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Life cycle assessment of vermicomposting process

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Summary:

The thorough evaluation of vermicomposting's environmental impact underscores its potential to transform agricultural methods significantly. Apart from its immediate advantages in reducing greenhouse gas emissions and nutrient runoff, vermicompost presents a versatile solution to sustainability challenges in contemporary farming.

Utilizing vermicompost as a fertilizer not only enriches soil fertility but also promotes soil health by introducing beneficial microorganisms. This microbial activity facilitates nutrient circulation and improves soil structure, resulting in enhanced water retention and reduced erosion.

Furthermore, the organic composition of vermicompost reduces the risk of chemical leaching into groundwater, thus protecting water quality and biodiversity in adjacent ecosystems. By mitigating the adverse effects associated with synthetic fertilizers, vermicomposting aligns with the principles of regenerative agriculture, fostering long-term ecological equilibrium and resilience.

This study delves into the production process of vermicomposting at Edelmark AS to evaluate its life cycle implications. Employing a functional unit of 1 kg of vermicompost, this thesis assessed its environmental footprint concerning global warming and eutrophication. Utilizing the EcoInvent database and ReCiPe midpoint impact assessments, determined that the process results in 0.10999 kg CO2 eq for global warming, 1.18 × 10-8 kg P eq for freshwater eutrophication, and 2.17 × 10-9 kg N eq for marine eutrophication.

These findings highlight the viability of vermicompost as a sustainable alternative to traditional fertilizers in plant production. Its utilization of digested feed minimizes environmental impacts typically associated with conventional fertilizers.

Preface

This thesis delves into the transformative potential of vermicomposting within the realm of agricultural practices. The thorough evaluation presented here underscores its ability to significantly alter conventional methods, offering a promising solution to the sustainability challenges faced by modern farming.

Vermicompost, beyond its immediate benefits in curbing greenhouse gas emissions and nutrient runoff, emerges as a versatile tool for enhancing agricultural sustainability. By leveraging vermicompost as a fertilizer, not only does it enrich soil fertility, but it also introduces beneficial microorganisms, fostering a cascade of effects that promote soil health. This microbial activity facilitates nutrient circulation, improves soil structure, and mitigates erosion, resulting in enhanced water retention and soil stability.

This study offers a comprehensive examination of the vermicomposting process at Edelmark AS, shedding light on its life cycle implications. Utilizing a functional unit of 1 kg of vermicompost. Leveraging data from the EcoInvent database and ReCiPe midpoint impact assessments, this thesis quantified the process's contributions to global warming, freshwater eutrophication, and marine eutrophication.

The findings of this study underscore the viability of vermicompost as a sustainable alternative to traditional fertilizers in plant production. By capitalizing on its utilization of digested feed, vermicompost not only minimizes environmental impacts but also presents a promising avenue for advancing sustainable agriculture practices.

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Nomenclature

SWM	Solid Waste Management
GHG	Greenhouse Gases
GAP	Gut Associated Process
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
FU	Functional Unit
MSW	Municipal Solid Waste
g	gram
cm	centimeter
D_{AB}	Diffusivity of component A through component B
D_{im}	Diffusivity of component i through gas mixture
C_A	Concentration of component A
R	Universal Gas Constant
T	Temperature
ε	Energy of molecular attraction
M_i	Molecular Weight of component i
P	Pressure
r_{ij}	Molecular separation at collision
Ω	Collision function
k	Boltzmann’s constant

1 Introduction

The management of solid waste is deeply influenced by income levels, regional factors, and the source of waste generation, shaping the scale and sophistication of waste management systems. Disparities in income dictate investment in advanced infrastructure, while regional conditions and waste sources diversify challenges faced by management systems. Context-specific approaches are essential for effective waste management planning, considering income, region, and source intricacies.

The circular economy concept promotes recycling and reusing waste to minimize generation, emphasizing a "cradle to cradle" approach. Multidisciplinary efforts target systems of production and use, incorporating organic waste management to address issues from industrialization and urbanization.

Solid waste management remains critical for urban areas experiencing rapid population growth and increased garbage production. It aligns with sustainable development goals, facilitating access to clean water, sustainable cities, climate change mitigation, and promoting green growth. However, challenges persist, especially in developing countries, where limited resources and inadequate landfill standards contribute to environmental pollution. Gas emissions from decomposition, particularly methane, pose a significant threat, while the management of liquid leachate presents risks to local water systems.

1.1 Background

Vermicomposting utilizes earthworms and microorganisms to efficiently convert organic waste into high-quality compost, rich in nutrients and beneficial microbes. This eco-friendly approach accelerates decomposition, producing nutrient-rich earthworm castings that enhance soil health and promote plant growth. Vermicompost offers numerous advantages over traditional composting, including faster biodegradation and improved soil properties. Additionally, vermicompost-derived products such as vermiwash and vermiponic nutrient medium contribute to sustainable agriculture practices. Studies have shown that vermicompost application reduces pollutant concentrations in soil and plays a vital role in circular bio-economy systems by maximizing organic waste utilization. Overall, vermicomposting presents an efficient and sustainable solution for recycling organic waste and enhancing agricultural productivity.

1.2 Edelmark AS company

Established in 2020, Edelmark has taken a forefront position in the field of vermicomposting research in Norway, following its inception as a sole proprietorship in 2013. During its early stages, the company's primary focus was on researching, developing, and promoting solutions for small-scale earthworm composting (vermicompost) and organic plant cultivation at a small farm in Hokksund. Edelmark currently manufactures a liquid fertilizer product, a result of four years of research based on the vermicomposting process, and has concentrated its efforts on research and development of solid composting products. Presently, Edelmark AS is collaborating with USN and Høgskolen i Innlandet (INN) on a research project titled 'Different bio-wastes to diverse products'. The project's main goal is to experiment with and document the transformation of various types of organic wastes into organic fertilizers and soil amendments through earthworm composting, thereby facilitating the efficient and profitable production of nutrient-rich and environmentally friendly organic products in both solid and liquid forms.

Edelmark's vision is to be a pivotal contributor to the green shift by developing technologies and advocating efficient processes that utilize organic waste or Bioresources as raw materials to produce valuable products that support organic farming, while simultaneously addressing environmental challenges associated with waste disposal.

1.3 Objective

This thesis tries to understand if using vermicomposting is appropriate alternative for producing fertilizer. For doing so, LCA is carrying out. These are the main objectives:

- LCA of Vermicomposting
- Comparing Vermicomposting to other fertilizers

1.4 Methods

For Doing the life cycle assessments of vermicomposting process, this report uses necessary data from Edelmark AS company and calculate mass transfers using mass equations. Also, there are some missing data for the process. For completing the LCA, Ecoinvent 3.6 database is choosen to fulfill the requirement data.

1.5 Report structure

For analyzing the result from LCA of vermicomposting, two comparisons will be conducted. First, comparing the result with literature which done the LCA for vermicomposting and second, comparing the result with fertilizer production to get some sense about what is the benefits of proposed process.

Next chapter will delve deeper into the waste and vermicomposting as a waste management system.

2 Literature review

This chapter delve deeper into the problem and provide some insight about waste, waste management systems and vermicomposting.

2.1 What is waste?

Waste is a byproduct of urbanization, economic growth, and population increase. As cities and nations expand, generating more waste due to increased consumption and participation in global trade, effective management through treatment and disposal becomes essential.

Globally, the average waste generation stands at 0.74 kilograms per capita per day, yet national rates vary widely, ranging from 0.11 to 4.54 kilograms per capita per day. The volumes of waste generated generally align with income levels and urbanization rates. In 2016, an estimated 2.01 billion tonnes of municipal solid waste were generated, projected to reach 3.40 billion tonnes by 2050 under a business-as-usual scenario. [1]

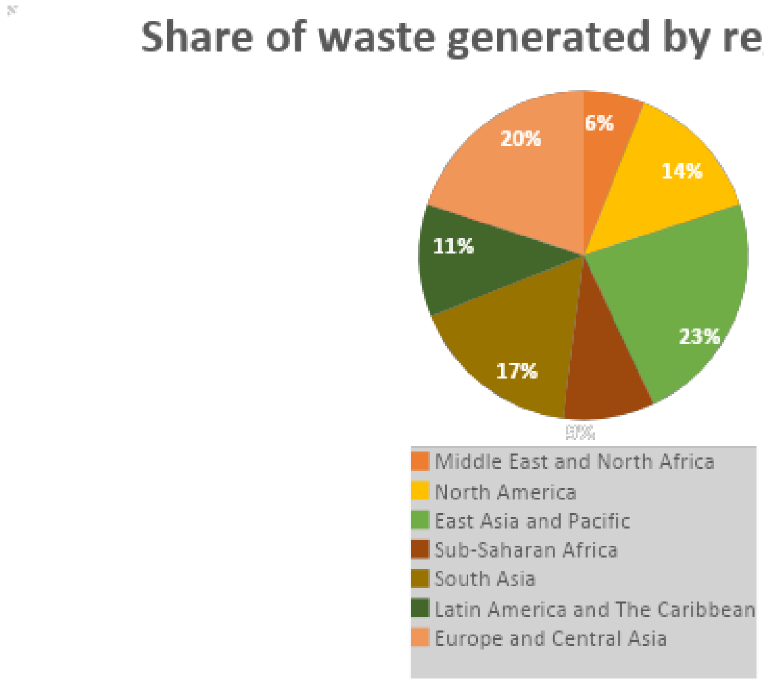

Figure 2.1 - Waste generation by region (percent) [1]

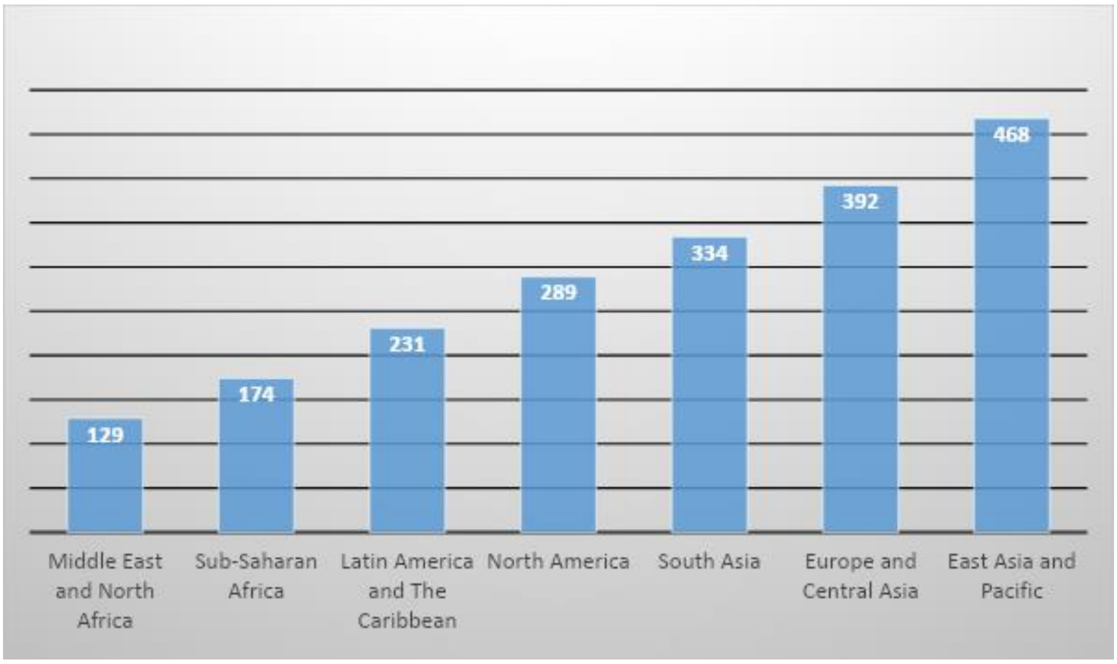

Figure 1.2 - Waste generation by region (tonnes) [1]

Recent waste production aligns with initial projections, accompanied by notable improvements in tracking and reporting. Global waste generation in 2016 was approximately 2.01 billion tonnes, with significant contributions from the East Asia and Pacific, and Europe and Central Asia regions, constituting 43 percent (figure 2.1). In contrast, the Middle East, North Africa, and Sub-Saharan Africa jointly account for 15 percent. The East Asia and Pacific region produced the most waste (468 million tonnes), while the Middle East and North Africa produced the least (129 million tonnes) (figure 2.2).

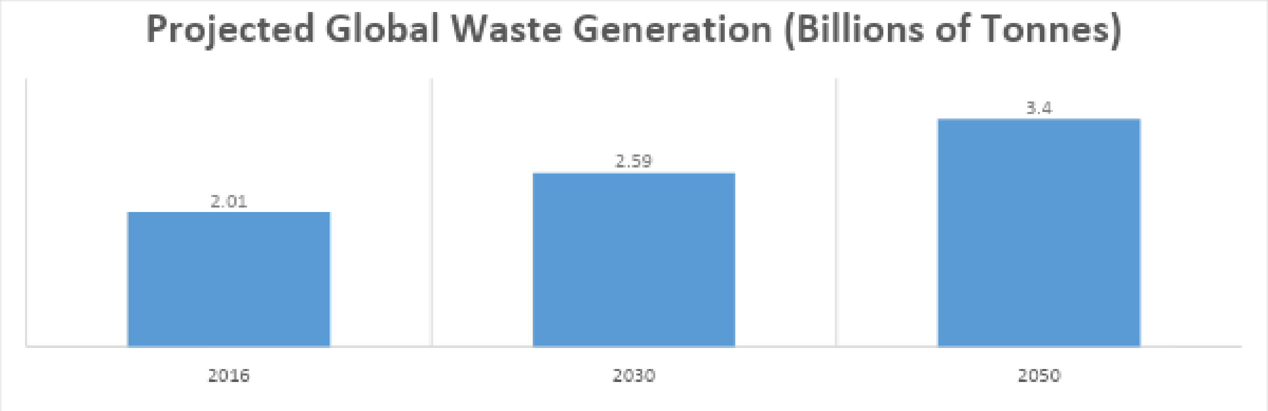

Figure 2.3 - Projected Global Waste Generation (Billions of Tonnes) [1]

By 2030, the world is expected to generate 2.59 billion tonnes of waste annually (figure 2.3). By 2050, waste generation across the world is expected to reach 3.40 billion tonnes.

By 2050, waste generation in low-income countries is projected to more than triple. Currently, the East Asia and Pacific region leads global waste generation at 23%, while the Middle East and North Africa contribute the least at 6%. By 2050, Sub-Saharan Africa, South Asia, and the Middle East North Africa regions are expected to triple, double, and double waste generation, respectively. [1]

An understanding of solid waste and its composition is essential to explore the production rate and projections.

Solid waste is a term that encompasses all forms of discarded materials, rubbish, or refuse. It can be classified based on its origin, such as municipal solid waste, health care waste, and electronic waste (e-waste). [2] Globally, food and green waste dominate the waste composition, making up 44 percent, while dry recyclables (plastic, paper, cardboard, metal, and glass) contribute another 38 percent (figure 2.4). Waste composition varies with income levels, with organic matter decreasing as income rises (figure 2.5). Higher-income countries exhibit a larger share of consumed goods like paper and plastic compared to lower-income countries. The level of detail in waste composition data increases with higher income levels.

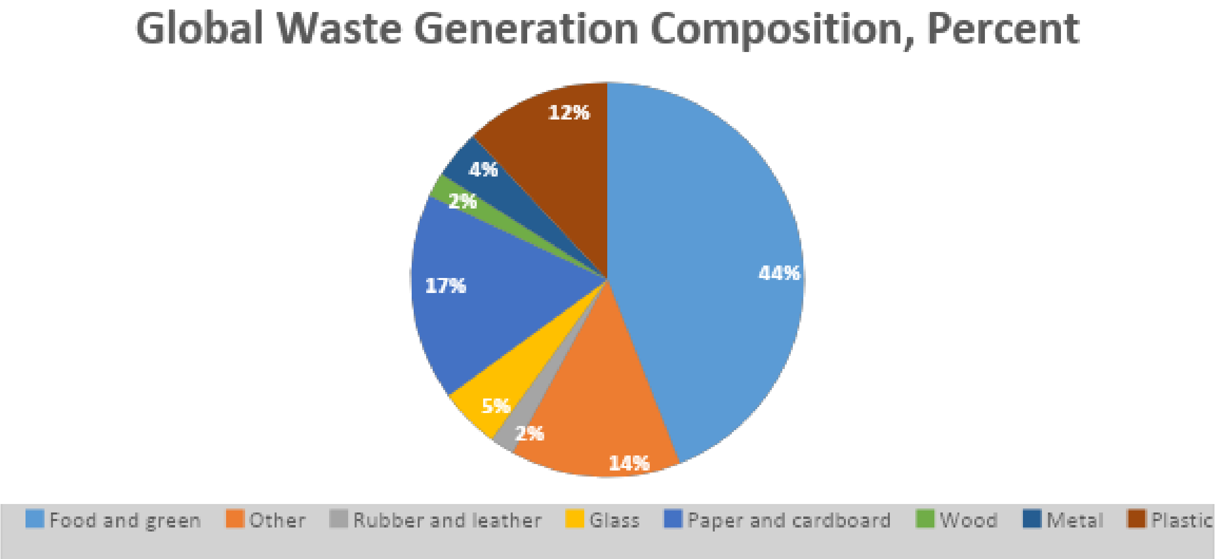

Figure 2.4 - Global Waste Generation Composition, Percent [1]

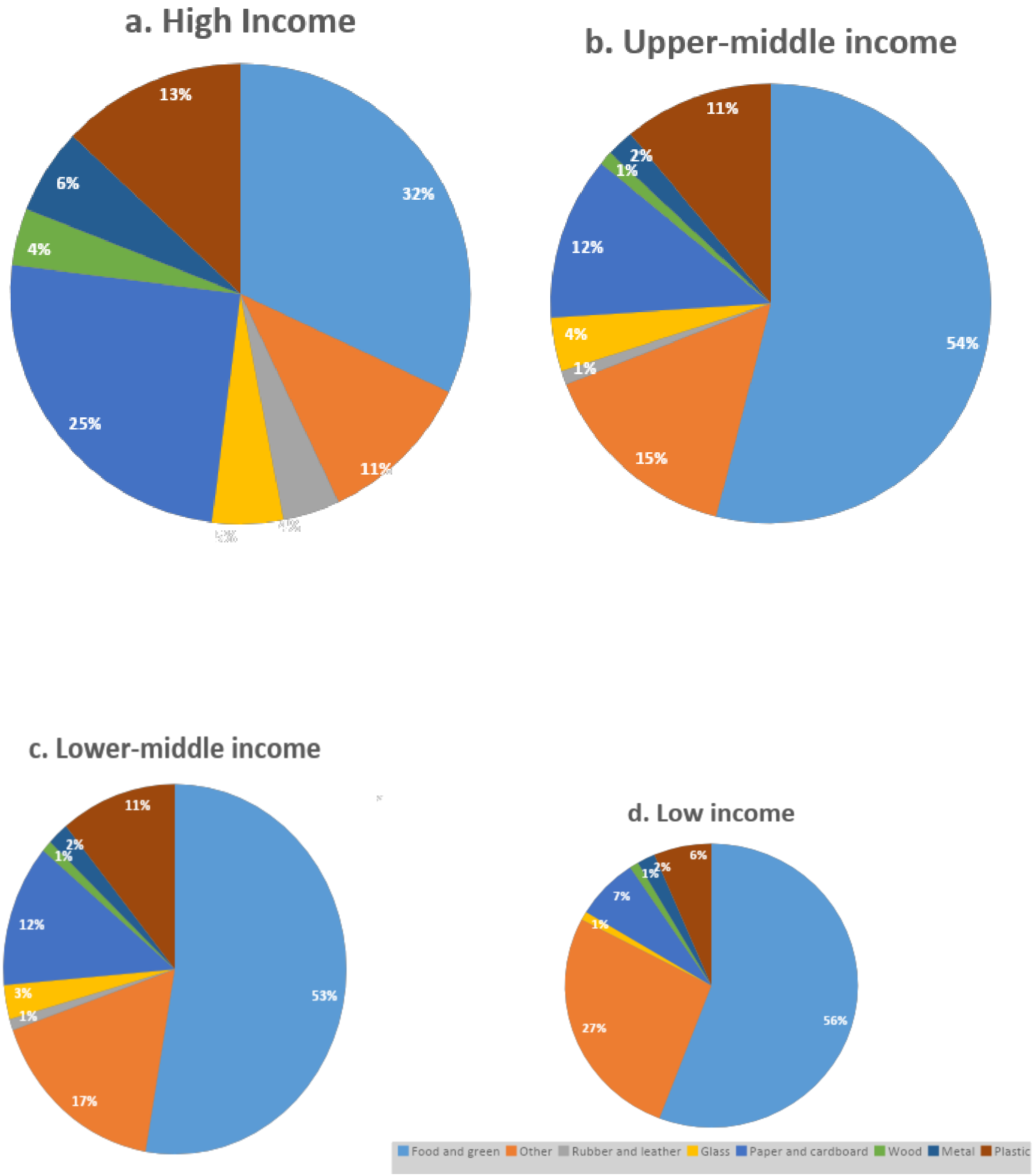

Figure 2.5 - Global Waste Generation Composition, by Income [1]

Table 2.1 provides a summary of the composition of household solid waste in Norway.

Table 2.1 - Solid waste composition in Norway [4]

	Year 2022	Percentage
EAK The whole country	**0 In total**	100
	1 Residual waste	41.28

	2 Separated	58.72
	2.01 Paper	9.61
	2.02 Glass	3.72
	2.03 Plastics	2.45
	2.04 Metals	4.20
	2.05 Electronics	2.24
	2.06 Food and other wet organic	9.52
	2.07 Tree	10.70
	2.08 Garden waste	7.21
	2.09 Textiles	0.00
	2.10 Sorted to incineration	0.00
	2.11 Hazardous waste	3.38
	2.12 Other	0.40
	2.13 Construction waste	2.36
	2.14 Polluted masses	1.83
	2.15 Plaster	0.89
	2.16 Tires	0.18

Solid waste management is a critical global concern impacting individuals worldwide. Both individuals and governments significantly influence consumption and waste management, thereby affecting community health, productivity, and cleanliness. Inadequate waste management leads to ocean pollution, drainage blockages, floods, disease spread, respiratory problems, harm to animals, and hampers economic development. Also, improper disposal of solid waste can lead to substantial health issues and create an extremely unpleasant living environment. Inadequate disposal may give rise to breeding sites for insect vectors, pests, snakes, and vermin, heightening the risk of disease transmission. Additionally, it has the potential to pollute water sources and the surrounding environment. [5] Immediate and comprehensive action at all societal levels is necessary to address the uncontrolled and poorly managed waste resulting from economic growth. It’s worth mentioning that due to their high costs, traditional waste management methods become less viable, particularly in underdeveloped or developing countries. [6]

As the statistics show, solid waste is profoundly influenced by the interplay of income levels, regional characteristics, and the source of waste generation, as well as solid waste management systems. Income disparities play a pivotal role in shaping the scale and sophistication of waste management infrastructure, with wealthier regions often investing in advanced systems. Regional factors, encompassing climate conditions and geographical considerations, contribute to variations in waste composition and disposal methods. Source-specific influences, such as industrial versus residential waste, further diversify the challenges faced by waste management systems. These factors collectively underscore the need for context-specific approaches in waste management planning, as income, region, and source intricately intertwine to dictate the effectiveness and sustainability of waste management strategies.

The concept of the circular economy emphasizes recycling and reusing waste, including water, energy, and resources. It aims to reduce the intensity of basic materials use by promoting recycling and reuse, thus minimizing waste generation. In this approach, waste is considered a resource for other processes, reflecting a shift toward a "cradle to cradle" concept. The circular economy involves a multidisciplinary approach, focusing on systems of production and use. To address organic waste from rapid industrialization and urbanization, a new approach to food production is initiated, incorporating organic waste collection and recycling. [33]

The issue of managing solid waste (SWM) remains a significant concern for society and governance, particularly in urban regions grappling with rapid population growth and escalating garbage production. The importance of SWM in realizing sustainable development is underscored in numerous global development agendas, charters, and visions. For instance, sustainable SWM can contribute to the achievement of several of the United Nations' Sustainable Development Goals, including access to clean water, building sustainable cities, combating climate change and promoting sustainable consumption and production behaviors. Moreover, it encourages a circular urban economy that advocates for decreased consumption of finite resources, the reuse and recycling of materials to eliminate waste, the reduction of pollution, cost savings, and the promotion of green growth. The breakdown of waste into its chemical components is a frequent cause of environmental pollution in local areas, particularly in developing countries. Due to limited resources, few landfills in these nations adhere to the environmental standards followed by industrialized countries. Additionally, the problem is exacerbated by the challenges associated with rapid urbanization. One of the primary environmental concerns is the release of gas during the decomposition process. Bacteria produce methane through anaerobic respiration, and this gas can make up to 50% of landfill gas during maximum decomposition. This gas contributes to the greenhouse effect and climate change. The management of liquid leachate varies across developing world landfills, and it poses a threat to local water systems. [36]

2.2 Solid Waste Management Methods

Various approaches to solid waste management will be discussed in the following section. There are two main approaches: thermo-chemical conversion and biological conversion.

1. Thermo-chemical Conversion refers to the process of thermally decomposing organic matter to generate heat energy or fuel oil or gas. This method is particularly beneficial for waste that has a high proportion of organic non-biodegradable matter and a low moisture content. Thermo-chemical conversion, distinguished by its high temperature and conversion rates, is ideally suited for feedstock with lower moisture content and is generally less product-selective. The primary technological alternatives in this category encompass Combustion, Pyrolysis, Gasification, and Incineration. Combustion is a series of exothermic chemical reactions between a fuel and an oxidant, resulting in heat production and chemical species conversion. Incineration is a waste treatment method that involves burning organic substances found in waste materials. This process ensures controlled waste burning, with heat recovery to produce steam, which subsequently generates power via steam turbines. Pyrolysis and Gasification are sophisticated thermal treatment methods that serve as alternatives to Incineration. They are characterized by the conversion of waste into product gas, which serves as an energy carrier for subsequent combustion in, for instance, a boiler or a gas engine. [37]
2. Biological Conversion: These methods rely on the enzymatic breakdown of organic matter by microbes to create compost or produce biogas like methane (waste-to-energy) and residual sludge (fertilizer). Biological processes are primarily divided into two categories: Aerobic processes necessitate oxygen/air for the decomposition of organic matter to yield usable compost. Examples of these processes encompass windrow composting, aerated static pile composting, in-vessel composting, vermicomposting, and so on. Anaerobic processes occur in the absence of oxygen/air to generate usable methane gas. Examples of these processes include low-solids anaerobic digestion (wet process), high solids anaerobic digestion (dry process), and combined processes.

   Composting involves the microbe-assisted decomposition of organic waste materials in specific vessels, resulting in the production of humus-rich manure. This traditional process is predominantly employed in rural areas. [7, 8, 9] Composting is divided into anaerobic and aerobic categories based on the decomposition process. Aerobic composting, occurring in the presence of oxygen, involves the breakdown of organic matter by aerobic microorganisms. This process produces carbon dioxide, ammonia, water, heat, and stable humus. Unlike anaerobic composting, aerobic microorganisms decompose intermediate compounds, resulting in compost with a stable organic form and minimal phytotoxicity risk. The generated heat accelerates the breakdown of proteins, fats, cellulose, and hemi-cellulose, leading to a shorter processing time. High temperatures in aerobic composting eliminate pathogens and weed seeds. While more nutrients are lost compared to anaerobic composting, it is considered more efficient for agricultural production. [31]

   Composting objectives can be met through vermicomposting, an enzymatic degradation process in earthworms' digestive systems. Vermicompost, derived from the organic fraction of municipal solid waste, outperformed traditional compost. It underwent a thermophilic phase, reducing pathogens and enhancing nutrient concentrations, soil microbial size, and activity, resulting in a higher ryegrass yield.[32]

In their study, Chan et al. [47] found that GHG emissions from composting and vermicomposting varied significantly over time and were influenced by factors such as temperature, moisture content, and waste properties. Proper management of composting systems could potentially mitigate these emissions. Home composting stands out as a promising option compared to centralized composting, anaerobic digestion, landfilling, and incineration, offering lower on-site emissions and reduced transportation and processing needs.

In a comparison between composting and vermicomposting of biodegradable waste, Komakech et al. discovered that the vermicomposting process resulted in 78.19% fewer GHG emissions compared to composting, which released 80.9 kg CO2-eq/ton-of-waste. The substantial variation in GHG emissions observed was attributed to the differing amounts of solid waste involved in the treatment processes, as well as the duration and conditions of the processes [25].

This report will discuss vermicomposting for solid waste management.

2.3 Vermicomposting

Vermicomposting is a biotechnological approach that utilizes specific earthworm species to enhance waste conversion, creating high-quality compost. Unlike conventional methods, vermicomposting relies on earthworms and microorganisms to speed up decomposition. Through this process, organic matter undergoes a significant transformation in earthworm guts, resulting in nutrient-rich earthworm castings abundant in microbial activity, plant growth regulators, and pest repellent properties. This eco-friendly method reduces landfill waste while generating nutrient-rich compost, which serves as an excellent soil conditioner and fertilizer. Overall, vermicomposting offers an efficient and sustainable solution for recycling organic waste and promoting soil health. [48]

Vermicompost, rich in nutrients and microbes, enhances crop yield and soil health. Unlike inorganic fertilizers, it helps control greenhouse gas emissions, promoting sustainable crop production. The application of vermicompost improves soil properties, including organic carbon, water holding capacity, aeration, and porosity, leading to increased productivity and better plant growth. [10, 11]. Comparing vermicomposting to traditional composting, vermicomposting has the upper hand in terms of the duration of the biodegradation process. Typically, traditional composting takes a longer time to yield high-quality fertilizer. [24] Vermicompost-tea, the liquid part of vermicompost, is highly effective in breaking down organopesticides and pharmaceutical residues (like diclofenac, triclosan, and ibuprofen) in contaminated soil. This efficacy is attributed to the abundant carboxylesterase enzyme potential in vermicompost. [12]. Using a vermiponic nutrient medium, derived from vermicompost, enhances the growth, nutrient content, chlorophyll levels, and protein, starch, and sugar content in plants like Amaranthus viridis. [13]. Additionally, Vermiwash, a liquid extract from vermiculture, serves as a suitable growth medium for hydroponic plant production.

In vermicomposting, microbes play a crucial role in breaking down organic polymers, releasing nutrients and energy. Earthworms, acting as ecological engineers, enhance biomass breakdown and, in collaboration with gut symbiotic microbes, expedite the conversion into vermicompost. This process, known as vermitechnology, produces a nutrient-rich and eco-friendly fertilizer. [10]

This versatile technology, vermicomposting, operates efficiently both indoors and outdoors year-round. It can be categorized into batch and continuous feed. In batch systems, organic waste is added in single or multiple batches, while continuous systems can be manual or automated. Automated systems use a scraper to remove mature vermicompost continuously, with a device adding fresh waste at set intervals. [10]

The studies indicated that the use of vermicompost lowered pollutant concentrations in soils. For instance, it reduced pesticide (Chlorpyrifos) concentrations in the presence of microorganisms and microbial activities resulted in decreases in herbicides and heavy metals. Vermicompost application also reduced the concentration of cadmium ion (Cd+) and copper ion (Cu+) in tropical soils. Additionally, vermicompost contributed to weakening the polarity of polyaromatic hydrocarbons (PAHs), transferring organic chemicals to the compost. [33] Also, Vermiculture plays a crucial role in the circular economy as part of Integrated Biomass Systems (IBS), utilizing organic waste through vermicomposting to generate biofertilizer and produce biogas for agricultural and energy needs. This circular bio-economy approach maximizes the utilization of organic waste resources. [33]

2.3.1 Steps of Vermicomposting

The vermicomposting process consists of two distinct stages related to earthworm activity:

1. Active Stage: In this stage, earthworms process waste, changing its physical state and microbial composition. The length of this stage is variable and depends on the type and density of earthworms, as well as the speed at which they consume and process the waste.

2. Maturation-like Stage: In this stage, earthworms move towards newer layers of undigested waste, leaving microbes to decompose the waste that the earthworms have processed.

The decomposition of organic waste during vermicomposting is initially due to gut associated processes (GAPs). These include changes to decaying organic matter and microorganisms during their passage through the earthworm's gut. These changes include the addition of sugars and other substances, alterations in microbial diversity and activity, changes in microfauna populations, and the digestion, assimilation, and production of mucus and excretory substances like urea and ammonia. Decomposition is also enhanced by endosymbiotic microbes in the earthworm's gut, which produce enzymes that break down cellulose and phenolic compounds. Other physical changes to the substrate, such as aeration and homogenization caused by the earthworm's digging activities, also promote microbial activity and further enhance decomposition. [38]

After the GAPs, the resulting earthworm casts undergo cast associated processes (CAPs), which are more closely related to aging processes, the action of the microflora and microfauna in the substrate, and the physical modification of the egested materials. During these processes, the effects of earthworms are mainly indirect and result from the GAPs. In vermicomposting systems, earthworm casts are always mixed with material not ingested by the earthworms, and the final vermicompost is a mixture of the two different fractions. During this aging, vermicompost reaches its peak in terms of biological properties that promote plant growth and suppress plant diseases. [38]

2.3.2 Important Factors in Vermicomposting

Eisenia andrei and Eisenia fetida are commonly chosen among various earthworm species for treating MSW, regarding their high fecundity, rapid growth, and optimal performance at temperatures around 30 ± 2 °C [16, 17]. Notably, Eisenia fetida excels in sequestering heavy metals, reducing their bioavailability through bio-mineralization. The earthworm's skin tissues secrete extracellular polymeric substance (EPS) under metal stress, binding with heavy metals and limiting their mobility, effectively trapping them on the skin [19]. Variations in earthworm activity intensity depend on factors such as species, population density, waste type, presence of toxic substances, and mass flow rate. The contribution of earthworm gut microbes involves the production of enzymes that break down organic polymers into monomeric units [10].

In Biruntha et al.'s study, vermicomposting of different waste materials using Eudrilus eugeniae (50 days) revealed that the characteristics of raw materials fed into the vermi reactor significantly influence earthworm growth and reproduction [15]. In a different research, it was discovered that the vermicomposting process, when using E. foetida (an epigeic species), yielded the highest nutrient content (N, P) in the compost for industrial waste. This was followed by institutional waste, agroresidues, and kitchen waste. [39]

Katiyar et al. investigated various process variables, including pH, salinity, moisture levels, temperature, carbon-to-nitrogen (C/N) ratio, nitrogen (N), phosphorus (P), potassium (K), presence of pathogens, and monoculture trends, to understand their impact on vermicompost yield and its effect on the growth of chili and brinjal. The study highlighted the significant influence of two different earthworms on vermicast recovery. Specifically, vermicompost enriched with E. fetida notably enhanced the yield of chili and brinjal [16].

In addition to these factors, parameters like temperature, moisture, aeration, and light play crucial roles in vermicompost production [18]. In another study by Katiyar et al., the effects of reactor geometry with varying surface area-to-volume ratios were explored. Reactors with the highest surface area-to-volume ratio, outperformed reactors with lower ratios in terms of vermicompost quality indicators such as C:N ratio, nutrient content, zoomass increase, and vermicast recovery [20]. It's important to note that all factors influencing the vermicomposting process are intricately connected to the earthworm species used during the biodegradation process [23].

In their study, Jjagwe et al. [46] examined vermicomposting as a cattle manure management technique in Uganda using material flow analysis. This approach tracks the movement of elements or pollutants through ecosystems. The results indicated increases in nutrients and decreases in carbon, pH, and volatile solids over time. Approximately 46% of input materials were converted to vermicompost, 2% to earthworm biomass, and 52% lost to the atmosphere. Carbon and nitrogen losses were 68.5% and 18.2%, respectively. Vermicomposting was found to conserve more nutrients and emit fewer greenhouse gases compared to other manure management methods.

Having gained insights into what vermicomposting entails and the parameters affecting its output, the next section will delve into life cycle assessments.

2.4 LCA and environmental impact

Life Cycle Assessment (LCA) serves as an analytical tool that comprehensively captures the overall environmental impacts of a product, process, or human activity, spanning from raw material acquisition through production and use to waste management. While LCA has its limitations, including interpretation challenges despite the International Standardization Organization's (ISO) general framework, its unique ability to provide a holistic view makes it valuable in environmental management [21].

LCA employs a "cradle-to-grave" methodology, assessing industrial systems from the extraction of raw materials to product creation and eventual return of all materials to the earth. It examines each stage of a product's life as interdependent, where one operation influences the next. LCA allows for estimating cumulative environmental impacts, considering stages often overlooked in traditional analyses (e.g., raw material extraction, transportation, product disposal). By encompassing the entire product life cycle, LCA offers a comprehensive view of environmental aspects, providing a more accurate understanding of environmental trade-offs in product and process selection. [35]

In "cradle-to-grave" context, the LCA of Solid Waste Management (SWM) systems becomes crucial. LCA serves as a system analysis tool for evaluating the total environmental impacts of SWM options within a defined boundary, increasingly being utilized in decision-making processes and strategic planning [14].

The existing Life Cycle Assessment (LCA) methodology for waste management systems, in accordance with ISO standards [22], involves four interconnected phases:

- Precisely defining the study's goal and scope, which includes selecting a functional unit—a quantified description of the product system's performance. This step entails identifying the specific waste management systems for comparison and the environmental impact categories to be evaluated.
- Compiling an inventory of relevant energy and material inputs, along with environmental releases, through Life Cycle Inventory (LCI) analysis. This encompasses activities such as raw material extraction, transportation, processing, and waste disposal, including energy and material inputs.

The Life Cycle Inventory (LCI) analysis hinges on several factors: the nature and amount of natural resources (such as water and energy) utilized, the materials employed in product manufacturing, the modes of transportation used, the product's usage throughout its life, and its ultimate disposal method. The impact and consideration of these elements can vary across different regions. For instance, one area might lack sufficient resources to manufacture a particular product, while another might employ distinct technologies for material production or rely more heavily on renewable energy sources or fossil fuels. These regional disparities can influence the assumptions and constraints of the necessary Life Cycle Assessment (LCA) study. [35]

- Assessing potential environmental impacts linked to identified inputs and releases through Life Cycle Impact Assessment (LCIA). This phase involves evaluating the significance of various environmental stressors, such as greenhouse gas emissions, energy consumption, water use, and waste generation.

  These indicators are derived through a sequence of steps suggested by ISO standards 14042, with some steps being mandatory and others optional. The mandatory steps include the definition and classification of impact categories, and characterization. Optional steps encompass normalization and weighting. Impact categories are defined and chosen to illustrate the impacts triggered by emissions and natural resource consumption during the production, usage, and disposal of the product or process under consideration. In most Life Cycle Impact Assessment (LCIA) methodologies, the emissions and resource consumption are linked to three primary protection areas: ecosystem quality, human health, and natural resources. These three main areas of protection are associated with several impact indicators that convey the environmental impact (midpoint and endpoint indicators).

  In the LCIA phase, characterization can occur through two approaches along the impact pathway of an impact indicator: the midpoint approach and the endpoint approach. Midpoint characterization models the impact using an indicator before reaching the endpoint categories, while endpoint characterization extends modeling until the endpoint categories are defined by areas of protection. In other words, midpoint methods are based on early changes in the cause-effect chain, whereas endpoint or damage methods rely on later changes in the environmental mechanism.

  In the midpoint approach, the cause-effect chain is initiated by a specific process or activity that results in emissions, leading to primary environmental changes. These initial changes, often chemical and physical, occur early in the cause-effect chain. For instance, when studying climate change's primary effects, changes in atmospheric gas concentrations or infrared radiation are observed. At this stage, the Life Cycle Inventory (LCI) results reflect contributions to various environmental issues like global warming or stratospheric ozone depletion. This is known as the midpoint approach, also referred to as the problem-oriented approach.

  As the cause-effect chain progresses, biological changes often occur, manifesting as damages to ecosystems, human health, and resources. For example, an increase in skin cancer could be a health damage resulting from stratospheric ozone depletion. This is termed the endpoint approach, also known as the damage-oriented approach.

Table 2.2, shows an overview of the widely used LCIA methodologies. The modelling approach to which each methodology belongs (midpoint, endpoint, combined or other) and the corresponding impact categories are demonstrated.

Table 2.2 - Summary of LCIA methods[49]

Method	Impact categories (Midpoint categories)	Damage categories (Endpoint categories)	Areas of protection
CML	Depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification and eutrophication.	-	Human health, natural environmental, man made environment, human resources
EDIP 2003	Global warming, ozone depletion, acidification, terrestrial eutrophication, aquatic eutrophication, photochemical ozone formation, human toxicity, ecotoxicity, and noise	-	Human health, Ecosystem and resources
TRACI	Ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health non cancer, human health criteria pollutants, eco-toxicity, and fossil fuel depletion	-	Human health, Ecosystem and resources
Eco-indicator 99	-	Climate change, ozone layer depletion, acidification, eutrophication, carcinogenic, respiratory effects, ionizing radiation, ecotoxicity, land-use, mineral resources, fossil resources	Human health, Ecosystem and resources

EPS 2000	-	Life expectancy, severe morbidity and suffering, morbidity, severe nuisance, nuisance crop production capacity, wood production capacity, fish and meat production capacity, base cation capacity, production capacity for water, share of species extinction, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil) and depletion of mineral reserves	Human health, Ecosystem production capacity, biodiversity and abiotic stock resources
RECIPE	Climate change, ozone depletion, terrestrial acidification , freshwater eutrophication , marine eutrophication , human toxicity, photochemical oxidant formation, particulate matter formation , terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation , urban land occupation, natural land transformation , water depletion , mineral resource depletion, fossil fuel depletion	damage to human health, damage to Ecosystem diversity and damage to resources availability	Human health, Ecosystem and resources
LIME	Ozone layer depletion, global warming, acidification, photochemical oxidant formation, regional air pollution, human-toxic chemical, eco- toxic chemical, eutrophication, land use, waste landfill, resource and consumption	Cataract, skin cancer, other cancer, respiratory disease, thermal stress, infectious disease, hyperalimentation, disaster causality, agricultural production, forestry production, fishery production, loss in land-use, energy consumption, user cost, terrestrial Ecosystem, aquatic Ecosystem	Human health, social welfare, net primary production and biodiversity

LUCAS	Climate change, ozone depletion, acidification, photochemical smog, respiratory effects, aquatic eutrophication, terrestrial eutrophication, ecotoxicity, human toxicity, land-use and abiotic resource depletion.	-	Human health, Eco system quality, and resources
MEEup	-	-	Energy consumption, water consumption, materials in use, waste and to incinerator), hazardous waste generation, emissions to air
BEES	-	-	Global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, smog, ecotoxicity, ozone depletion, and human health
IPCC	-	-	Climate change

Normalization, while optional according to ISO standards [22], offers the advantage of contextualizing the results of characterized impact indicators. It is formulated in a way that enables comparison of impact indicators, by dividing the sum of each category indicator result by a reference value.

Weighting, like normalization, is considered optional under ISO standards [22]. However, both normalization and weighting are crucial when a clear comparison of multiple solutions is required. Weighting involves transforming the results of normalized indicators from different impact categories into other values using numerical factors (weighting factors), which are based on subjective evaluations. These weighting factors incorporate social, political, and ethical factors. The weighting process involves multiplying the weighting factors by the normalization result for each impact category. Weighting is typically applied using linear weighting factors. The weighting factors for each impact category signify the relative environmental importance of each impact category. These factors are subjective and can vary geographically based on socioeconomic criteria. For instance, the "water consumption" impact category may hold significant importance in drought-stricken countries, while its relative importance in countries with abundant water supplies is lower. Another example is the "respiratory effects" impact category, which can be highly significant in areas with high emission rates that subsequently impact human health through respiratory effects.

- Interpreting the results to facilitate more informed decision-making by stakeholders. This step may include comparing the environmental performance of diverse waste management systems and pinpointing opportunities for enhancement.

  A sensitivity check is a process used to determine if uncertainties in data or chosen evaluation methods influence the final results and conclusions of a study. Its goal is to establish confidence in the study's results in relation to its overall objective. This check is primarily used to test the study's assumptions. It can be conducted by creating "what if" scenarios, where the value of various input parameters is systematically altered, or by using simulations, such as Monte Carlo simulations.

The interpretation of findings in studies involves comparing data and results with previous research, and placing them in the context of decision-making and limitations. If uncertainties are high or some decisions are crucial, the process may require recollection of data or a more refined analysis. If results are incomplete or unacceptable for conclusions and recommendations, previous steps must be repeated until the results align with the study's goals. [21]

A major challenge in Life Cycle Assessment (LCA) practice is the lack of readily available inventory data. Public databases like the US EPA’s Toxic Release Inventory (TRI) and Australia’s National Pollutant Inventory (NPI) are free and easily accessible, but not easily adaptable for most life cycle studies as they report data for individual sites or facilities, not industry averages. [21]

The EcoInvent database, created by Europeans, is a successful example of a publicly available database that can be used effectively in life cycle studies. It provides comprehensive and industry-specific data, making it a valuable resource in the field of LCA. [21]

In the inventory analysis stage, every process of the flow crossing the product system must be specified to establish the assessment's starting point. Often, third-party databases are used to create a comprehensive Life Cycle Inventory (LCI) that describes the performance of product processes and stages. There are several major LCI databases, each with its own characteristics. For example, ecoinvent is a widely used professional LCI database, the World-Food LCA Database is sector-based, and the European Reference Life Cycle Database (ELCD) collects data from leading EU-level business associations. [40]

The investigated LCI database and their features are presented in Table 2.3.

Table 2.3 - LCI database and their features [40]

Databases	Features
Ecoinvent	It comprises LCI data from the energy, transport, building materials, chemicals, paper and pulp, waste treatment and agricultural sectors, based on the Swiss and European demand patterns
GaBi	It includes all relevant information in view of the data quality and scope of the application of the respective LCI result/data set, and the data is presented with the referenced functional unit
World Food LCA Database (WFLDB)	WFLDB represents agricultural primary products and processed food products, and it assists companies and environmental authorities in processes of eco-design of food products and Environmental Product Declarations (EPD)
European Reference Life Cycle Database (ELCD)	ELCD comprises LCI data from EU business associations and other sources for key materials, energy carriers, transport, and waste management
U.S. Life Cycle Inventory Database	It serves as a central repository for information about the total energy and resource impacts of developing and using various commercial building materials, components, and assemblies

The choice of database and impact assessment significantly influences the Life Cycle Assessment (LCA) outcome. Pauer et al. compared three databases: GaBi, Ecoinvent 3.6, and the Environmental Footprint Database. While climate change category results were similar across databases, this wasn't the case for other impact categories. Ecoinvent 3.6 typically yielded higher results than GaBi, partly because Ecoinvent datasets often include more background processes. Notable discrepancies were found in Life Cycle Impact Assessment (LCIA) implementation, such as ecoinvent's lack of regionalisation for water use. Effective communication of LCIA results necessitates a thorough understanding of the product system being analysed, database quality issues, and LCIA methodology. [41]

Conducting an LCA can be demanding in terms of resources and time. The thoroughness of the LCA depends on the user's preferences, but gathering data may pose challenges, and data availability significantly influences the accuracy of results. It is crucial to consider data availability, study duration, and financial resources in relation to the anticipated benefits of the LCA.

It's important to note that LCA alone does not determine the most cost-effective or efficient product or process. Instead, the information from an LCA should be viewed as a component in a broader decision-making process that assesses trade-offs with cost and performance, such as in Life Cycle Management. [35]

2.5 Literature review on LCA of waste management systems

Life Cycle Assessment (LCA), which helps quantify a process's environmental impacts, is primarily used in most studies to evaluate and compare the efficiency of two or more alternative Municipal Solid Waste (MSW) treatment methods, as carried out in the majority of these studies. [42] For instance, Sarigiannis et al.'s study explored the integration of various options such as landfilling, combustion, and composting. [43] In another study, Rajaeifar et al. examined and evaluated different municipal solid waste management (MSW) scenarios in Tehran, Iran, using a comparative life cycle assessment approach. They considered five different scenarios: anaerobic digestion, landfilling combined with composting, incineration, incineration combined with composting, and anaerobic digestion combined with incineration. [44]

The objectives of studies vary, and so does the selection of Functional Units (FUs) to align with these goals. A review by Igbal et al. [42] identified four classes of FUs: i) unit-based (e.g., 1 tonne of MSW), ii) generation-based (e.g., amount of MSW generated by a community or city in a specific timeframe), iii) input (disposal) based (e.g., amount of MSW entering a treatment/disposal facility), and iv) output-based (e.g., amount of energy or resource recovered). The most common FU is unit-based, primarily '1-tonne-MSW'. Generation-based FUs are also common but more complex to handle in calculations. Disposal or input-based FUs are specific to studies focusing on treatment facilities' performance, excluding collection, transportation, and recycling impacts. Output-based FUs are rare and specific to studies comparing technologies based on energy or resource recovery. [42]

System boundaries, or 'boundary settings', are crucial for an LCA model. In waste management systems, it's impractical and beyond the scope to account for each waste item's life cycle in the stream, so waste entering the system is considered to have 'zero burden'. The 'cradle' of waste items is the point when an item is deemed valueless and discarded. Hence, the 'cradle-to-grave' term in waste management LCA is referred to as a 'gate-to-grave' approach. [42]

Following inventory analysis, the Life Cycle Impact Assessment (LCIA) is the next key stage of LCA, assessing the potential environmental impacts' magnitude and significance. Characterization factors can vary among LCIA methods based on the region and calculation methods, and there's no consensus on a single best method that can be generalized. [42]

In the review investigation of Igbal et al. the name and frequencies of the different LCIA methods are as follows: CML used by 27% of studies, ReCiPe by 10%, Eco-indicator by 8%, EDIP by 8%, IMPACT by 4%, and TRACI by 1%. [42]

2.5.1 LCA and Vermicomposting

During vermicomposting, microbes emit GHGs and volatile substances. Nitrate emissions rise, likely due to earthworm activity. CO2 emissions are higher initially, exceeding CH4 emissions. Vermicomposting reduces methane emissions compared to traditional methods, due to aerobic condition promoted by earthworms. Increased moisture can raise CH4 and N2O emissions by creating anaerobic pockets in the compost pile. [49]

Generally, the reuse of solid waste through composting and vermicomposting processes has a positive impact on the environment [23].

In the table 2.4, summary of recent LCA of waste management system were presented:

Table 2.4 - summary of Vermicomposting LCA in literature

goal and scope	functional unit	System Boundaries	LCI	LCIA (Impacts)	results	ref
Evaluate different manure management systems in Kampala, Uganda in terms of global warming potential and eutrophication potential	one tonne of impurity-free animal waste treated to produce a quality soil improver/fertilizer	The system started with waste reception and ended after fertilizer application in the field. Waste generation, collection and sorting steps were excluded as they were the same across systems.	Material/energy inputs, emissions and outputs were quantified for each life cycle stage and system based on measurements and literature data.	calculate GWP and eutrophication potential for each system.	The emissions factors for the vermicompost system were found to be 10.8, 62.3 and 12.8 g/ Megagram biowaste for methane, nitrous oxide and ammonia, respectively. satisfactory performance of vermicomposting in terms of global warming and eutrophication potential, although if the vermicompost generated is dumped, this could lead to increased eutrophication.	[26]
Evaluate the environmental impacts of the earthworms' (Eisenia foetida) production system reared on	production of 1 kg of dried earthworm meal and 80 kg of vermicompost	a "from cradle to gate" approach was applied with two different subsystems	collected over a three-month experimental test performed in year 2017, with questionnaires during interviews	Climate change (CC), Ozone depletion (OD), Terrestrial acidification	Between earthworm rearing and processing, the first one is the main responsible for the environmental impact for all the	[27]

a low-quality substrate made of fruit and vegetable waste (FVW)			with the farmer and during surveys to the experimental site	(TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PM), Metal depletion (MD) and Fossil depletion (FD).	evaluated impact categories except than for freshwater eutrophication and ecotoxicity. GHG emissions during composting are the main hotspots for Climate Change.	
investigate the environmental profile of the bioconversion process of FVW into earthworm dried meal as a novel food and feed protein source	1 kg of dried meal of earthworm	production process of earthworm meal was divided in two subsystems: - production of fresh earthworms and vermicompost, - in which fresh earthworms are used for the meal production.	The same as [27]	The same as [27]	main process hotspots are the emissions of methane, dinitrogen monoxide and ammonia taking place during vermicomposting, as well as FVW transport and electricity consumed during fresh earthworm processing. Respect to the one used as feed, the dried meal with food purpose shows a higher impact due to the higher economic value and to the higher electricity consumed during	[28]

					freeze drying compared to the oven-drying process for feed meal production.	
compare the existing MSWM system with other alternatives in terms of their environmental impacts in order to choose the best environmentally friendly options	the annual production of MSW, approximately equal to 229,207 t generated in 2018, with the hypothesis that the amount of MSW produced in 2018 was similar to the amount produced in 2016	generation, storage, collection, transportation, treatment and final disposal of MSW, as well as recycling. Open-loop recycling and the utilization of the electricity produced outside the boundaries of the system are considered, avoiding allocation issues	data were gathered from local documentation, field inspections of the sanitary landfill and MSWM facilities, and from interviews with local engineers and experts in the field of SWM	global warming potential (GWP100) (kg CO2-eq); eutrophication potential (EP) (kg PO43--eq); acidification potential (AP) (kg SO2-eq); and human toxicity potential (HTP) (kg 1,4-DCB-eq)	The implementation of AD, incineration with energy recovery and composting, and materials recycling in conjunction with controlled sanitary landfill, are the most preferable options in terms of environmental impacts.	[29]
evaluate vermicomposting as an environmentally friendly way of achieving the valorisation of grape marc waste	treatment of 1 tonne of grape marc	system divided into three subsystems (SS): Distillation, Seed oil extraction, Vermicomposting	most of the data related to the system correspond to primary data, while those relating to the background system water, electricity, fuel and chemicals) were taken from the coinvent® v3.5 database.	Global Warming (GW), Stratospheric Ozone Layer Depletion (SOD), Ozone Formation (OF), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Human Toxicity (HT), Terrestrial	energy requirement of the distillation process is an important hot spot of the process. Although the valorization route has some poor results in terms of the two environmental indicators (carbon footprint and normalised impact index), when economic revenues were included in this analysis, its environmental performance was better than that of other alternatives for bio-waste recovery.	[30]

				Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET) and Fossil Resource Scarcity (FRS)		

3 Methods

This chapter will discuss how to implement life cycle assessment of vermicomposting for Edelmark AS company, according to ISO 14044 [22]. This assessment will be performed in openLCA software which is developed for assessing environmental impact of processes for the period of one year of vermicomposting production.

3.1 First Step of LCA

3.1.1 First step of LCA - Goal, scope and functional unit

The primary aim of the study is to evaluate and compare vermicomposting for producing a soil fertilizer from biodegradable waste in Norway in terms of their environmental impacts. And perform sensitivity analyses to understand the influence of different parameters on the overall environmental performance of vermicomposting in Norway. The main scenario's environmental impacts will be compared to the production process of mineral fertilizer taken from literature.

The functional unit for this study is production of 1kg of vermicompost. This is because the interest was to obtain a quality soil fertilizer, and this could only be obtained when the same soil composition is produced.

3.1.2 First step of LCA - Impact categories and assessment method

A life cycle assessment is supposed to cover all kinds of environmental impacts. In the 2021 index tracking countries' progress towards the Sustainable Development Goals, Norway secured the seventh position. It has completely accomplished six goals and is making substantial progress towards an additional four. However, similar to numerous other OECD nations, Norway continues to confront "significant" or "major" hurdles in several goals, encompassing climate action, sustainable consumption behaviors, and biodiversity conservation. [45] Regarding this, Global Warming (GW) Eutrophication (E) are proposed impact categories that will be discussed in this thesis. The characterisation factors for these categories are as follow: for global warming, kg of CO_2-equivalents for CO_2, CH_4 and N_2O, for eutrophication, kg of phosphate-equivalents for nitrogen oxides (NO_x), ammonia (NH_3) and nitrate (NO_3)). For these categories of impacts, CML and ReCiPe Midpoint are the chosen ones.

3.1.3 First step of LCA - System Boundaries

System is consist of four main processes: transporting the feed from the biogas plant to the vermicomposting plant, feeding transported waste into the vermicomposting unit, packaging vermicompost and transporting packaged vermicompost to the farm. According to the aforementioned system, the system boundary is represented in Figure 3.1.

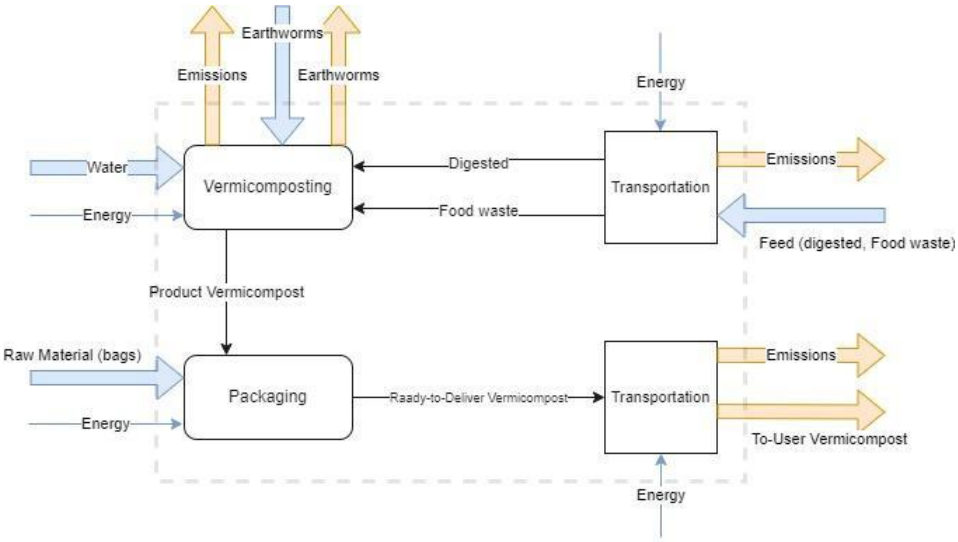

Figure 3.1 - System boundary of Vermicomposting Plant

3.2 Second step of LCA - LCI

For calculating the assessment, data needs to be obtained. Table 3.1 and Table C.1, shows the data collected from Edelmark AS company.

Table 3.1 - data provided for the system

Stream	**Parameter**	**Amount**
Waste into Vermicomposting process	Frequency of feeding	Once a Week
Waste into Vermicomposting process	Feed every time	10 lit / m2
Water into Vermicomposting process	Frequency of feeding	3 times a week
Water into Vermicomposting process	Feed every time	5 lit / m2
Vermicompost from Vermicomposting process	Frequency of harvesting	Once a Week
Vermicompost from Vermicomposting process	Produce every time	6.5 kg / m2

3.3 Assumptions

- No electricity for vermicomposting process: Due to negligible amount, heating is neglected.
- No transportation: due to closeness of vermicomposting to waste plant and market, transportation for this study is neglected.
- No change in Earthworm's mass during the period of study. Earthworms typically live about 8 years and because the time span of our study is 6 months, changes in earthworms are neglected.
- For the simplicity, it assumed the molar fraction of each component through the week is constant
- Vermicompost in Edelmark company is delivered in 1000 liters plastic bags. Density of product vermicompost is 0.7 g/cm3. The packaging used for one plastic bag is 150 g.

Since emissions data from vermicomposting is a molar fraction, it needs to transform to cumulative mass to be used in our LCA. For this, following assumptions are to be made:

- Mass transfer from the vermicomposting facility is an axial transfer from soil to surrounding air.
- There is no cumulation and it’s a steady state condition.
- There is no convective mass transfer above the soil.
- Approximately one meter above the surface is air without any change in molar fraction in the whole time span.
- Due to the low pressure of the surrounding area, diffusion is assumed to be ideal.

Regarding these assumptions, for calculation of cumulative mass of emitted gasses, according to mass balance, equation (3.1) can be deducted.

$$D_{iM}\frac{\partial^2 C_i}{\partial z^2}=0 \tag{3.1}$$

In equation (3.1), Dim is diffusivity of component i in the mixture, Ci is the concentration of component i and z is the axis where mass transfer occurred.

For calculation of diffusivity of component i in the mixture, equation (3.2) can be used.

$$D_{iM}=\frac{1-y_i}{\sum_j^m \frac{y_j}{D_{ij}}} \tag{3.2}$$

In equation (3.2), yi is the molar fraction of component i and Dij is diffusivity of component i through component j.

For calculation of Dij, the Wilke-Lee equation can be used, equation (3.3). [50]

$$D_{ij} = \frac{10^{-4}\left(1,084 - 0,249\sqrt{{}^{1}\!/_{M_i} + {}^{1}\!/_{M_j}}\right)T^{1,5}\left(\sqrt{{}^{1}\!/_{M_i} + {}^{1}\!/_{M_j}}\right)}{P(r_{ij})^2\Omega}$$

(3.3)

$$\Omega = f(\frac{kT}{\varepsilon_{ij}})$$

(3.4)

In equation (3.3), Mi is molecular weight of component i, T is Temperature in K, P is absolute pressure in Pa, rij is molecular separation at collision in nm and omega is collision function which can be obtained from figure 3.1. k is Boltzmann’s constant and epsilon is energy of molecular attraction which can be calculated from equation (3.6). Molecular separation at collision can be calculated according to equation (3.5).

$$r_{ij} = \frac{r_i + r_j}{2}$$

(3.5)

$$\varepsilon_{ij} = \sqrt{\varepsilon_i \varepsilon_j}$$

(3.6)

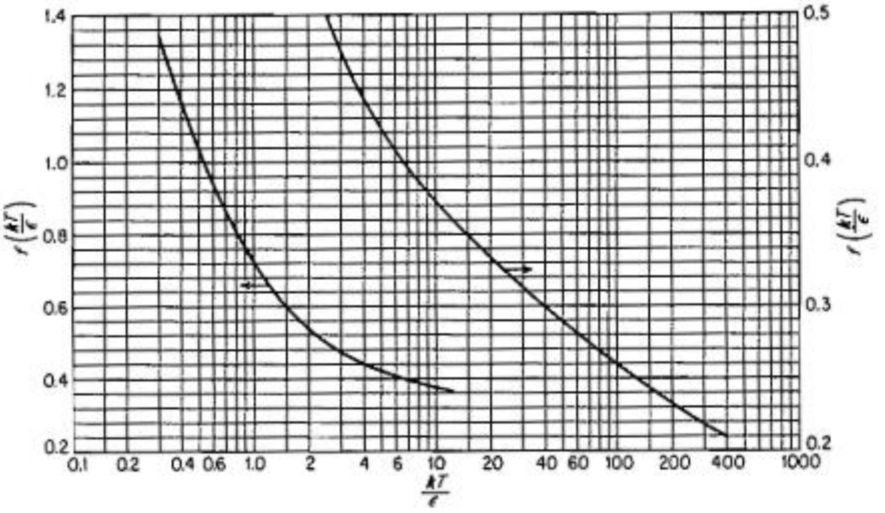

Figure 3.1 - Collision function [50]

Necessary data for diffusivity calculator can be found in the literature and shown in Table 3.2.

Table 3.2 - data for calculation of diffusivity [50]

Parameter	Component	Amount
M (g/gmol)	N2	14
	O2	32
	CO2	44
	NH3	17
r (nm)	N2	0.3798
	O2	0.3467
	CO2	0.3941
	NH3	0.2900
E/k (K)	N2	71.4
	O2	106.7

	CO2	195.2
	NH3	558.3
R (m3 * Pa) / (gmol * K)	-	8.3145
P (pa)	-	101325

For these calculations, python code was written and the code is presented in appendix A.

By using the formulas and data obtained from the mentioned company, data has been prepared that is presented in Table 3.3 for environmental impact analysis.

Table 3.3 - Data Calculated for LCA Calculation

Parameter	Unit	Data
packaging film, low density polyethylene (EcoInvent database)	kg	0.00015
Vermicompost (Product – regarding Functional unit)	kg	1
Feed	l	1.538
Tap water (EcoInvent database)	kg	2.307
Ammonia	kg	0.282
Carbon Dioxide	kg	0.109

Using the data in Table 3.3, LCA was performed for vermicompost.

To understand the performance of the vermicompositing process of the mentioned company, a fertilizer was chosen which is used in Europe for comparison (this fertilizer has, on average, less environmental impact than other fertilizers in the database) and for its data, the ecoinvent database was used.

3.4 OpenLCA Software

For pupose of LCA calculation, openLCA software was used. openLCA is a complimentary, professional-grade Life Cycle Assessment (LCA) and Footprint software, equipped with a wide array of features and accessible databases, developed by GreenDelta. As an open-source software, openLCA's source code is freely accessible and can be modified by anyone.

Initially, openLCA's primary application was environmental life cycle assessment, LCA. However, it was later expanded to also support economic life cycle assessment models, particularly in conjunction with LCA, in the form of Life Cycle Costing. Recently, in October

2013, a method for a comprehensive sustainability assessment, implemented during the European 7th FP PROSUITE project, was released as a free plugin for openLCA.

openLCA is a desktop application that operates without internet access. Additionally, openLCA can be configured to interact with a web-based database, which can be utilized for data and model exchange, among other things.

In the next chapter, life cycle assessment of vermicomposting will be discussed.

4 Result and Discussions

The output data of this life cycle assessments for vermicomposity using OpenLCA is shown in Table 4.1.

Table 4.1 – Impact Assessments for Vermicomposting

Impact Category	Eldenmark AS	Literature [25]	Unit
Global Warming	0.10999	17.7	kg PO4 eq
Eutrophication	-	0.168	kg PO4 eq
Freshwater eutrophication	1.18×10^{-8}	-	kg P eq
Marine eutrophication	2.17×10^{-9}	-	kg N eq

As can be seen from Table 4.1, due to the low amount of released gases and materials from the vermicomposting process, the range of environmental effects categories is very low.

As can be seen from the comparison of Eldenmark AS and study of Komakech et al. [25] which was focused on same idea of the comparison of the vermicompost and fertilzer, the process investigated in the mentioned company has shown lower values for environmental impacts, which is related to the fact that the amount of gases emitted is much lower than the sample. There are others based on which the environmental assessment has been done.

Also, in the field of global warming, vermicomposting has shown better results, and this can be due to the fact that the amount of carbon dioxide released in the vermicompost production process was low. And no more greenhouse gases are released. In this way, with the number of 0.10999 kg of carbon dioxide eq, it has provided one of the lowest global warming rates.

As it can be seen from the comparison of table 4.1 and 4.2, the eutrophication created in vermicomposting processes and fertilizer production have been compared with each other, which can easily be seen that the amount of eutrophication in vermicompost with numbers of 1.18 x 10-8 and 2.17 x 10 -9 is much lower than the fertilizer production process with values of 0.00023 and 0.00015, which can be attributed to the lack of release of compounds that create eutrophication.

Table 4.2 - LCA for NPK fertilizer from database

Impact Category	NPK (15-15-15) fertilizer production	Unit
Global Warming	1.02486	kg CO2 eq
Freshwater eutrophication	0.00023	kg P eq
Marine eutrophication	0.00015	kg N eq

This study has set to understand the environmental impact of Eldenmark AS's vermicomposting process and find out whether it is a sustainable replacement for other fertlizers. In general, by comparing the production processes of vermicompost and fertilizer, it can be seen that the environmental effects of the vermicompost production process are much less than the other investigated process. In this way, the use of vermicompost for soil fertility for use in agriculture is more economical from an environmental point of view, which makes the production process of vermicomposting in the mentioned company one of the strong substitutes for replacing fertilizers.

As the studied vermicomposting process is a good alternative for the industrail fertilizer, there is downfall in this process that can be optimized from environmetal viewpoint which the usage of plastic bags for packaging the final products. It can be easily altered with more sustainable and green bag and reduce the environmental impact of the process.

For development of the LCA study for studied process, there was limitaions that effect the final outcomes, include:

- Emissions from vermicomposting process can be more percise. More accurate measuements of output of process can lead to more percise results.
- Timespan of the study affects the result of LCA, due to the choice of season which study covers. If the study covers cold weather, energy will be used to maintain the temperature of the ficility. Energy spends also contribute to environmental impact of the studied process.

For future development, these points are suggested:

- Data collection can be more accurate.
- One of the final products of vermicomposting process is earthworm. Earthworm can be used as a protein source. It can be more accurta to investigate this usage which may affect final result of the LCA study.
- For more accurate decision for whether vermicompost is a proper alternative for fertilizer, percise measurments of final product is needed to find more accurate fertilizer to compare with. Also, economical and social point of view can affect the final result which in this study is not covered.

4.1 Conclusion

In this report, production process of vermicomposting in Edelmark AS was used to investigate the life cycle assessments of vermicomposting. With functional unit of 1 kg of vermicompost, environmental impact of this process regarding global warming and eutrophication was calculated using EcoInvent database and ReCiPe midpoint impact assessments. Global Warming 0.10999 kg CO2 eq, freshwater eutrophication 1.18 × 10-8 kg P eq and marine eutrophication 2.17 × 10-9 kg N eq were the result of this assessments.

These results show that vermicompost is a strong alternative for fertilizer agent for plant production. Due to digested nature of feed for this production, it can reduce environmental impact of fertilizers.

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6 Appendices

Appendix A

This chapter present the code written in Python to calculate the mass transfers from bioreactor producing vermicompost.

First step - importing necessary libraries:

```
import math
import pandas as pd
```

Second step – defining basic functions and parameters (according to equations in chapter 2 – Methods):

```
"""
0 = N2
1 = O2
2 = CO2
3 = NH3
"""
M = [14, 32, 44, 17] # g/gmol
R = 8.3145 # (m3 * Pa) / (gmol * K)
y2 = [0.79, 0.21, 0, 0] # molar fraction
P = 101.325 * 1000 # Pa
sigma = [0.3798, 0.3467, 0.3941, 0.2900] # nm (from Treybal)
def k_T_e_ab(i, j, T):
    epk = [71.4, 106.7, 195.2, 558.3] # K (epsilon/k)
    e_k_ab = math.sqrt(epk[i] * epk[j])
    return T * (1 / e_k_ab)

# function of omega is a logarithmic equation of epsilon to k * T
# it's based on the graph
def omega(i, j, T):
    x = k_T_e_ab(i, j, T)
    p_x = math.log(x)
    y = - 0.01779 * math.pow(p_x, 3) + 0.12491 * math.pow(p_x, 2) - (0.34328 * p_x) + 0.71918
    return y
```

Third step – defining diffusivity of gas mixture (according to equations in chapter 2 – Methods):

```
def Dif(i, j, T, P): # m2/s
    numerator = math.pow(10, -4) * math.pow(T, 1.5) * (1.084 - 0.249 * math.sqrt((1 / M[i])+ (1 / M[j]))) * (math.sqrt((1 / M[i])+ (1 / M[j])))
    denominator = P * math.pow((1/2 * (sigma[i] + sigma[j])), 2) * omega(i ,j, T)
    return numerator/denominator

def Dam(y, i, T, P): # m2/s
    numerator = (1 - y[i])
    denominator = 0
    for j in range(4):
        if j == i:
            continue
        denominator = denominator + y[j] / Dif(i, j, T, P)
    return numerator/denominator
```

Fourth step – defining gas flux in one week (according to equations in chapter 2 – Methods):

```
def F(T, P, y, y2, i): # gmol / m2 * week
    numerator = Dam(y, i, T, P) * P * (y[i] - y2[i])
    denominator = R * T
    return numerator/denominator * 604800
```

Fourth step – calculating mass transfer using our data:

```
# importing the data
project_data = pd.read_csv('project_data.csv')
# calculating the flux CO2 and Ammonia
flux = []
for j in [2, 3]:
    flux_j = []
    for k in range(17):
        x = list(project_data.iloc[k, 2:])
        temp = project_data.iloc[k, 1]
        flux_j.append(F(temp, P, x, y2, j) * M[j] / 1000) # kg / m2
```

```
    flux.append(flux_j)

# defing the dataframe for our data
project_data['CO2 Flux (kg / m2)'] = flux[0]
project_data['NH3 Flux (kg / m2)'] = flux[1]
```

Fourth step – calculating overall mass transfer in 24 weeks (according to chapter 2 – Methods):

```
co2_column = project_data['CO2 Flux (kg / m2)']
# assuming week first to 6th is similar to 7th and week 24th is similar to 23rd
overall_co2 = co2_column[0] * 6 + co2_column[16] + co2_column.sum()
nh3_column = project_data['NH3 Flux (kg / m2)']
overall_nh3 = nh3_column[0] * 6 + nh3_column[16] + nh3_column.sum()
```

Appendix B:

This chapter presents the procedure of applying LCA using OpenLCA open source software.

First step: Adding the processes (Vermicomposting and Packaging)

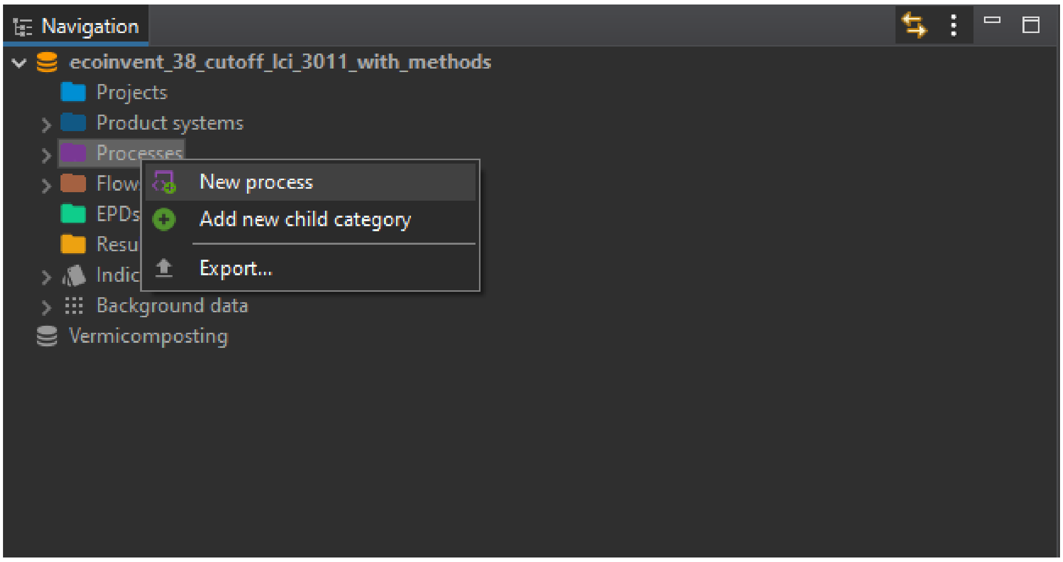
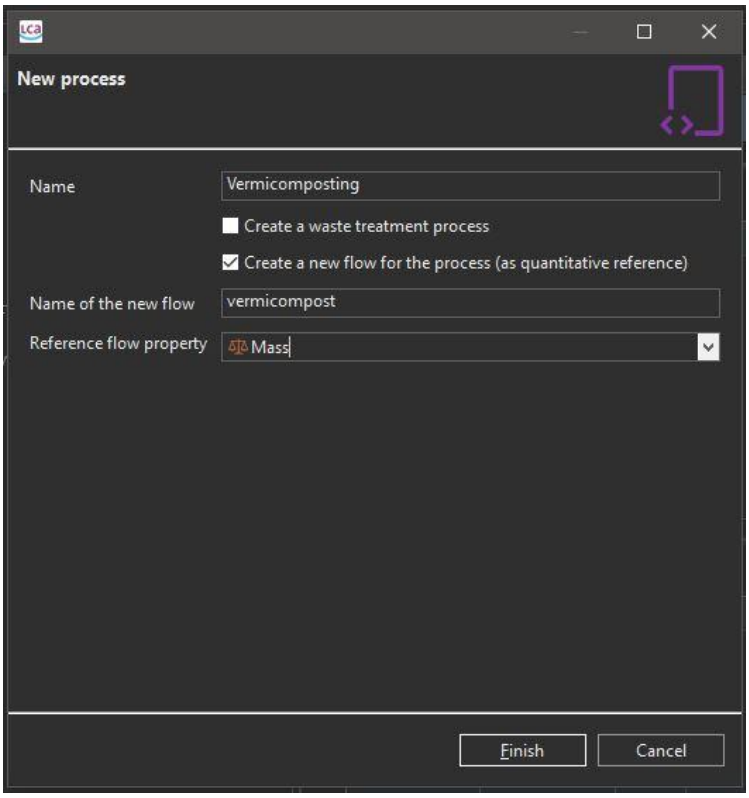


Figure B.1 – adding new process



Name: Vermicomposting

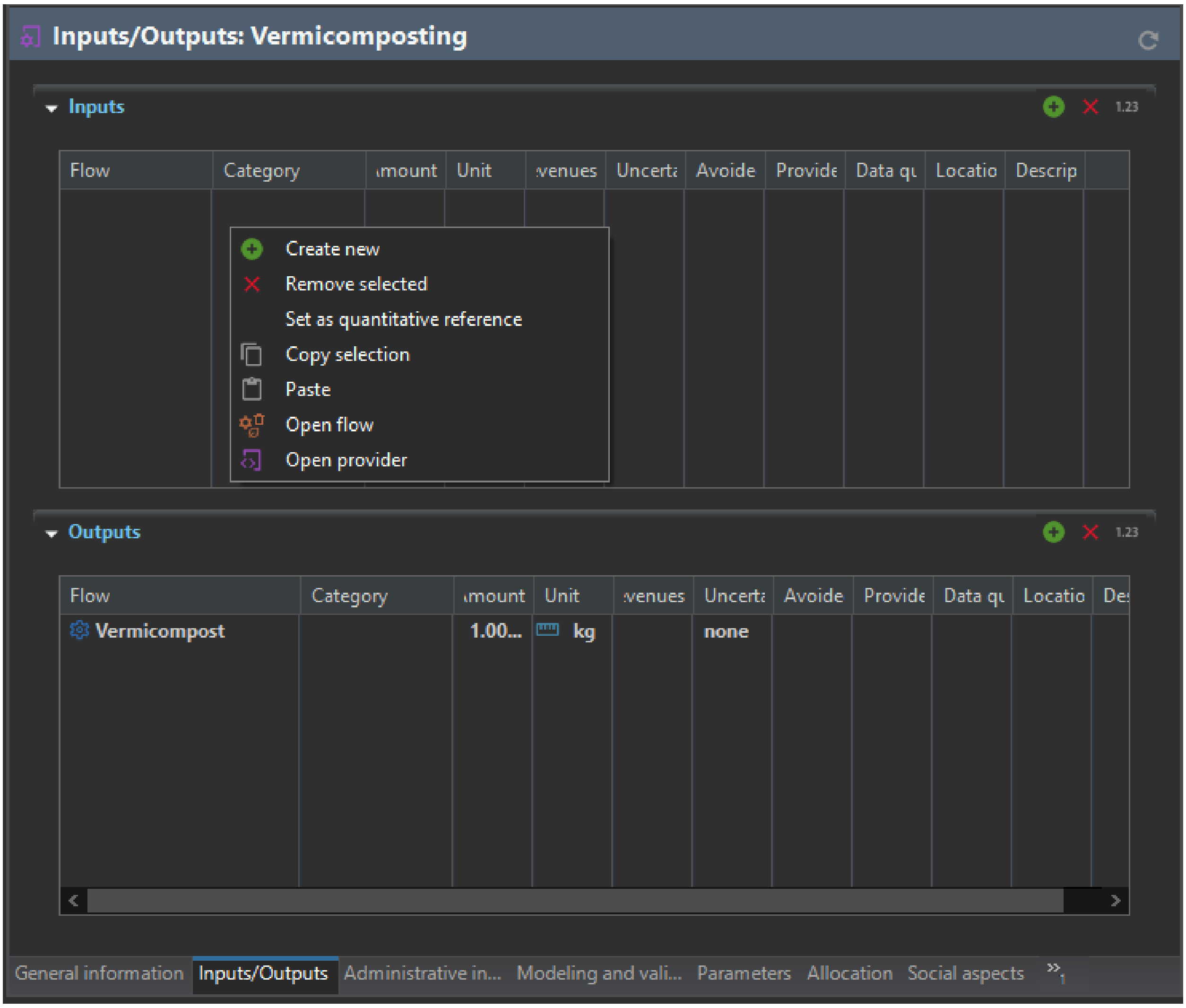
☐ Create a waste treatment process

☑ Create a new flow for the process (as quantitative reference)

Name of the new flow: vermicompost

Reference flow property: Mass

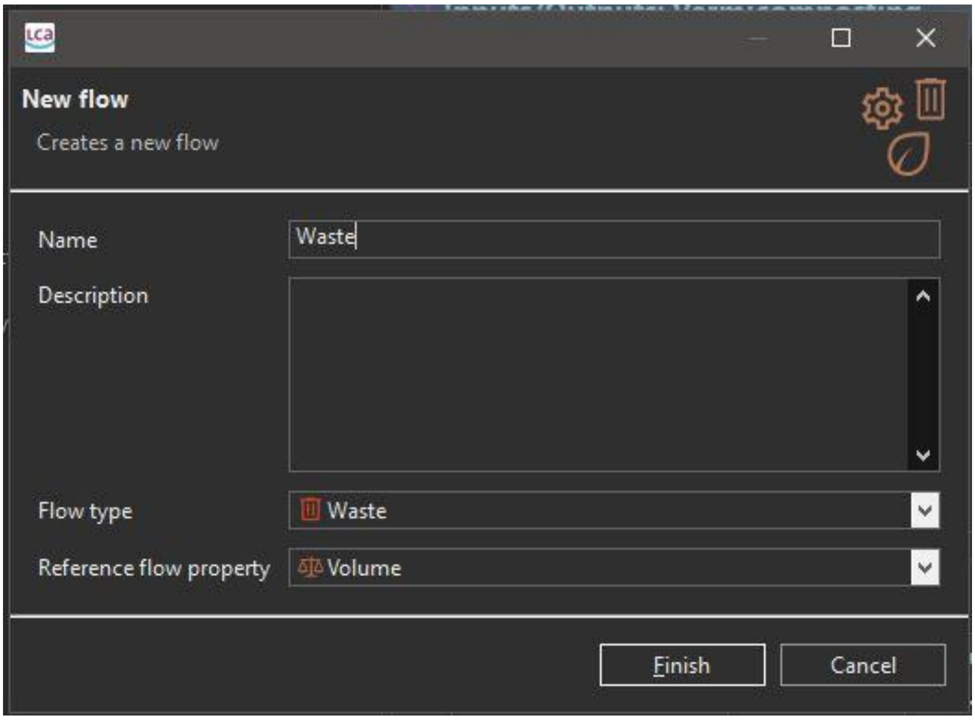
Figure B.2 – filling process form



Flow	Category	mount	Unit	venues	Uncert	Avoide	Provide	Data qu	Locatio	De
Vermicompost		**1.00...**	**kg**		**none**					

Figure B.3 – adding flow for the process

Figure B.4 – adding non-existing flow (Feed and Vermicompost product)



New flow

Creates a new flow

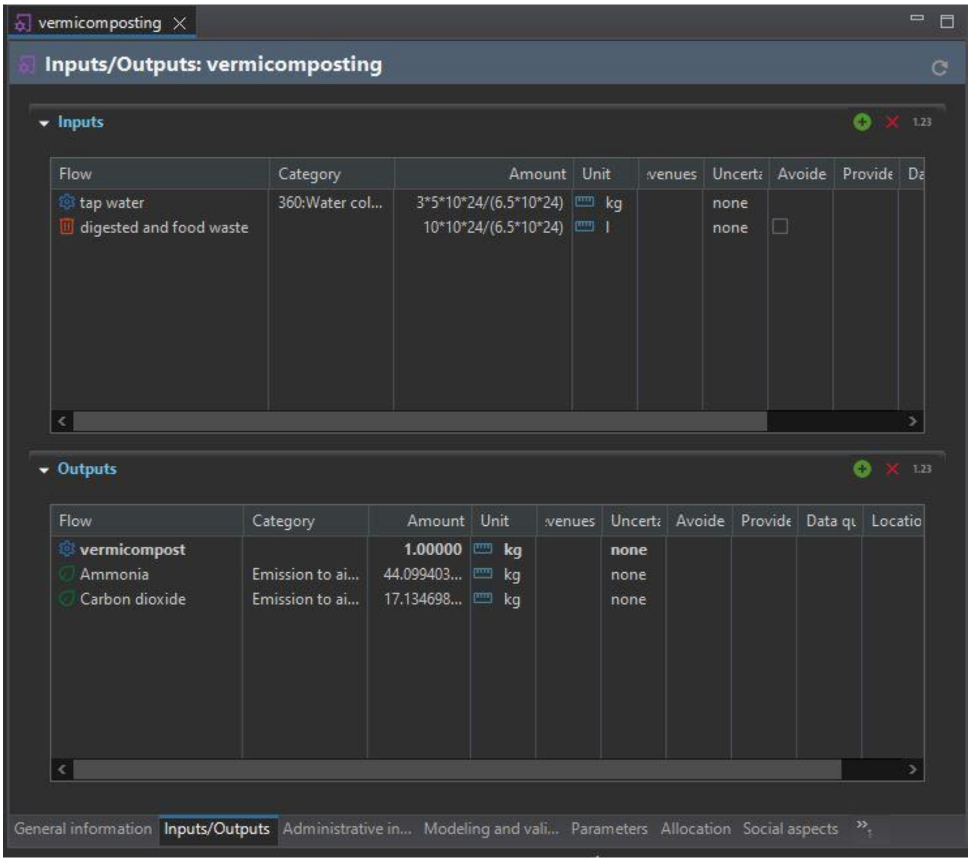
Name: Waste

Description:

Flow type: Waste

Reference flow property: Volume

Figure B.5 – filling new flow form for Feed



Inputs/Outputs: vermicomposting

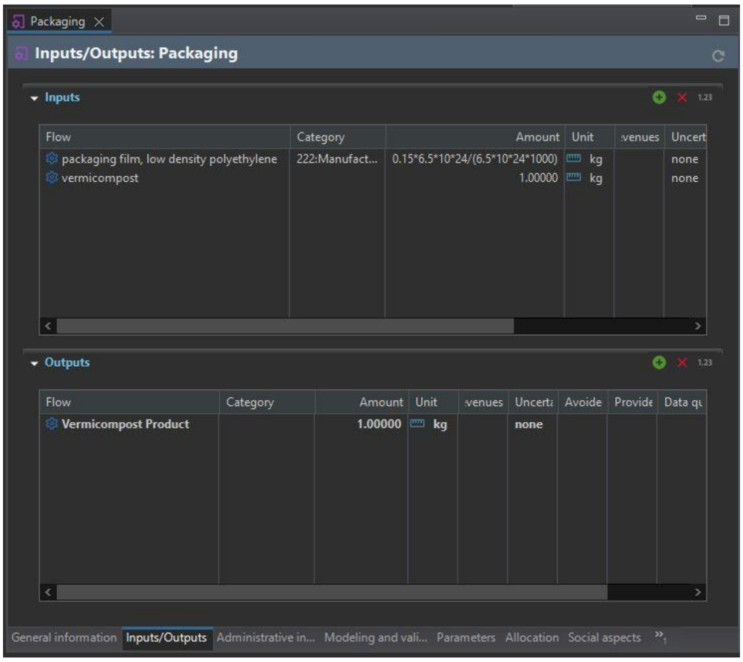
Inputs

Flow	Category	Amount	Unit	:venues	Uncert:	Avoide	Provide	Da
tap water	360:Water col...	3*5*10*24/(6.5*10*24)	kg		none			
digested and food waste		10*10*24/(6.5*10*24)	l		none	☐		

Outputs

Flow	Category	Amount	Unit	:venues	Uncert:	Avoide	Provide	Data qu	Locatio
vermicompost		**1.00000**	**kg**		**none**				
Ammonia	Emission to ai...	44.099403...	kg		none				
Carbon dioxide	Emission to ai...	17.134698...	kg		none				

Figure B.6 – completing Vermicomposting process



Inputs/Outputs: Packaging

Inputs

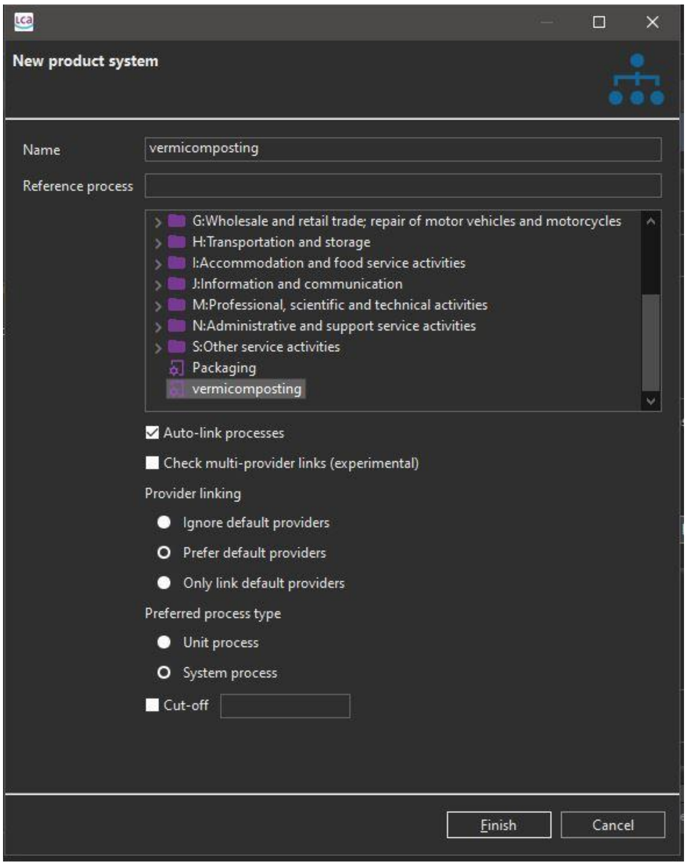
Flow	Category	Amount	Unit	:venues	Uncert
packaging film, low density polyethylene	222:Manufact...	0.15*6.5*10*24/(6.5*10*24*1000)	kg		none
vermicompost		1.00000	kg		none

Outputs

Flow	Category	Amount	Unit	:venues	Uncert:	Avoide	Provide	Data qu
Vermicompost Product		**1.00000**	**kg**		**none**			

Figure B.7 – completing Packaging process

Second step: Creating Product Systems



Name: vermicomposting

Reference process:

- G:Wholesale and retail trade; repair of motor vehicles and motorcycles
- H:Transportation and storage
- I:Accommodation and food service activities
- J:Information and communication
- M:Professional, scientific and technical activities
- N:Administrative and support service activities
- S:Other service activities
- Packaging
- vermicomposting

☑ Auto-link processes

☐ Check multi-provider links (experimental)

Provider linking

- ● Ignore default providers
- ○ Prefer default providers
- ● Only link default providers

Preferred process type

- ● Unit process
- ○ System process

☐ Cut-off

Figure B.8 – adding new product systems

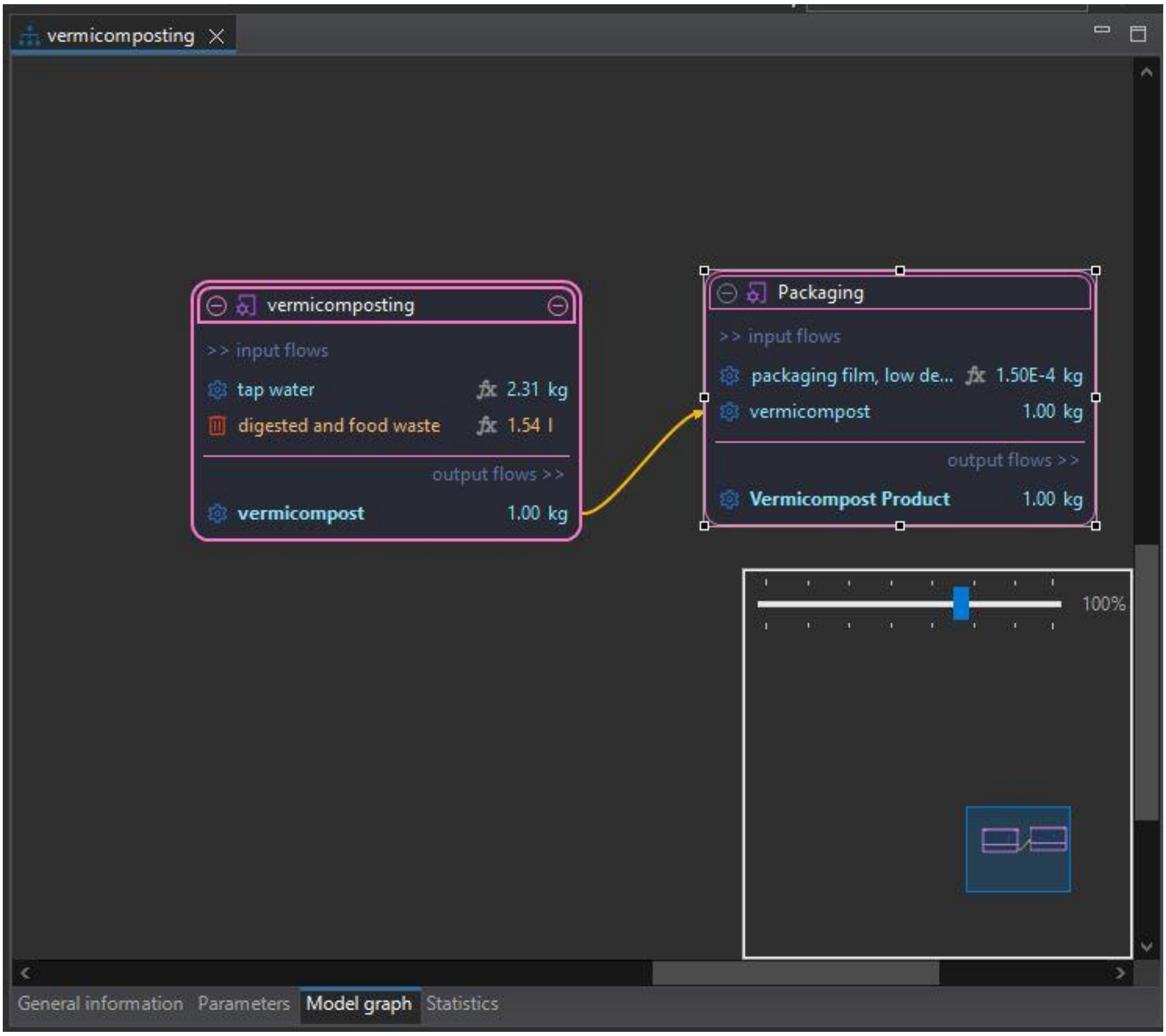
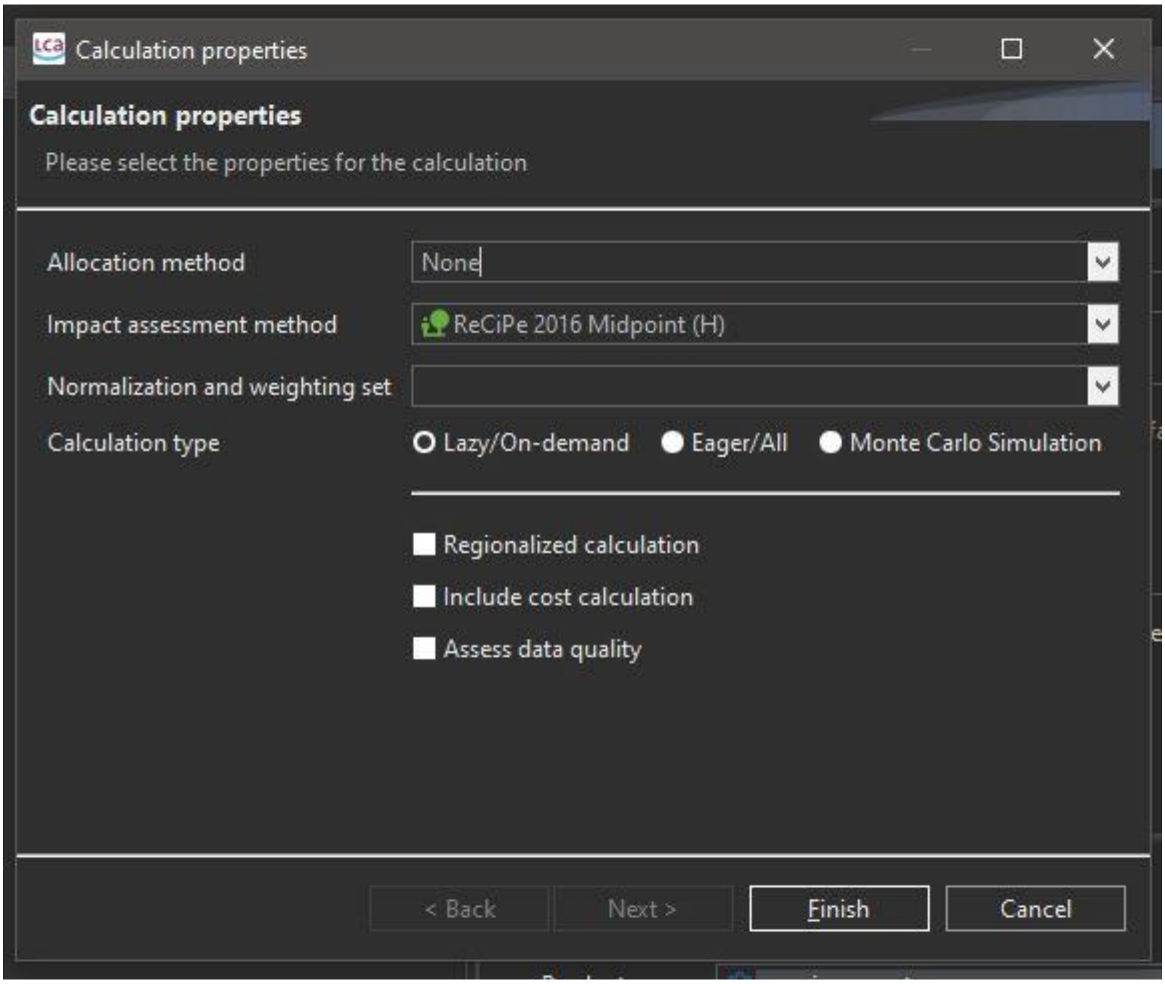


Figure B.9 – completing model graph of product system

Third step: Calculating LCA



Calculation properties

Calculation properties

Please select the properties for the calculation

Allocation method: None

Impact assessment method: ReCiPe 2016 Midpoint (H)

Normalization and weighting set:

Calculation type: ○ Lazy/On-demand ● Eager/All ● Monte Carlo Simulation

☐ Regionalized calculation

☐ Include cost calculation

☐ Assess data quality

Figure B.10 – calculation settings

Appendix C:

Table C.1 - Emissions from Vermicomposting Process

	Week number	Measuring point	Average Temp	Average CH4	Average CO2	Average O2	Average NH3
1	7	A	**19.33**	**0.00**	***3.1***	***19.40***	***27.67***
		B	**20.00**	**0.00**	***1.03***	***21.13***	***21.00***
Average			**19.67**	**0**	**2.07**	**20.27**	**24.33**
2	8	A	**21.33**	**0.00**	***4.43***	***19.40***	***18.33***
		B	**22.00**	**0.00**	***2.73***	***21.13***	***15.67***
Average			**21.67**	**0**	**3.58**	**20.27**	**17.00**

3	8	A	22.67	0.00	***3.47***	***19.30***	***7.59***
		B	22.00	0.00	***2.53***	***19.90***	***7.48***
Average			**22.33**	**0.00**	**3.00**	**19.60**	**7.53**
4	8	A	24.00	**0.00**	***2.33***	***20.33***	***17.33***
		B	23.33	**0.00**	***4.53***	***17.73***	***17.00***
Average			**23.67**	**0.00**	**3.43**	**19.03**	**17.17**
5	9	A	24.00	**0.00**	***3.33***	***18.23***	**17.08**
		B	25.00	**0.00**	***2.43***	***18.7***	**17.13**
Average			**24.50**	**0.00**	**2.88**	**18.47**	**17.10**
6	9	A	25.33	**0.00**	***6.73***	16.37	**17.11**
		B	26.67	**0.00**	***4.67***	18.1	**17.11**
Average			**26.00**	**0.00**	**5.70**	**17.23**	**17.11**
7	9	A	27.67	**0.00**	***4.4***	19.6	**17.11**
		B	27.33	**0.00**	***4.2***	19.46666667	**17.11**
Average			**27.50**	**0.00**	**4.30**	**19.53**	**17.11**
8	10	A	28.67	**0.00**	***2.73***	19.46666667	**17.11**
		B	28.33	**0.00**	***3.70***	18.4	**17.11**
Average			**28.50**	**0.00**	**3.22**	**18.93**	**17.11**
9	10	A	29.00	**0.00**	***2.83***	19.46666667	**17.11**
		B	29.00	**0.00**	***2.27***	20.03333333	**17.11**
Average			**29.00**	**0.00**	**2.55**	**19.75**	**17.11**
10	11	A	32.00	**0.00**	***3.20***	**18.66666667**	**17.11**
		B	31.33	**0.00**	***3.87***	**18.4**	**17.11**
Average			**31.67**	**0.00**	**3.53**	**18.53**	**17.11**
11	11	A	30.67	**0.00**	***2.87***	**19.33**	**17.11**
		B	30.33	**0.00**	***3.53***	**19.2**	**17.11**
Average			**30.50**	**0.00**	**3.20**	**19.27**	**17.11**
12	12	A	34	**0.00**	***3.47***	18.57	**17.11**
		B	31.67	**0.00**	***4.20***	17.90	**17.11**
Average			**32.83**	**0.00**	**3.83**	**18.23**	**17.11**

13	12	A	33.33	**0.00**	***2.40***	19.17	**17.11**
		B	32.33	**0.00**	***5.23***	17.50	**17.11**
Average			**32.83**	**0.00**	**3.82**	**18.33**	**17.11**
14	13	A	32.67	**0.00**	***1.90***	20.77	**17.11**
		B	31.67	**0.00**	***3.73***	19.13	**17.11**
Average			**32.17**	**0.00**	**2.82**	**19.95**	**17.11**
15	13	A	31.33	**0.00**	***1.20***	20.23	**17.11**
		B	31.00	**0.00**	***2.90***	19.00	**17.11**
Average			**31.17**	**0.00**	**2.05**	**19.62**	**17.11**
16	14	A	31.33	**0.00**	***2.57***	19.60	**17.11**
		B	31.33	**0.00**	***6.53***	15.83	**17.11**
Average			**31.33**	**0.00**	**4.55**	**17.72**	**17.11**
17	15	A	28.00	**0.00**	***2.73***	19.80	**17.11**
		B	28.00	**0.00**	***4.03***	18.13	**17.11**
Average			**28.00**	**0.00**	**3.38**	**18.97**	**17.11**
18	16	A	29.33	**0.00**	***1.43***	20.07	**17.11**
		B	28.33	**0.00**	***2.20***	20.07	**17.11**
Average			**28.83**	**0.00**	**1.82**	**20.07**	**17.11**
19	17	A	26.33	**0.00**	***2.03***	19.90	**17.11**
		B	26.00	**0.00**	***5.13***	17.70	**17.11**
Average			**26.17**	**0.00**	**3.58**	**18.80**	**17.11**
20	18	A	26.33	**0.00**	***2.03***	19.90	**17.11**
		B	26.00	**0.00**	***5.13***	17.70	**17.11**
Average			**26.17**	**0.00**	**3.58**	**18.80**	**17.11**
21	18	A	27.67	**0.00**	***3.37***	17.83	**17.11**
		B	27.67	**0.00**	***3.90***	18.10	**17.11**
Average			**27.67**	**0.00**	**3.63**	**17.97**	**17.11**
22	19	A	26.67	**0.00**	***3.97***	18.17	**17.11**
		B	27.33	**0.00**	***4.20***	18.13	**17.11**
Average			**27.00**	**0.00**	**4.08**	**18.15**	**17.11**

23	20	A	28.00	**0.00**	***4.40***	17.77	**17.11**
		B	27.33	**0.00**	***4.33***	17.60	**17.11**
Average			**27.67**	**0.00**	**4.37**	**17.68**	**17.11**
24	21	A	28.67	**0.00**	***4.7***	**17.37**	**17.11**
		B	28.00	**0.00**	***4.5***	**17.30**	**17.11**
Average			**28.33**	**0.00**	**4.60**	**17.33**	**17.11**
25	22	A	30.00	**0.00**	***5.3***	**16.90**	**17.11**
		B	29.67	**0.00**	***5.43***	**16.50**	**17.11**
Average			**29.83**	**0.00**	**5.37**	**16.70**	**17.11**
26	23	A	30.33	**0.00**	***5.53***	**16.80**	**17.11**
		B	30.33	**0.00**	***5.47***	**16.60**	**17.11**
Average			**30.33**	**0.00**	**5.50**	**16.70**	**17.11**