***2.95.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	2.87.E-01	2.22.E+00	2.15.E-01	7.86.E-01	8.56.E-01	1.03.E-01	4.47.E+00	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	2.61.E+01	2.02.E+02	5.10.E+01	1.01.E+03	2.65.E+02	9.33.E+00	1.56.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	3.98.E+02	3.08.E+03	1.26.E+02	2.49.E+03	8.25.E+02	1.42.E+02	7.06.E+03	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	1.41.E-01	1.09.E+00	6.42.E-02	1.07.E+00	1.19.E-01	5.05.E-02	2.53.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	2.46.E-04	1.90.E-03	1.69.E-05	5.72.E-05	5.58.E-05	8.81.E-05	2.36.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	4.60.E-01	3.55.E+00	9.75.E-01	2.56.E+00	2.10.E+00	1.64.E-01	9.81.E+00	kg 1,4-DCB-Eq
[C720]	ADP minerals	2.65.E-03	2.05.E-02	7.39.E-03	3.78.E-03	1.91.E-01	9.50.E-04	2.26.E-01	kg Sb-Eq
[C729]	ADP fossils	4.66.E+04	3.60.E+05	2.39.E+03	3.34.E+05	8.45.E+03	1.67.E+04	7.68.E+05	megajoule

D.3.3 Total Impact from Composting

Label	Impact Category	Total Impact	Unit
[C41]	Acidification	4.78.E+02	kg SO2-Eq
[C43]	***Climate change***	***5.10.E+04***	***kg CO2-Eq***
[C49]	Eutrophication	1.17.E+02	kg PO4-Eq
[C53]	Freshwater aquatic ecotoxicity	7.17.E+03	kg 1,4-DCB-Eq
[C61]	Human toxicity	1.39.E+04	kg 1,4-DCB-Eq
[C76]	Photochemical oxidation	4.64.E+00	kg ethylene-Eq
[C86]	Stratospheric ozone depletion	4.35.E-03	kg CFC-11-Eq
[C90]	Terrestrial ecotoxicity	8.18.E+01	kg 1,4-DCB-Eq
[C720]	ADP minerals	8.80.E-01	kg Sb-Eq
[C729]	ADP fossils	1.05.E+06	megajoule

D.3.4 Percentage Contribution Result for Composting

Label	Impact Category	Collection	Processing	Transport	Total
[C41]	Acidification	2.13%	96.54%	1.32%	100.00%
[C43]	***Climate change***	***8.54%***	***86.16%***	***5.29%***	***100.00%***
[C49]	Eutrophication	1.85%	97.01%	1.15%	100.00%
[C53]	Freshwater aquatic ecotoxicity	6.12%	90.09%	3.79%	100.00%
[C61]	Human toxicity	14.14%	77.10%	8.76%	100.00%
[C76]	Photochemical oxidation	14.13%	77.11%	8.76%	100.00%
[C86]	Stratospheric ozone depletion	18.57%	69.92%	11.51%	100.00%
[C90]	Terrestrial ecotoxicity	11.82%	80.86%	7.33%	100.00%
[C720]	ADP minerals	26.81%	56.60%	16.59%	100.00%
[C729]	ADP fossils	6.30%	89.80%	3.90%	100.00%

D.4 Contribution Result for the ReStore model

Alternative	Climate Change Score (kg CO_2–eq)			
	Collection	Processing	Transport	Total
WtE	5.74.E+03	2.98.E+04	9.50.E+00	**3.56.E+04**
Bio-digestion	4.76.E+03	4.70.E+04	3.61.E+03	**5.54.E+04**
Composting	4.45.E+03	4.50.E+04	2.41.E+03	**5.18.E+04**

D.4.1 Percentage Contribution Result for the ReStore model

Alternative	Collection	Processing	Transport	Total
WtE	16%	84%	0.03%	100%
Bio-digestion	9%	85%	6.52%	100%
Composting	8.59%	87%	4.64%	100%

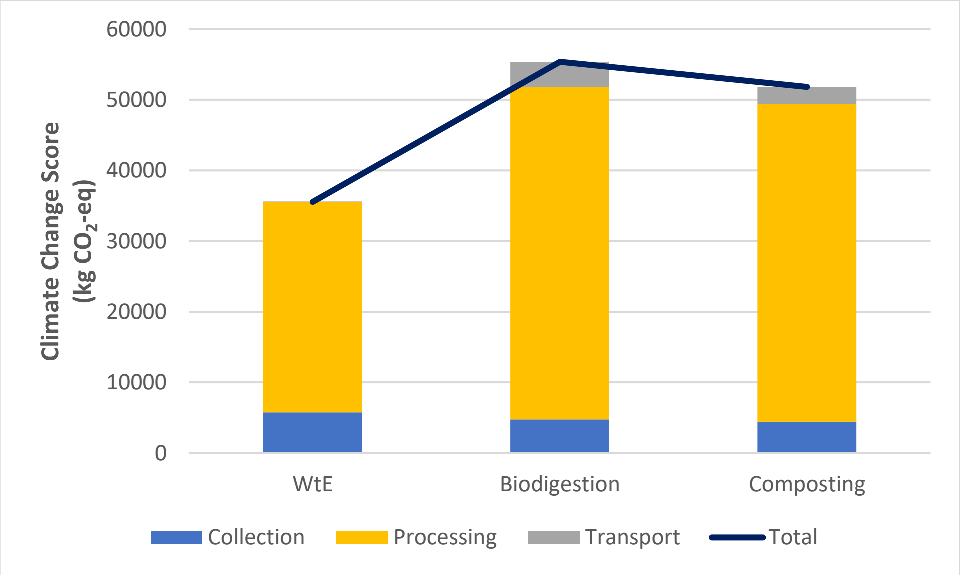

Figure D.1 Contribution analysis results of the ReStore model per each phase

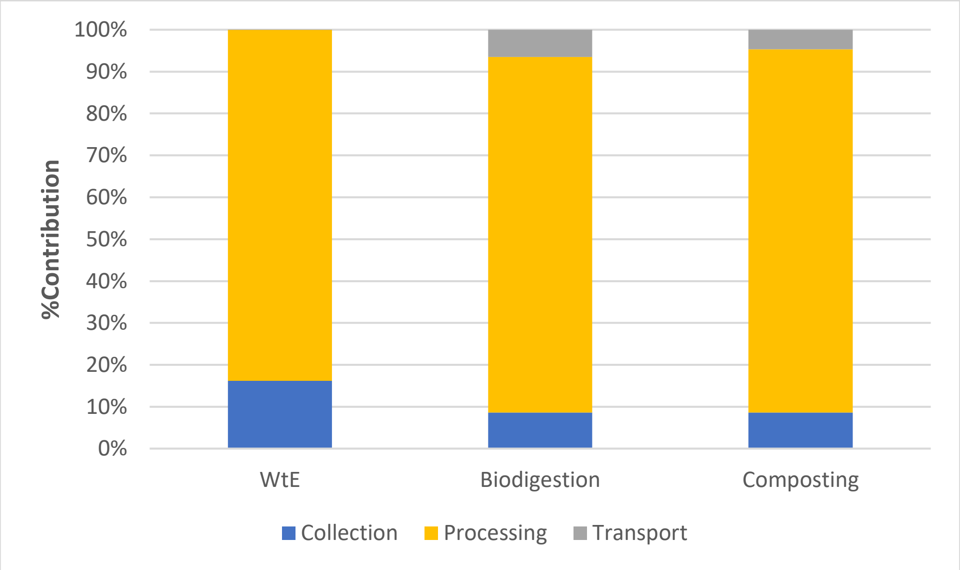

Figure D.2 Percentage contribution per each phase for the ReStore model

Appendix E. Sensitivity Analysis

E.1 Sensitivity towards changes methods to solve multifunctional process

Using substitution in the LCA model

Impact Category	WtE	Bio-digestion	Composting	Unit
Acidification	-1.03.E+01	1.53.E+01	4.39.E+02	kg SO2-Eq
Climate change	***-1.89.E+04***	***9.32.E+03***	***1.82.E+04***	kg CO2-Eq
Eutrophication	-6.15.E+00	1.01.E+01	1.10.E+02	kg PO4-Eq
Freshwater aquatic ecotoxicity	-1.05.E+03	2.62.E+03	4.98.E+03	kg 1,4-DCB-Eq
Human toxicity	-1.31.E+03	2.36.E+03	4.56.E+03	kg 1,4-DCB-Eq
Photochemical oxidation	-7.88.E-01	7.31.E-01	1.53.E+00	kg ethylene-Eq
Stratospheric ozone depletion	-1.61.E-04	1.47.E-03	1.41.E-03	kg CFC-11-Eq
Terrestrial ecotoxicity	-6.33.E+00	4.16.E+01	6.32.E+01	kg 1,4-DCB-Eq
ADP minerals	2.96.E-01	1.83.E-01	2.54.E-01	kg Sb-Eq
ADP fossils	-3.66.E+05	3.10.E+04	2.28.E+05	megajoule

Using economic allocation in the LCA model

Impact Category	WtE	Bio-digestion	Composting	Unit
Acidification	1.52.E+01	1.06.E+02	2.13.E+02	kg SO2-Eq
Climate change	***6.71.E+03***	***8.75.E+03***	***1.13.E+04***	kg CO2-Eq
Eutrophication	3.44.E+00	2.57.E+01	5.34.E+01	kg PO4-Eq
Freshwater aquatic ecotoxicity	7.02.E+02	1.36.E+03	2.66.E+03	kg 1,4-DCB-Eq
Human toxicity	2.88.E+03	3.02.E+03	3.45.E+03	kg 1,4-DCB-Eq
Photochemical oxidation	9.47.E-01	1.14.E+00	1.11.E+00	kg ethylene-Eq
Stratospheric ozone depletion	1.24.E-03	1.19.E-03	1.11.E-03	kg CFC-11-Eq
Terrestrial ecotoxicity	1.48.E+01	2.15.E+01	3.56.E+01	kg 1,4-DCB-Eq
ADP minerals	3.45.E-01	3.15.E-01	3.04.E-01	kg Sb-Eq
ADP fossils	9.39.E+04	1.18.E+05	1.45.E+05	megajoule

Sensitivity towards changes methods to solve multifunctional process in the ReStore model

Methods	WtE	Bio-digestion	Composting	Unit
Substitution	-1.98.E+04	7.41.E+03	2.06.E+04	kg CO2-Eq
Economic allocation	6.22.E+03	1.09.E+04	1.21.E+04	kg CO2-Eq

E.2 Sensitivity towards changes in types of electricity

The electricity produced from WtE and bio-digestion alternative was initially assumed to be equivalent with electricity from the Dutch electricity mix. In the sensitivity analysis, the electricity is switched to be equivalent to the electricity generated from natural gas power plant (Scenario 1) and coal power plant (Scenario 2).

Analysed in the ReStore model using substitution to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (Dutch Electricity Mix)	-1.98.E+04	7.41.E+03	2.06.E+04	kg CO2-Eq
Scenario 1 (Electricity from natural gas)	-1.46.E+04	7.66.E+03	2.06.E+04	kg CO2-Eq
Scenario 2 (Electricity from coal)	-4.51.E+04	6.24.E+03	2.06.E+04	kg CO2-Eq

Analysed in the ReStore model using system expansion to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (Dutch Electricity Mix)	3.56.E+04	5.54.E+04	5.18.E+04	kg CO2-Eq
Scenario 1 (Electricity from natural gas)	3.27.E+04	5.02.E+04	4.43.E+04	kg CO2-Eq
Scenario 2 (Electricity from coal)	6.31.E+04	8.18.E+04	7.39.E+04	kg CO2-Eq

Analysed in LCA model using substitution to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (Dutch Electricity Mix)	-1.89E+04	9.32E+03	1.82E+04	kg CO2-Eq
Scenario 1 (Electricity from natural gas)	-1.37E+04	9.44E+03	1.82E+04	kg CO2-Eq
Scenario 2 (Electricity from coal)	-4.95E+04	8.61E+03	1.82E+04	kg CO2-Eq

Analysed in the LCA model using system expansion to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (Dutch Electricity Mix)	3.64E+04	5.72E+04	5.10E+04	kg CO2-Eq
Scenario 1 (Electricity from natural gas)	3.06E+04	5.14E+04	4.56E+04	kg CO2-Eq
Scenario 2 (Electricity from coal)	6.76E+04	8.25E+04	7.75E+04	kg CO2-Eq

E.3 Sensitivity towards changes in types of mineral fertiliser

The electricity produced from WtE and bio-digestion alternative was initially assumed to be equivalent with potassium fertiliser. In the sensitivity analysis, the electricity is switched be equivalent to the nitrogen fertiliser in the form of urea (Scenario 1) and phosphate fertiliser in the form of muriate potash (Scenario 2).

Analysed in ReStore model using substitution to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	-1.98E+04	7.41E+03	2.06E+04	kg CO2-Eq
Scenario 1 (nitrogen fertilizer)	-1.98E+04	6.89E+03	2.04E+04	kg CO2-Eq
Scenario 2 (potassium fertilizer)	-1.98E+04	7.52E+03	2.06E+04	kg CO2-Eq

Analysed in ReStore model using system expansion to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	3.56E+04	5.54E+04	5.18E+04	kg CO2-Eq
Scenario 1 (nitrogen fertilizer)	3.63E+04	5.57E+04	5.20E+04	kg CO2-Eq
Scenario 2 (potassium fertilizer)	3.58E+04	5.52E+04	5.18E+04	kg CO2-Eq

Analysed in LCA model using substitution to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	-1.89E+04	9.32E+03	1.82E+04	kg CO2-Eq
Scenario 1 (nitrogen fertilizer)	-1.89E+04	7.30E+03	1.74E+04	kg CO2-Eq
Scenario 2 (potassium fertilizer)	-1.89E+04	8.03E+03	1.78E+04	kg CO2-Eq

Analysed in LCA model using system expansion to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	3.64E+04	5.72E+04	5.10E+04	kg CO2-Eq
Scenario 1 (nitrogen fertilizer)	3.84E+04	5.79E+04	5.23E+04	kg CO2-Eq
Scenario 2 (potassium fertilizer)	3.76E+04	5.76E+04	5.18E+04	kg CO2-Eq

Aside from mineral-based fertilisers, sensitivity analysis was also conducted on another type of product. In this case, peat was selected to be equivalent with compost (Scenario 1).

Analysed in ReStore model using substitution to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	-1.98.E+04	7.41.E+03	2.06.E+04	kg CO2-Eq
Scenario 1 (peat)	-1.98.E+04	5.23.E+03	1.58.E+04	kg CO2-Eq

Analysed in ReStore model using system expansion to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	3.56.E+04	5.54.E+04	5.18.E+04	kg CO2-Eq
Scenario 1 (peat)	4.79.E+04	6.70.E+04	5.66.E+04	kg CO2-Eq

Analysed in LCA model using substitution to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	-1.89.E+04	9.32.E+03	1.82.E+04	kg CO2-Eq
Scenario 1 (peat)	-1.89.E+04	8.32.E+03	1.78.E+04	kg CO2-Eq

Analysed in LCA model using system expansion to solve multifunctional process

Scenario	WtE	Biodigestion	Composting	Unit
Baseline scenario (potassium fertilizer)	3.64.E+04	5.72.E+04	5.10.E+04	kg CO2-Eq
Scenario 1 (peat)	3.74.E+04	5.89.E+04	5.17.E+04	kg CO2-Eq

4413TRP30Y - Thesis Research Project
Master Thesis in Industrial Ecology
Leiden University - Faculty of Science
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