TALLINN UNIVERSITY OF TECHNOLOGY

SCHOOL OF ENGINEERING

Department of Civil Engineering and architecture

A comparison of the carbon footprint of biodegradable waste treatment technologies in Estonia

Biolagunevate jäätmete käitlustehnoloogiate süsiniku jalajälje võrdlus Eestis

MASTER THESIS

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Tallinn 2021

(*On the reverse side of title page*)

AUTHOR’S DECLARATION

Hereby I declare that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

26.05.2021

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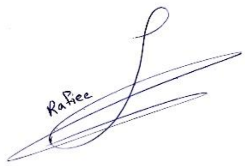

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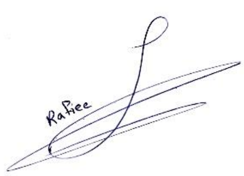

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Department of Civil Engineering and architecture

THESIS TASK

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Study programme: EABM, Environmental Engineering and Management

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Thesis topic:

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Thesis main objectives:

1. The calculation of carbon footprint of three biowaste treatment technologies
2. Decide which biowaste treatment technology can be implemented in practice

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Completing literature review and introduction	10.03.2021
2.	Writing methodology and working with Open LCA	01.05.2021
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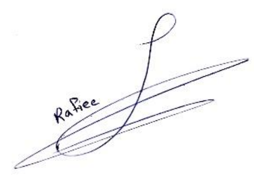

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LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
WWTP	Wastewater Treatment Plant
VAT	Value-Added Tax
GWF	Global Warming Factor
WW	Wet Waste
HFW	Household Food Waste
DM	Dry Matter
FM	Facilities Management
GW	Green Waste
UPFW	Unprocessed Food Waste
PFW	Processed Food Waste
BtB	biowaste to bioenergy
HC	hydrothermal carbonization
GHG	emissions of greenhouse gasses
LCA	Life Cycle Assessment
IPCC	Intergovernmental Panel on Climate Change
GTP	Global Temperature Potential
MSW	Municipal Solid Waste

1. INTRODUCTION

One of the leading global concerns is food waste. The world's developing economies waste food worth billions of dollars per year. The issue does not stop at that point when food is wasted, More than 95% of food waste ends up in landfill sites, wherein anaerobic conditions, methane, carbon dioxide, and other greenhouse gasses are formed[1].

The depth of the tragedy is more apparent. It shows the last update of the produced waste and its impact on the earth, contributing to greenhouse gas emissions that lead to climate change [2]—also, more food waste, more exposed the natural resources to the risk.

Throwing away edible food means financial losses. The amount of food thrown away amounts to a family of four, losing nearly $1,760 annually. Moreover, the food that ends up in the waste stream requires resources, the cost of which is passed on to local utilities and facilities, to handle its disposal and diversion[1][3].

From pollution to overpopulation, human activities drive up the earth's temperature, leading to a change in the world around us. One of these changes is global warming, which means the average global temperature was increasing over recent years. This temperature acceleration is the leading cause of climate change.

One of the reasons is the greenhouse effect of gases. Gases in the atmosphere, such as water vapor, carbon dioxide, methane, nitrogen oxides, and chlorofluorocarbons, trap heat near the earth through a naturally occurring greenhouse effect. This process begins with the sun and the energy radiated to the earth, and they absorb some of this energy, and the rest shine back into space [4].

Naturally occurring gases in the atmosphere trapped some of this energy and reflected, warming the earth. Scientists now believe that the greenhouse effect is being intensified by the extra greenhouse gases humans have released. One of the sources of emitting greenhouse gases is waste treatment facilities and plants.

The amount of municipal solid waste produced globally is 2,01 billion tons annually, with at least 33 percent of that not managed environmentally [5]. It predicted that this amount would reach 3,40 billion tons by 2050 [1][5].

One methodology to evaluate the environmental impact from different treatment methods is calculating the carbon footprint, which assesses the effect of all greenhouse gases released during these processes expressed as carbon dioxide equivalent[6].

Carbon footprint results can give an excellent vision to waste managers to choose the most environmentally sustainable treatment method.

This study aims to investigate the environmental impact of different bio-waste treatment methods, using carbon footprint methodology and the appropriate treatment option will be recommended based on the assessment. Different waste treatment scenarios such as composting, incineration, and anaerobic digestion of municipal solid waste (MSW) were selected for the comparison.

2. THEORETICAL BACKGROUND

2.1 European and Estonian legislation

According to the European Commission, biodegradable waste, also called bio-waste, is" biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants. It does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste such as natural textiles, paper, or processed wood.
It also excludes those by-products of food production that never become waste[7]". According to a report[5], 44% of the waste composition is food and green, contributing to the environmental problems if they are not managed well.

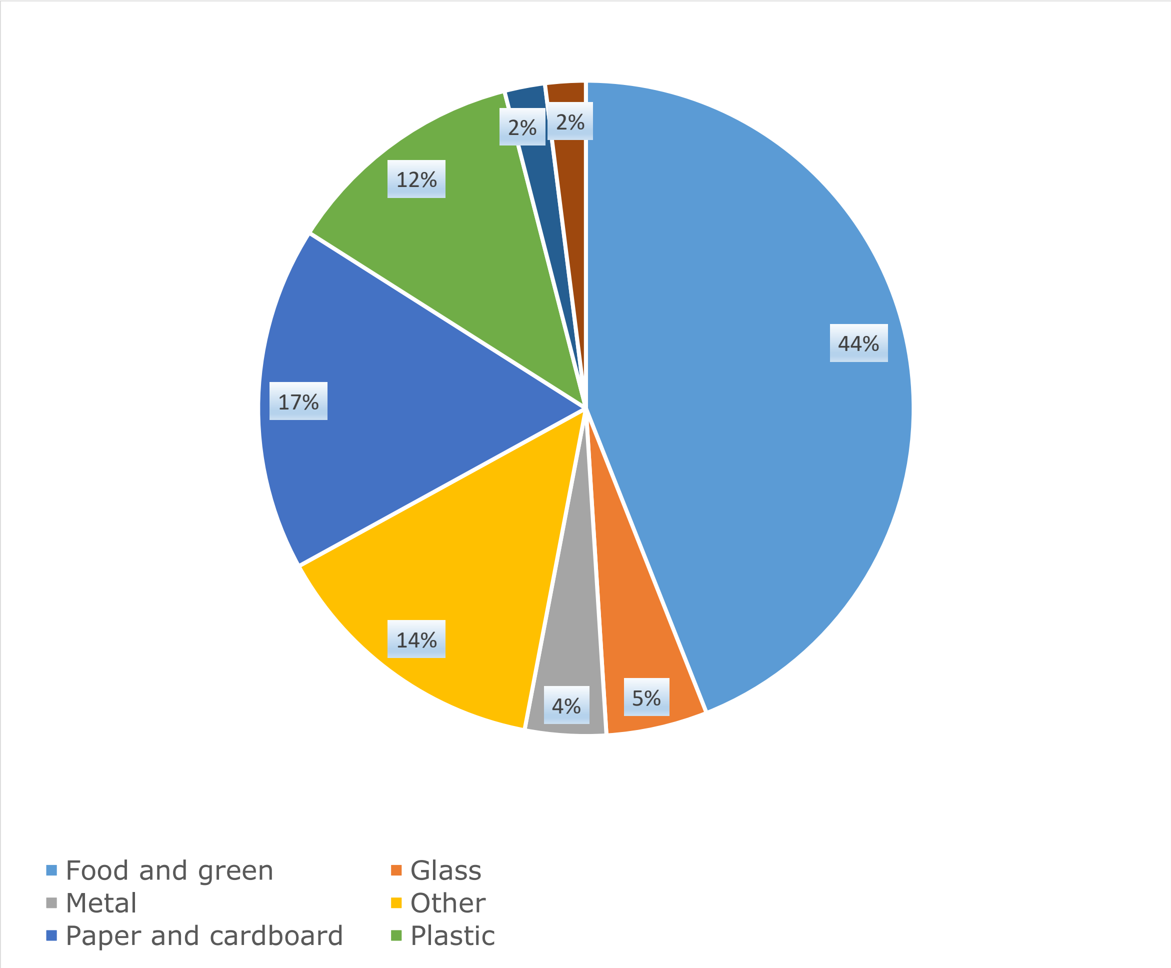

Figure 2.1 Global waste composition [5]

According to the Waste Act, as determined by the European Parliament and waste framework directive (2008/98/E.C. emendation) [8], the amount of waste entering aerobic or anaerobic biodegradable waste treatment can be counted as recycled.

Mainly the output of these treatments is digestate or compost. It is highlighted in paragraph 56 that the Member States should collect biodegradable waste separately for several reasons [8]. In the own version of the waste directive, referring to article 10, Member States shall take the appropriate steps to ensure that waste is recovered during recovery operations [9].

The deadline for the implementation of this rule is Dec. 31, 2021. From Jan. 01, municipal bio-waste can be considered recycled only if collected separately or separated at the source. The importance of choosing the most appropriate treatment method and the use of environmentally safe materials produced from bio-waste were some crucial points of article 22 of the waste directive [9]; moreover, in the emendation version, it is replaced by more paragraphs such as:

- By Dec. 31, 2023, the bio-waste should not be mixed with other waste types. However, it can be collected with some types of waste which has biodegradability or composability properties.

- Members states should encourage home composting

- Promote the use of materials produced from bio-waste[8]

Regarding the waste Act [8], there is a definition of waste treatment to prepare waste for recovery or disposal. This preparation consists of thermal, chemical, mechanical, or biochemical impact on waste to reduce the harmfulness, facilitate its management or disposal or enhance the waste’s recovery.

According to ECN [10] report, municipalities are in charge of MSW collection from households and larger blockhouses and collect the waste of parks and green areas. In Estonia, dominating composting is windrow one, while anaerobic digestion (AD) is used in Wastewater Treatment Plants (WWTPs) and Mechanical Biological Treatment (MBT) Mechanical Biological Treatment (MBT), and there are some AD plants for agricultural waste and biowaste.

In general, all the implementations and developments of the National Waste Management plan and other management policies are under the Ministry of Environment monitoring. The environmental board, which consists of six different regional offices, has the authority to issue permits. Municipalities are in charge of implementing the collection, transferring, and disposal of waste in Estonia [11]. There is a door-to-door collection of waste for 95% of Estonia’s population, and 40% of biowaste is collected separately by this scheme[11].

The Environmental Board of the Republic of Estonia [12] is responsible for reusing and recycling waste. However, there are no more options for some types of waste except for landfilling or burning. Although it is possible to use the energy generated from waste burning, it is not environmentally friendly and produces many harmful emissions and pollutants.

As a result, several companies, local governments, and organizations monitor waste collection and transportation to waste disposal to be able to minimize the effect of environmental pollution. The environmental board’s responsibility is to issue permits to these companies which monitor waste collection and disposal, check the amount of refuse they produce, what kind of treatment technologies they are using, and how energy-efficient they are.

To meet the European Union requirements and criteria, all efforts are to close numerous landfill sites, and up to now, more than three hundred of these site closures have been done successfully in Estonia [12]. Besides, after the closure, monitoring of these landfill zones should be continued.

The second national waste management plan in Estonia set a stricter target than the original target set by the European Union waste directive. The maximum amount for biowaste deposited in landfills by July 2020 shall not exceed 20% of the total amount of weight of municipal waste deposited in landfills [13]. In Estonia, this target was met in 2012 because mechanical biological treatment was used, and also more biodegradable and green waste were sent to other types of treatment facilities instead of landfills (Figure 2.2) [14].

This fast reduction of landfills is mainly due to the establishing mechanical biological treatment on a small scale in 2007, the introduction of landfilling tax, and the ban on landfilling of unsorted waste [14].

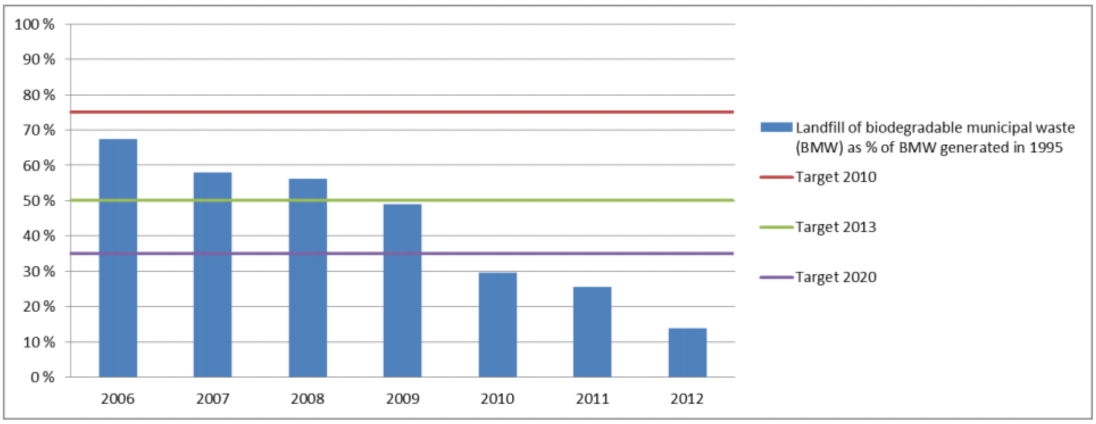

Figure 2.2 The percentage of sending biowaste to landfills from 2006 to 2012 in Estonia [14].

Another reason that caused a reduction in the amount of green waste to landfills is the gate fee for landfills, which is 31.5 Euros without VAT and 37.8 Euros with VAT[15],[16] and in 2012 it was even more expensive 50 Euros per one ton of biowaste. This reduction was a result of higher collection rate of separated bio-waste and the recycling of this bio-waste through composting which caused lower amount of waste to end up at landfill and a lower taxation for disposal.

Also, the price for emptying waste containers and transporting them is another essential factor that would be considered for landfilling. For example, in Tallinn, there are some fees based on the number of containers from different parts of the city to the landfill site. Table 1 shows some examples of these price lists [17]. As a result, most garden wastes were home composted [18].

Table 2.1 Emptying of 240 L bio-waste containers and transportation fee of Tallinn [17]

City Part	**Price without VAT (Euro)**	**Price Wit VAT (Euro)**
Viimsi	0.83	1.00
Old town	1.20	1.44
City center	1.07	1.28
Nõmme	1.16	1.39

2.2 Treatment Methods

The aim of getting rid of organic waste had numerous negative environmental consequences, from occupying lands to releasing greenhouse gas emissions, and the only benefit from this traditional waste management is economical[19]. Changes in the effect on the environment and the utilization of resources are not only due to changes in the methods of waste disposal but also primarily due to changes in the surrounding processes (energy and agriculture) triggered by changes in the practices of waste management [19].

Several aspects should be considered for choosing a waste treatment method, and assessment should include the evaluation based on economic, environmental, and social criteria [20]. Various researches used different scenarios based on the intended criteria[21][22][23]. There are many treatment methods applied for biowaste, among others are composting, incineration, anaerobic digestion, open dump, recycling, and sanitary landfilling.

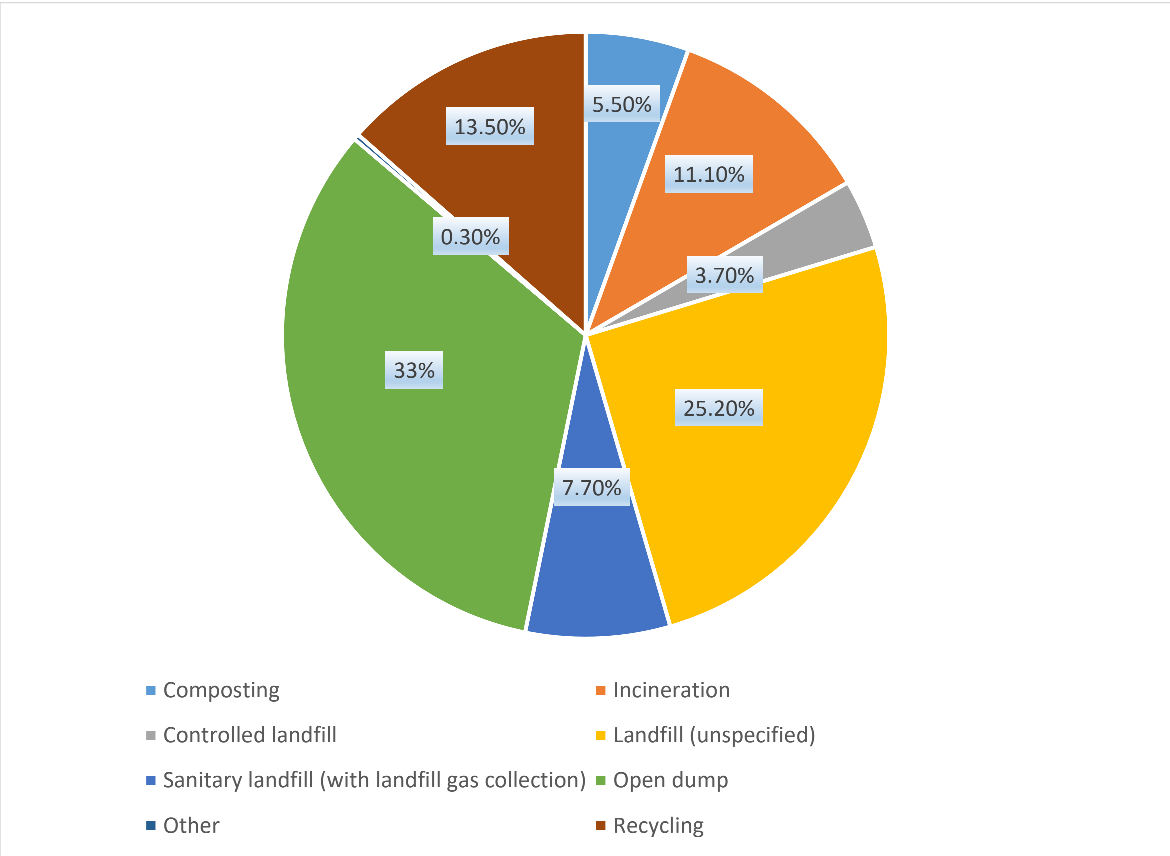

Figure 2.3 Global treatment and disposal of municipal solid waste[5]

2.2.1 Composting

Composting is a waste recycling process based on the biological degradation of organic matter under aerobic conditions in the presence of microorganisms, producing compost that is stabilized and sanitized [24] [25].

Hemidat et al.[26] found out the composting contribution to global warming. GHG emissions are highly dependent on various factors such as waste type and composition, the technology used for composting, and compost application. According to mentioned factors, the global warming factor (GWF) was between -900 (CO_2-equivalents tonne $^{-1}$ wet waste (WW)) and a net load of 300 (CO_2-equivalents tonne $^{-1}$ (WW)).

There are sub-technologies for this method like Indian Bangalore Composting, Vessel Composting, Windrow Composting, Vermicomposting, Static Composting, Sheet Composting, Indian Indore Composting, and Berkley Rapid Composting. However, windrow composting is the most common due to the lower operation cost, higher efficiency, and process and layout simplicity[27].

The second most used technology is in-vessel composting, which requires less space than windrow composting [28]. Windrow is the general term for a long pile of stack raw materials. This method is suitable for biowaste on a large scale and producing a large volume of compost. Aeration of the materials is crucial, and oxygen needs to be replenished as it is consumed; otherwise, the piles go anaerobic in the center, following a different decomposition process and produces foul odors. It is achieved by mixing fine dusty, wet, or soft materials.

Piles are customarily turned, which can be done mechanically or manually. As a result, air, and therefore oxygen, get into the pile. Besides, the materials at the exterior of the pile are now in the interior to be decomposed by microorganisms. This method needs much space because the windrows have sloped sides and cannot be put too close together.

However, in-vessel technology describes a group of methods that confine the composting materials within containers or vessels, Two factors; airflow and temperature can be controlled more easily compared with other types of composting techniques.

Turning or stirring takes place manually or mechanically. This method requires less surface area than windrow technology since the composting process is shorter than other types of composting.

It seems that compost quality highly depends on the separation at the source [29]. It means that if the impurities at the source of Household Food Waste (HFW) are adequately minimized, the quality of the resulting compost would be at the highest level. The contents of 1kg of compost and heavy metal contents are extracted with an ecoinvent database (Table 2.2 and 2.3) [30]. In these two tables, DM and FM compost stand for dry matter and facilities management.

Table 2.2 The content of 1 kg of compost[30]

Material	**Unit**	**Per kg DM compost**	**Per kg FM compost**	**Per kg FM bio-genic waste**
Calcium (total)	g/kg	50,41	26,57	13,28
Magnesium (total)	g/kg	5,25	2,77	1,38
Nitrogen (total)	g/kg	13,63	7,18	3,59
Phosphate (total)	g/kg	6,32	3,3	1,67
Potassium (total)	g/kg	12	6,32	3,16
Sulphur (total)	g/kg	1,91	1,01	0,50

Table 2.3 The heavy metal content of 1 kg of compost [30]

Heavy metal	**Unit**	**Per kg DM compost**	**Per kg FM compost**	**Per kg FM bio-genic waste**
Cadmium	g/kg	0,29	0,15	0,08
Copper	g/kg	38,105	20,08	10,04
Lead	g/kg	26,625	14,03	7,02
Mercury	g/kg	0,1	0,05	0,0
Nickel	g/kg	16	8,43	4,22
Zinc	g/kg	120,345	63,42	1,71

Composting also can be done indoors at the home scale, which can have its own merits such as cost-efficiency, replacement of chemical fertilizer, and less kteqCO2 emissions[31]. Cerda et al. presented a scheme of well-controlled and managed high-quality compost processes (Figure 2.4) [32].

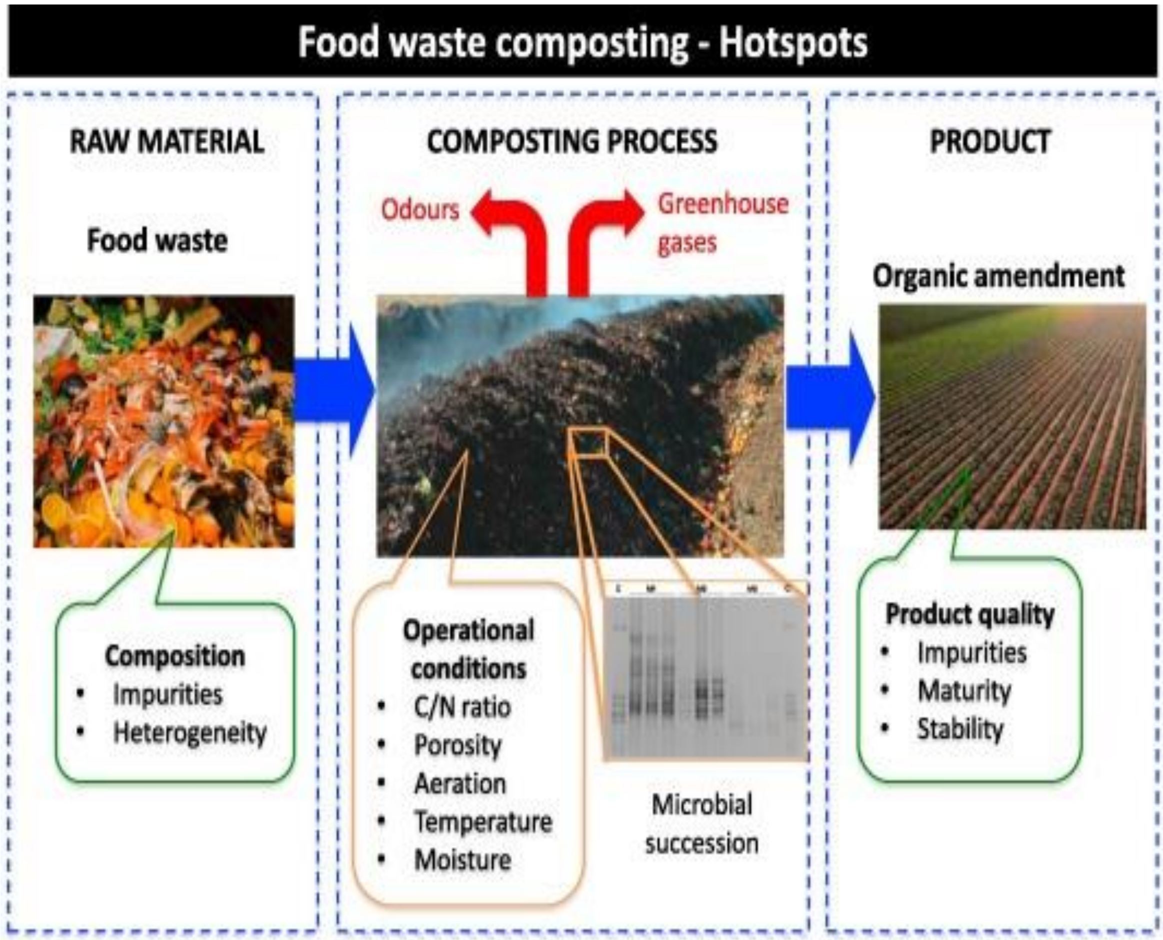

Figure 2.4 A well-controlled composting process[32]

Co-composting is a term that means composting of two or more waste types to enhance the procedure efficiency as well as product quality and save money. In one study, the effect of co-composting was measured with three options[33]. Co-composting materials were green waste (GW), unprocessed food waste (UPFW), and processed food waste (PFW).

Results from this investigation highlighted that among these three suggestions, including Treatment A (100%GW), Treatment B (40%UPFW + 60%GW), and Treatment C (50%GW + 30%UPFW + 20%PFW), treatment C had more superiorities compared to A and B, such as reaching out the thermophilic temperature in a shorter time, increase compost process effectiveness and better final product quality[33].

2.2.2 Anaerobic digestion

Anaerobic digestion can be defined as breaking down organic matter with microorganisms and closed spaces without air.[34]. It means that it happens in the absence of oxygen. Nowadays, this treatment method has become the center of attention to waste management. In AD, microorganisms produce biogas which is a mixture of methane and carbon dioxide [35], which can be used in combustion systems such as boilers, turbines, and fuel cells as renewable energy. Figure 2.5 shows the biogas production scheme[36].

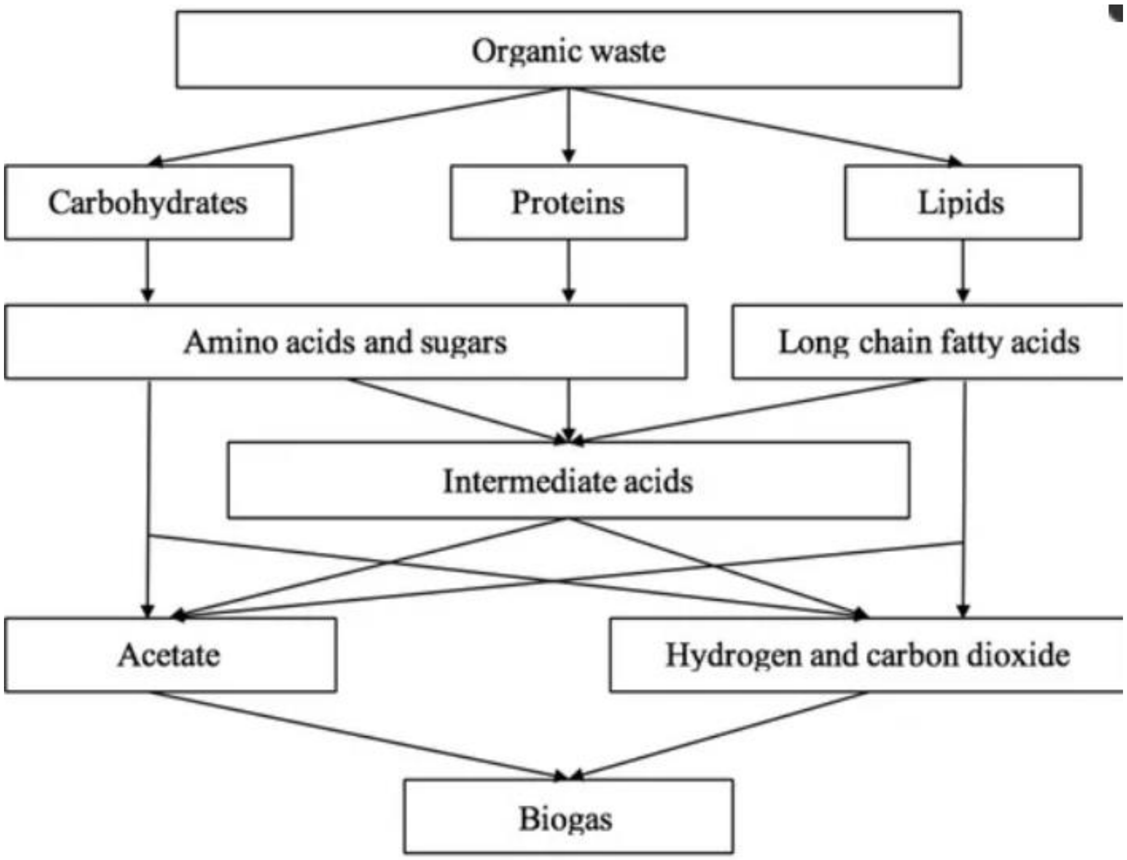

Figure 2.5 The scheme of biogas production[36]

Overall, AD is a way of recovering value from waste. However, compared with composting, AD is more complex, less stable, and slower, and there is no heat production inside the reactors. One of the benefits of compost and digest is long-term carbon storage; therefore, they can act as a soil conditioner [22]. The heavy metal content of digestate is shown in table 2.4 [37].

Table 2.4 The content of heavy metal of 1 kg of digestate[37]

Heavy metal	**Unit**	**Per kg DM digestate**	**Per kg FM compost**	**Per kg FM bio-genic waste**
Cadmium	g/kg	0,84	0,11	0,08
Copper	g/kg	116,08	15,90	10,06
Lead	g/kg	76,97	10,55	7,02
Mercury	g/kg	0,29	0,04	0,03
Nickel	g/kg	46,20	6,33	4,22
Zinc	g/kg	350,00	47,95	31,78

S. K. Bhatia [38]proposed to convert biowaste to bioenergy (BtB) technologies as a management solution. Figure 2.6 shows an overall scheme of biogas production from different biowaste. The primary resources of biowaste with their pre-treatments are illustrated fully in two sections.

Explanation of bio-based technologies and other methods of converting biowaste to energy were the main parts of this article. These technologies are biogas from biowaste, biodiesel from biowaste, bio-alcohol from bio-waste, and bioelectricity from biowaste. The rest of the non-bio-based mentioned methods were pyrolysis, gasification, incineration, hydrothermal carbonization (HC), and landfilling.

Although recently there was considerable attention to BtB, there are still some challenges such as sensibility of Methanogens to PH and temperature changes, longer hydraulic retention time to implement this technology on large scales.

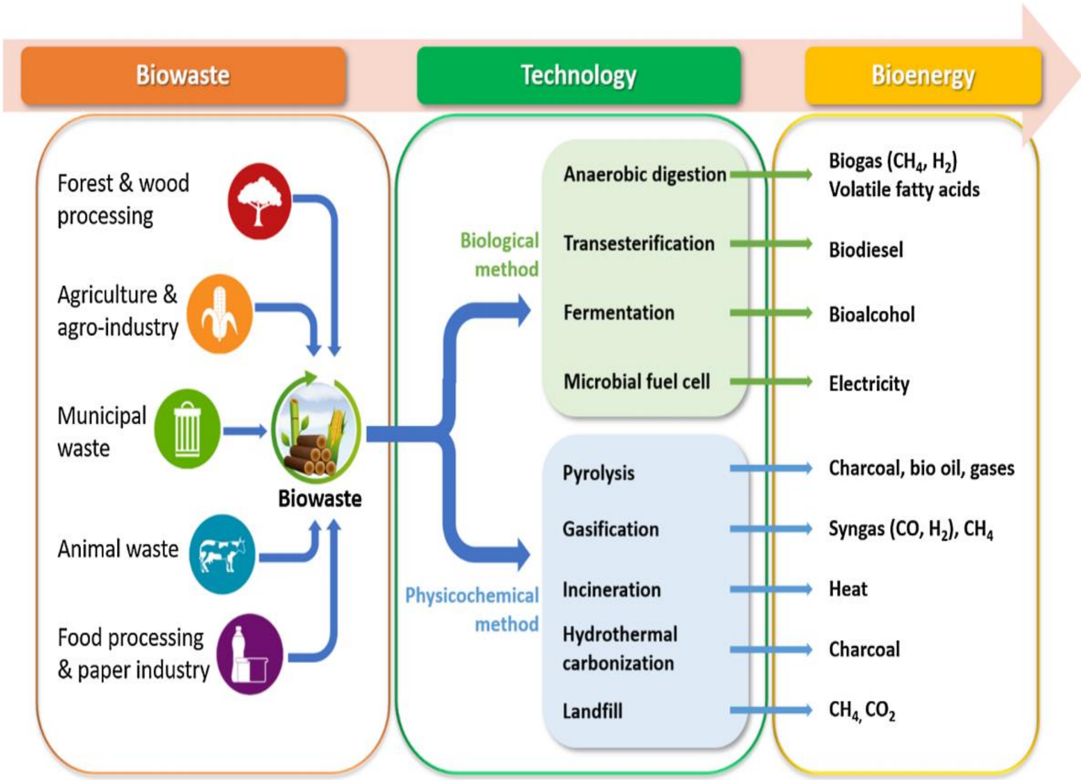

Figure 2.6 Overall scheme for bioenergy production from different biowastes [38]

Jelena Pubule et al. [39] worked on finding an optimal solution for biowaste management in Baltic states, including Latvia, Lithuania, and Estonia. Among various proposed solutions, collecting food waste separately with further anaerobic digestion is one of the best solutions to waste management. The second-best solution can be incineration with energy recovery and Mechanical Biological Treatment with Anaerobic Digestion. It is worth adding this point that Estonia has the best-developed waste management compared to two other states.

According to Timonen et al. [40], anaerobic digestion has fewer climate change emissions of raw materials and procedures than fossil energy and the production of mineral fertilizers.

Maria et al. investigated all environmental impact categories of two biowaste treatment scenarios to replace energy crops with biodegradable waste, including a base scenario as composting of bio-waste and a modified scenario where energy crops are used for anaerobic digestion is replaced by biodegradable waste. In the base scenario, the output of pre-treatment of organic fraction of municipal solid waste is compost and residual waste. From composting, some fertilizers are produced, and residual waste is incinerated. Separately, the energy crops would be transported and pre-treated and then will be subjected to anaerobic digestion with biogas generation. In the modified scenario composting is substituted by anaerobic digestion, and still, the remaining waste is incinerated. The digestate from anaerobic digestion is separated into solid and liquid fractions. The solid part was transported back to the composting facility. Results of this study showed that the environmental impact of the modified scenario was less than the base scenario, including global warming, photochemical ozone formation, acidification, particular matter, eutrophication terrestrial, water eutrophication, and resource depletion [16].

2.2.3 Incineration

Incineration is used as the most waste-to-energy technology worldwide [41]. It reduces waste volume by 90%, and by burning waste, it is possible to generate electricity and heat. Incineration can be applied as a good substitution of landfills since it has fewer environmental impacts than landfilling. In other words, incineration reduces the dependency on outrunning fossil fuels.

Additionally, the steam produced from incineration presents itself as a cost-energy-saving source if recycled. The heat created is used to make steam which in turn drives a turbine that generates electricity. Ash produced from this process can be used in construction and road-building industries and helps to save natural resources.

According to the same bio-waste management guideline [42], the performance of an incineration plant depends on several factors such as waste composition, emission control technology, energy balance (including energy recovery efficiency, type of energy recovered, alternative energy production), and efficiency of material recovery.

Meanwhile, potential pollutants and emissions such as dioxins, acid gases, nitrogen oxide, heavy metals, and particulates are the main concerns for both ecosystem and human health from this method. The nature of the waste and its calorific value are two essential factors that affect an MSW incineration plant's feasibility [43].

It is also highlighted that the high moisture content of food waste is one of this technology's issues, and it is more recommended for dry waste like bread [43]. A comparison between incineration and landfilling in five different scenarios proved that incineration with ash disposal to a landfill site has the best performance and the lowest impact categories, including GWP, acidification, and nutrient enrichment potential compared with the rest of incineration and landfill scenarios [44]. It means that although waste incineration increases CO2 emissions, it is safer for the environment than waste dumping that has been used for getting rid of garbage so far.

Di Maria et al. study [41] in Italy showed that incinerating organic fraction of municipal solid waste more environmental benefits were obtained than anaerobic digestion and composting; more energy is recovered during incineration.

Mayer et al.'s research revealed that waste treatment employing incineration and bio-gasification mainly impacts global warming potential (GWP) and fossil depletion potential (FDP) [41].

2.3 An overview of the environmental impacts of biowaste treatment options

Global Warming Potential (GWP) can be calculated based on the measurements of GHGs. Carbon dioxide is used as reference emissions, and CO2-e equivalents (are the GWP unit [6]. By quantifying the emissions of greenhouse gasses (GHG) and consequently calculating the carbon footprint of waste treatment, it is easier to understand the impact on the environment and compare emissions with each other.

In other words, carbon footprint impacts climate change and helps societies to approach a low-carbon economy. Life Cycle Assessment (LCA) methodology is used to evaluate the environmental impact of biowaste treatment options and understand which scenario performs better and has the least impact on the environment.

The study results in California, where different waste management options were assessed using LCA, confirmed that composting (windrow composting, aerated static pile composting) and anaerobic digestion (AD) have less GHG emissions compared with landfilling.

Joan Rieradevall et al.[45] carried out the study where they investigated the life cycle assessment of landfilling of biowaste in the following impact categories: global warming, acidification, eutrophication, and human toxicology at three stages of transport, management, and biodegradation with both energy recovery and without energy recovery.

Results proved that the biodegradation stage contributes to global warming and eutrophication, while transport has impacted human toxicology. Four different landfill biogas management options including; no biogas management (open dump), conventional landfill with flaring, combined heat and power (CHP) production in an internal combustion engine, and biogas upgrading for use as a fuel in buses with twelve scenarios and nine impact categories were discussed in Beylot et al.'s research[46].

Authors found out that although biogas produced from combined heat and power options have the lowest impact in terms of climate change, it generates more photochemical oxidant formation and marine eutrophication impact. There are two factors that landfill biogas emissions and biogas management are powerfully linked with, including soil top cover and combustion technology.

In one other case study in Barcelona [47], Spain, researchers investigated more impact categories for biowaste management systems both at present and in the future, including ozone layer depletion, global climate change, acidification, eutrophication, photochemical smog, ecotoxicity, human health under the criterion of air pollution and cancer and also no-cancer, diminution of fossil fuels, land use and water use. It is assumed that ozone layer depletion and eutrophication would disappear in the future among these potential impact categories.

Simultaneously, acidification, fossil fuel use, and water use would be increased because of growth in biowaste amount. Subsequently, in the collection stage and compost manufacturing stage, global warming will be decreased because of the change in disposal technology. Overall, the worst option which has the highest potential impacts is a landfill in the existing system. Incineration and bio-gasification are the processes that save emissions, contribute to acidification, ecotoxicity, and human health and also generate electrical power.

Bernstad et al. [48] reviewed 25 life cycle assessment studies of food waste management systems and compared them in terms of global warming. The food waste treatments used in this study were landfilling, thermal treatment, composting, and anaerobic digestion. The outcomes of all 25 studies were totally different since the system boundaries were different.

However, in all studies landfilling had the highest number of global warming. Composting was the second high value in terms of climate change after landfilling. In some studies, anaerobic digestion had more impact on climate change than incineration, and in other studies, vice versa.

According to a German study by Mayer et al., LCA results indicated that the combination of anaerobic digestion and composting has the best performance in environmental and economic aspects [41]. Waste treatment options were analyzed by Hermann et al.[22] to recognize the appropriate option from carbon and energy footprint at biodegradable material management stage, which is, to some extent, the same approach of this study but with different types of waste treatment method. According to the results, digestion is the promoted waste treatment since it produced more energy recovery, and the digested products can be used as a soil conditioner.

Pavlas et al. [49] compared the environmental impact and benefits of three currently used technology including composting, fermentation which is a type of anaerobic digestion process, and incineration as waste-to-energy (WtE) plants using Global warming potential indicator. It was concluded that all three treatment options were environmentally friendly due to the negative net global warming potential.

Although all mentioned biowaste treatment options were negative and saved GHG emissions. Anaerobic digestion saved more GHG than composting and incineration, it was highly dependent on heat utilization rate. If there was a high heat delivery it is comparable with anaerobic digestion and composting which saved more GHG emissions. However, if incineration is applied without heat recovery, then fermentation will be preferred.

Sharma et al. research in India [50]was performed to compare different environmental impact categories, including global warming, acidification, eutrophication, and human toxicity of combinations of three various compositions of municipal solid waste management scenarios such as landfill with biogas collection, incineration, and different combination of recycling, landfilling, composting and anaerobic digestion.

After sending municipal solid waste to landfills, it was found that it is impossible to collect all the produced gas, and a significant amount of it was lost, which contributed to global warming. The numbers of this study show that composting and landfilling have the least eutrophication and human toxicity, while the combination of recycling, anaerobic digestion, and landfilling has the least contribution to global warming. Finally, recycling and sanitary landfilling have the least impact on acidification.

3. METHODOLOGY

3.1 Carbon footprint methodology

The life cycle assessment evaluates and compiles the inputs/outputs and the potential impacts of a product system through its life cycle. According to the life cycle assessment framework, the quantification of the carbon footprint considers the entire life cycle of a product, including the acquisition of raw materials, design, production, transportation/delivery, use, and end-of-life treatment. Based on the life cycle assessment framework, in this study, the carbon footprint calculation includes transportation of the raw material, which is biowaste, to the treatment stage, their treatment, and evaluation of environmental impact from the treatment stage.

Open LCA 1.10.3 software was used to calculate the carbon footprint of three different biodegradable waste treatment scenarios. Ecoinvent 3.7 was the database with the aid of the CML indicator used for the calculation of environmental impact. Additionally, the standard for GHG accounting EVS-EN ISO14067:2018 was followed. The environmental impact category selected for assessment was Global Warming Potential at 100 years (GWP).

According to ISO14067, the climate change category is only used to address carbon footprint, and social or economic aspects cannot be assessed with this indicator. The carbon footprint of a product can be assessed as follow:

GHG emissions + GHG removals in a product system,

And if the aim is to calculate the partial carbon footprint of a product, it would be:

GHG emissions + GHG removals of one or more selected processes in a product system

Which is expressed as CO2 equivalents and based on life cycle assessment using the single impact category of climate change. Mass of a GHG is converted into CO2 equivalent by multiplying the mass of the GHG by the corresponding GWP or GTP (Global Temperature Potential) of that gas.

3.2 Goal and scope

This study aims to calculate the carbon footprint of three different biowaste treatment technologies, including composting, anaerobic digestion, and incineration. Estonia has been selected as a case study of this investigation.

Iru power plant, Tallinn landfill recovery center, and As Keskonnatennused are chosen treatment plants for incineration, composting, and anaerobic digestion technologies. Epler & Lorenz has been selected as waste collection stations. Among nine different counties in Estonia, Antsla vald collection station in Võru county was chosen because it has the longest distance to selected bio-waste treatment plants to see the environmental impact in the worst-case scenario.

3.3 Functional unit and system boundaries

One ton of separated biodegradable waste is considered as a functional unit, which compares the treatment technologies.

The first step of waste management is a waste collection from the containers, then delivered to waste stations. Biowaste is collected separately at the source in Estonia and will be sent to biowaste treatment centers. The starting point of the system boundaries of this study is the transportation of biowaste from MRF to treatment plants and finishes at the end of the treatment before sending the processed products and by-products. In other words, the system boundaries include the transportation and operation stage.

3.4 Scenarios

3.4.1 Windrow composting

A windrow composting system began with waste collection from the source and unloaded at a waste station, and there, the contaminant like the plastic bags of transferred biowaste will be removed physically. The removed contaminants are sent to the landfill, and the clean remaining feedstock will be stocked and transferred to the composting center.

The system boundary starts from this transportation to the waste treatment center. Moisture content (60%) is mixed with biowaste to acquire better compost products. Aeration of material is crucial. Oxygen needs to be replenished when consumed to avoid foul odors. It should be ensured that the material is porous enough for air to pass through. The piles are generally turned to get oxygen into the pile.

Besides, the material which is the exterior of the pile is going to the interior; therefore, they can be decomposed by microorganisms. After keeping the produced compost for several weeks to have some curing processes, prior to release to market, it goes under some test to ensure it complies with the necessary regulation and has the appropriate size. The system boundary ends before sending compost to the application sites.

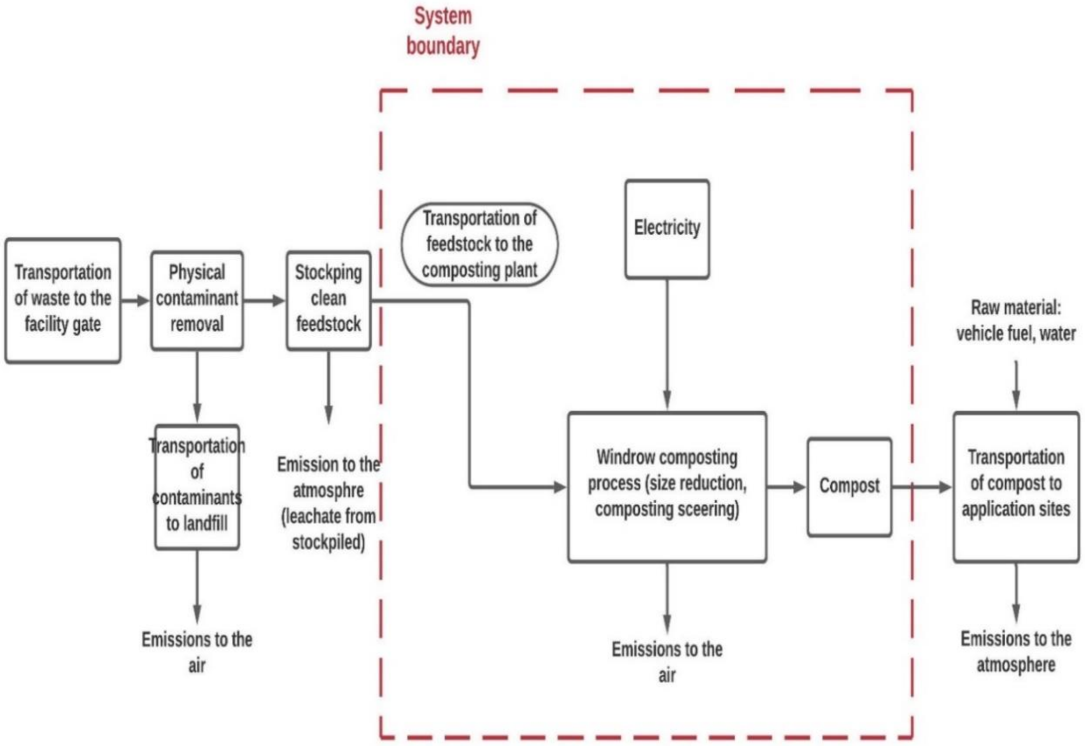

Figure 3.1 The scheme of biowaste windrow composting, including system boundary

3.4.2 Incineration with energy recovery

All the stages from waste collection to transportation for biowaste incineration are the same as composting, and also, the system boundary starts from transportation to the plant. All waste is unloaded in a waste bunker, a large and safe box made of fireproof concrete, in which fuel and garbage are stored.

Engineers and operators from the control center monitor the incineration operation. The next stage is the waste incineration boiler, the slopping and moving floor of the boiler automatically takes the ash out of the way.

The residual ash falls over the edge of the boiler grate, and after being quenched with water, it is directed to the ash hopper. The hot steam produced from the incineration boiler travels under high pressure from a heat exchanger to a turbine.

The steam goes under pressure through the sense blades of the turbine and makes it rotate quickly. The generator is linked to the turbine through a shaft, and when the generator rotates, electricity is produced.

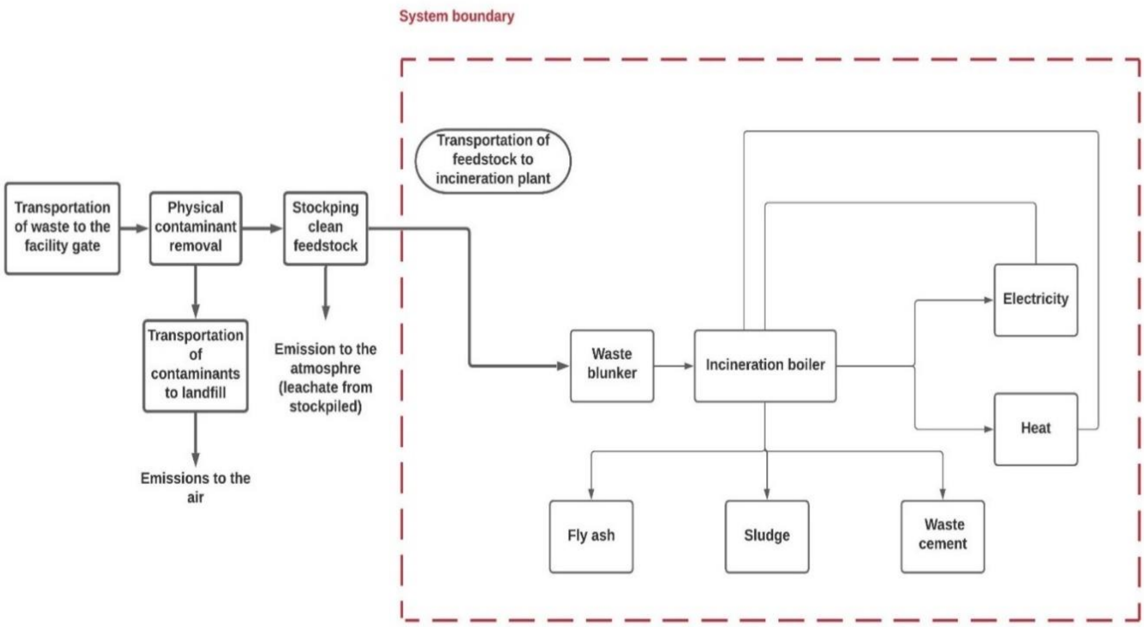

Figure 3.2 The scheme of biowaste incineration with fly ash extraction, including system boundary

3.4.3 Anaerobic digestion

The transportation of biowaste to the anaerobic digestion plant is like two previous treatment technologies, and only the distance from the waste station to the treatment center is different. At the plant, organic material is blended into a liquid and transferred to storage tanks.

These liquids are, in effect, the raw ingredients for the Anaerobic digestion recipe. A mix of the liquid is sent to the digester, which is an oxygen-free environment. The liquid in the digester is heated to 30 to 35 ℃ and mixed with paddles to avoid separation. In digester, microorganisms digest the organic fraction by breaking down the mixture and release methane-rich biogas.

The mix of the processed liquid and gas is the result of the digester. Then the gas will be extracted and sent for treatment and more processes which are called biogas. After the treatment, The biogas is ready to use for different purposes, and the digestate is treated to separate solids from the liquid. The solid is recycled back to agricultural land as fertilizer or other biological treatment processes.

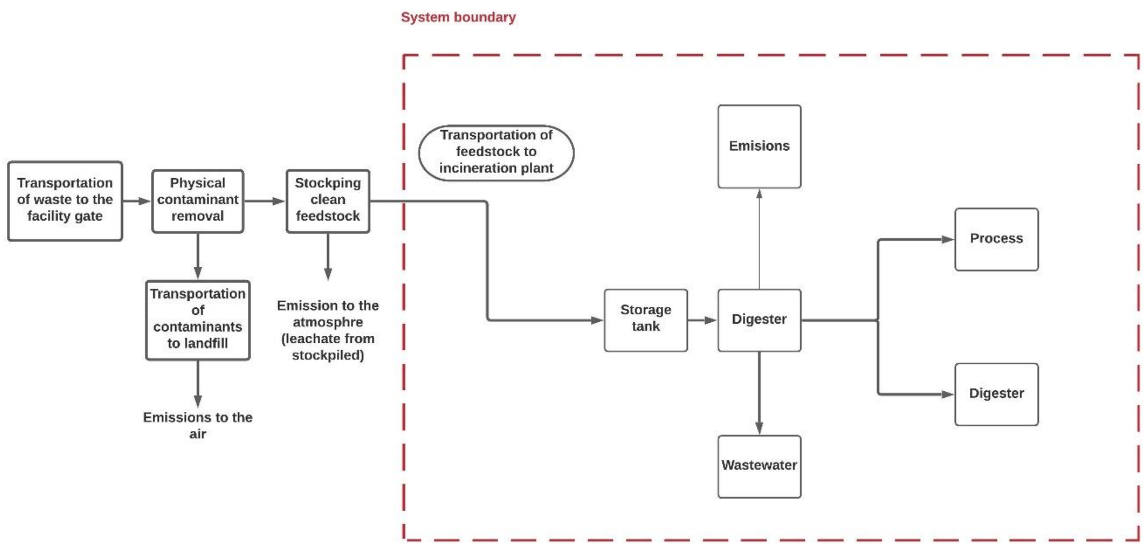

Figure 3.3 The scheme of biowaste anaerobic digestion, including system boundary

3.5 Assumptions and limitations

For more clarification, limitations and gaps that were existed during this study are described in this section.

3.5.1 Biowaste transportation to waste treatment plants

As mentioned in the previous chapter, waste is sent to waste stations after collection. There are many material recovery facilities and waste collection stations in Estonia responsible for sorting waste and preparing waste to sell manufactures as a raw material for new products.

Epler & Lorenz was selected among various companies. It covers nine counties in Estonia including Harjumaa, Ida-virumaa, Jõgevmaa, Lääne-virumaa, Põlvamaa, Tartumaa, Valgamaa, Viljandimaa, and Võrumaa. It was not possible to consider all these counties because each of them has many sub-locations for stations.

Therefore, the furthest one to a biodegradable waste treatment plant was selected because the aim was to consider the worst scenario from a distance point of view to see how much it impacts climate change. According to Google Maps, there are several routes from waste stations to biowaste treatment plants; therefore, the average distance was taken into account.

Table 3.1 Distances from waste-collecting stations to waste treatment centers

Waste treatment center	**Average distance (km)**	**Two-way trip distance (km)**
Composting	250	500
Incineration	251	502
Anaerobic digestion	201	402

The distances are presented in Table 3.1, and it is from Antsla vald collection station in Võru county to biowaste treatment centers. The reason for doubling distances in the last column in this table is that it is based on a two-way trip that a lorry takes to reach the plant and return to the collection stations.

3.5.2 Biowaste treatment centers

There are no particular biowaste treatment plants for incineration and anaerobic digestion technologies. Therefore, the following hypothesis was considered for biowaste treatment scenarios:

- For incineration, a municipal solid waste incineration plant at Iru Power station has been selected; therefore, generating electricity for a part of the city is possible. The heat and electricity were reused for incineration plants only since the amount of electricity and heat generated from biowaste incineration is less than municipal solid waste incineration and not enough to cover the city electricity. One of the reasons is that the calorific value from biowaste is less than municipal solid waste.

- There are some agricultural biowaste anaerobic digestion waste treatment centers in Estonia, but biodegradable waste is not included as their raw materials. For biowaste, the hypothetical location of anaerobic digestion waste treatment was assumed.

3.5.3 Extracted data

Data taken from the ecoinvent database was not updated for 2021, and it was a kind of estimation. The composting part was assumed from literature and the ecoinvent database that a 0.5 kg compost was produced for each kilogram of biowaste.

As a result, this 0.5 kg was multiplied by 1000 kg because the functional unit was 1000 kg of biowaste; therefore, all the amounts were 1000 times larger. The same approach was taken for obtained biogas from anaerobic digestion technology.

It means that according to the ecoinvent database, the amount of biogas produced from 1kg of biowaste under anaerobic digestion treatment was around 0.1 m3, and on a tone scale, it would be 100 m3.

3.5.4 Providers

In Open LCA software for each flow in inputs and outputs, some providers support the flows. Some of the providers were specified for Estonia, whereas, for the rest, global (GLO) or rest of the world (ROW) were chosen. Tables provided in appendixes 1,2,3 describe all the used providers for this study.

4. RESULTS AND DISCUSSION

4.1 Windrow composting

shows an overview of windrow composting treatment of biodegradable waste. It consists of all the inputs and outputs with the head of used providers to create and evaluate this treatment method. Moreover, it can be recognized that how different processes are linked to each other. The main flows in this treatment are the biowaste transferred from the waste station, the electricity, and machine operations on the site. The main product of this process is compost, and the additional outcomes are waste and wastewater.

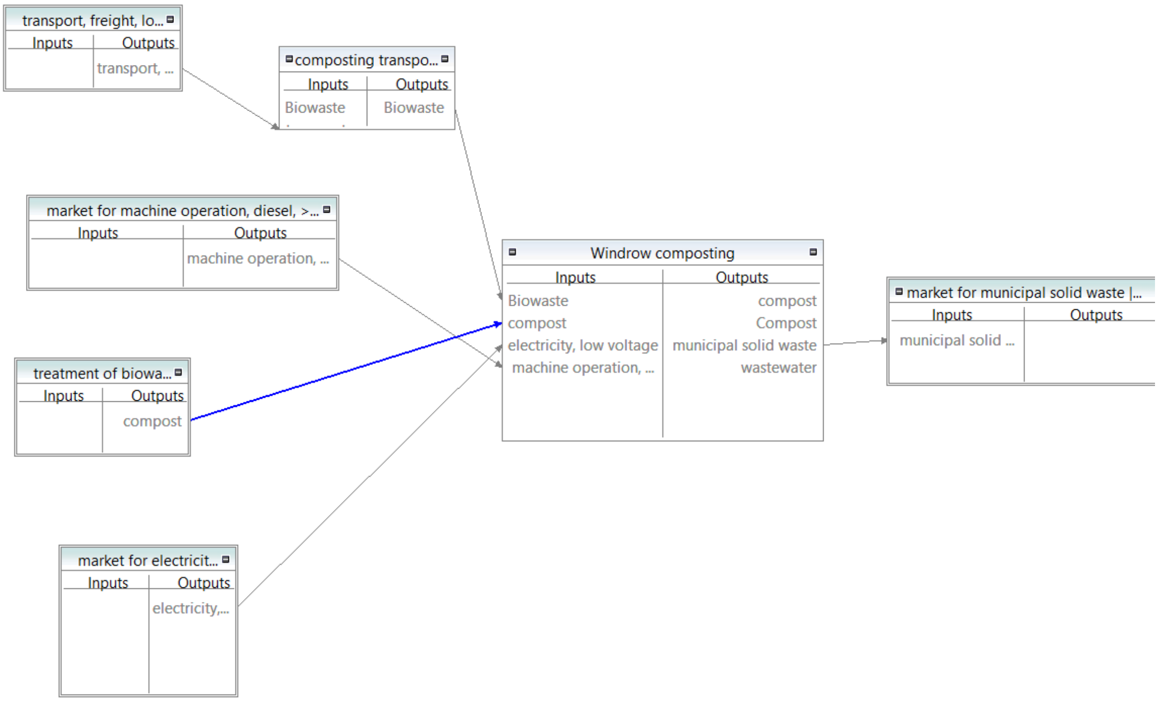

Figure 4.1 Model graph of biowaste windrow composting treatment

Figure 4.2 indicates the contributions of different processes mentioned in figure 4.1 to Climate change in 100 years perspective with kg CO2 equivalent unit. The highest amount of emissions in windrow composting is from the whole treatment process, and the second one is from the transportation of biowaste from the material recovery facility to the treatment center. The rest are related to electricity, machine operation, diesel, and municipal solid waste.

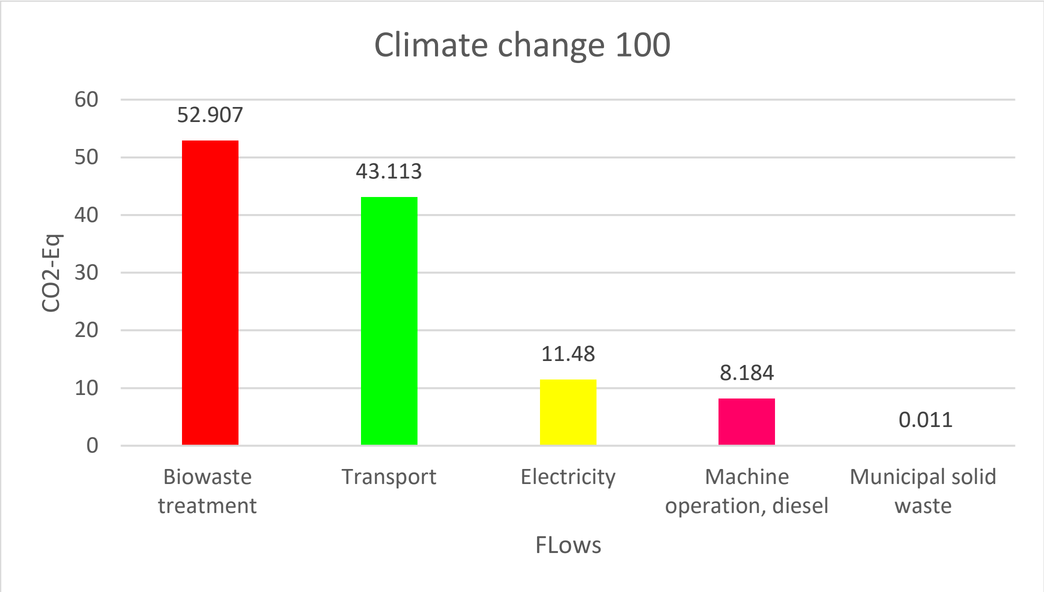

Figure 4.2 The bar chart of windrow composting of biowaste treatment (Kg CO2-eq) with climate change impact category

4.2 Biowaste incineration

Figure 4.3 presents the model graph of biowaste incineration. The heat and electricity produced along the treatment process were reused for the incineration process inside the treatment facility. Other main flows in this treatment technology are biowaste transferred from the waste station, natural gas for the incinerator, and water. The main product is fly ash. Other outputs from this process are biowaste burnt, sludge, water, activated carbon, and electricity (reused for the procedure mentioned before).

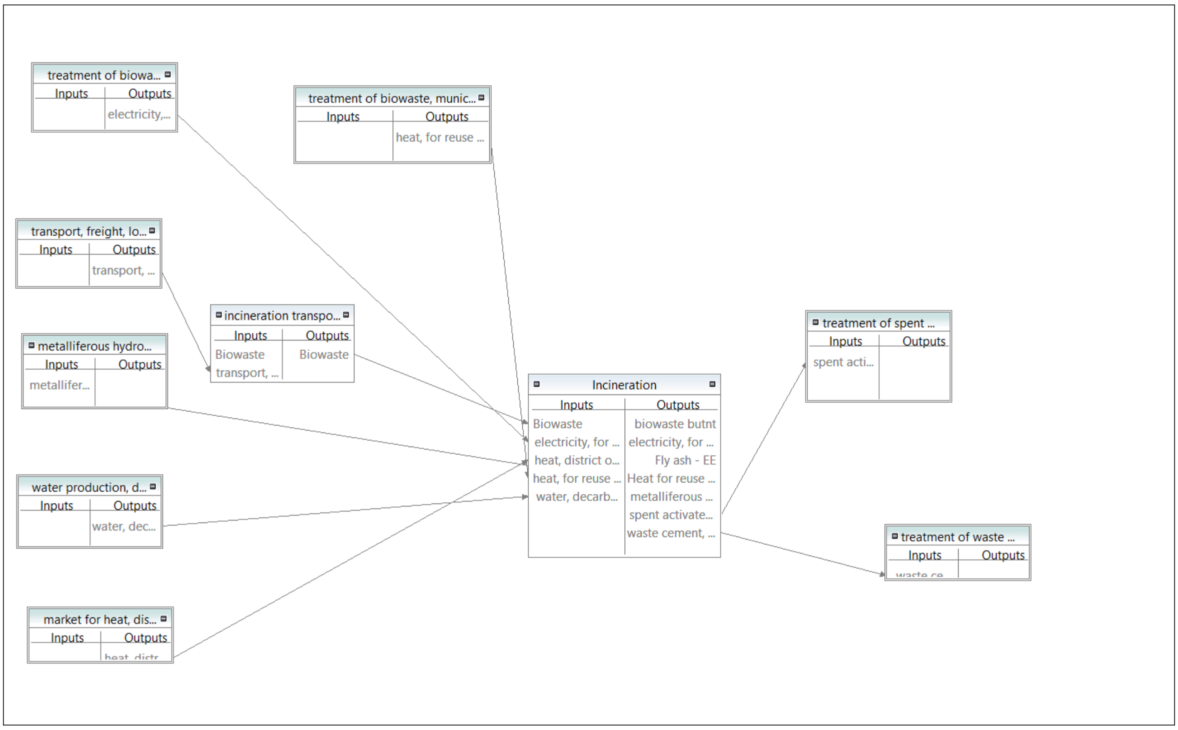

Figure 4.3 Model graph of biowaste incineration treatment

Additionally, Figure 4.4 reveals that the highest contribution to climate change for this technology is transferring biowaste from material recovery facility to the incineration plant. After that, the heat and natural gas for starting the burning process have the second rate in terms of emissions. It seems treatment of biowaste when electricity and heat are used again for treatment has no impact on climate change, but they also save some emissions; that is why the numbers of these processes are negative.

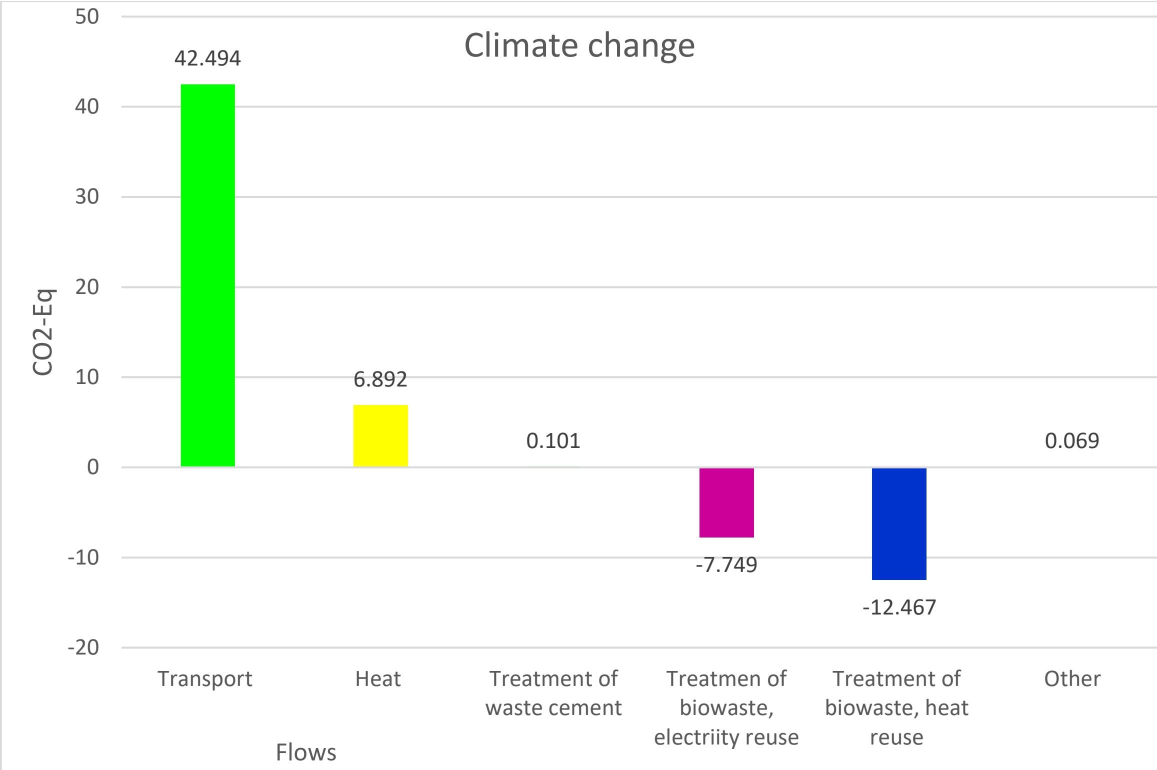

Figure 4.4 The bar chart of incineration of biowaste treatment (Kg CO2-eq) with climate change impact category

4.3 Biowaste anaerobic digestion

The model graph of treatment of biowaste by anaerobic digestion with providers is shown in Figure 4.5. The inputs of this process are transferred biowaste, digester, electricity, heat and water. The main product is biogas, and the rest of the outputs are digested sludge and wastewater.

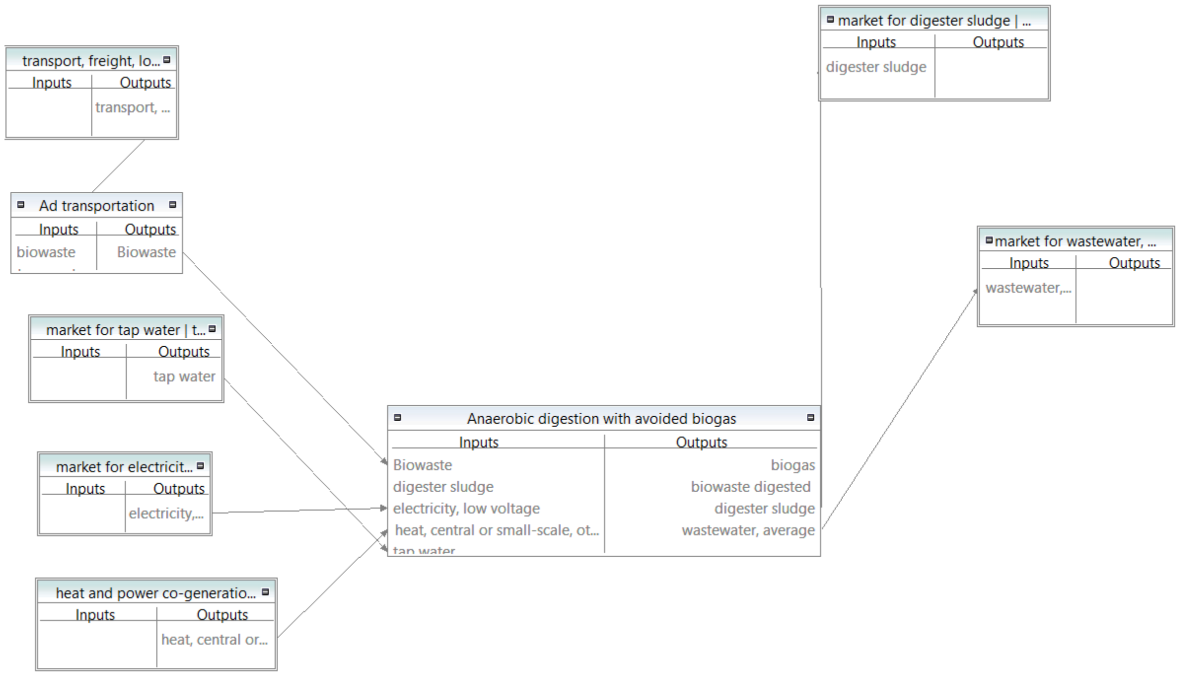

Figure 4.5 Model graph of biowaste anaerobic digestion treatment

As is shown in figure 4.6, sending biodegradable waste from the material recovery facility to an anaerobic digestion center has the most impact on climate change; moreover, the process of anaerobic digestion procedure has the second number of kg of CO2 equivalent. The effect and emissions from electricity and wastewater are not as significant as transportation and the whole process of biowaste treatment.

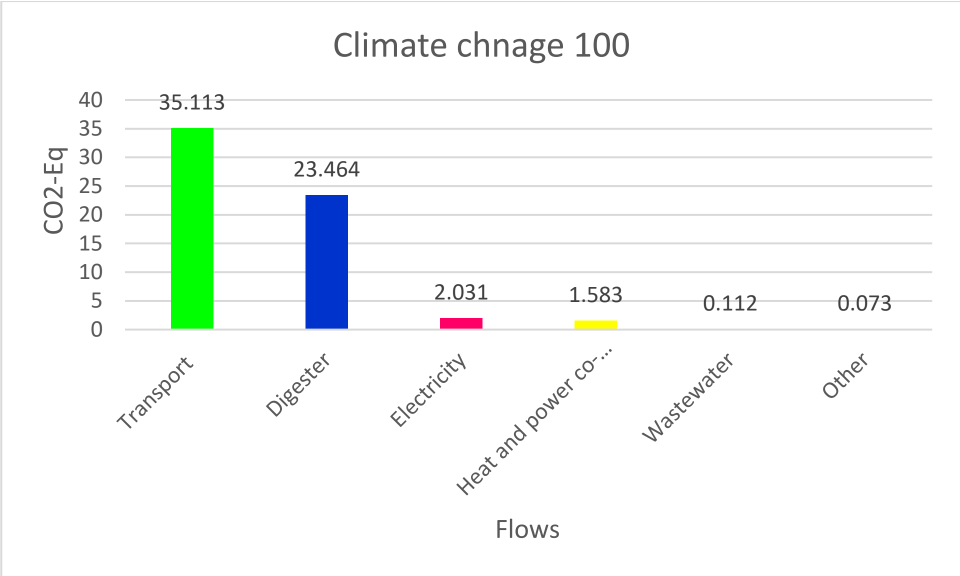

Figure 4.6 The bar chart of anaerobic digestion of biowaste treatment (Kg CO2-eq) with climate change impact category

4.4 Overall comparison of all treatment scenarios

Despite sections 4.1 to 4.3, the carbon footprint of each treatment method with bar chart and model graph were explained, the comparison of all treatments is illustrated in this section.

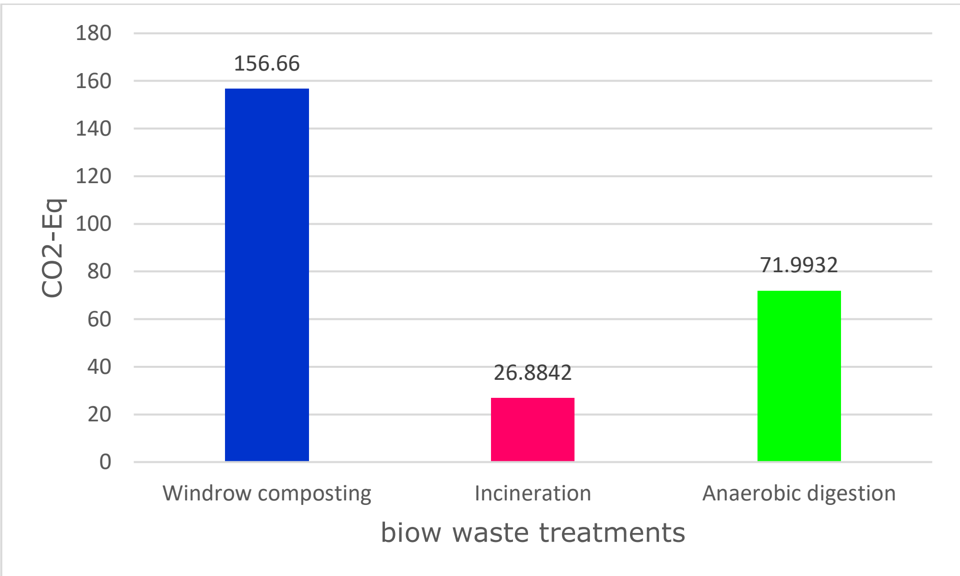

Figure 4.7 Comparison of biowaste treatment technologies

From figure Figure 4.7, it is clear that biowaste composting is releasing the highest amount of greenhouse gas emissions compared with anaerobic digestion and incineration. Moreover, biowaste incineration has the least carbon footprint, which can be justified so that since heat and electricity are reused in this process, the amount of emissions becomes less compared with anaerobic digestion.

In section 2.3, there was a review of Pavlas et al. research which was almost similar to this study. Therefore, a brief comparison is provided in Table 4.1 to compare the results and show the differences.

Table 4.1 A comparison between the current study and another study with global warming potential indicator

	Composting ($kg(CO_2)_{eq}.t_{waste}^{-1}$)		**Incineration ($kg(CO_2)_{eq}.t_{waste}^{-1}$)**		**Anaerobic digestion ($kg(CO_2)_{eq}.t_{waste}^{-1}$)**	
	Current study	Pavlas et al	Current study	Pavlas et al	Current study	Pavlas et al
Transportation	52,907	16,9	42,494	0*	35,113	16,9
Treatment	103,753	78	-15,6098	7,6	36,8802	92
Total	156,66	94,9	26,8842	7,6	71,992	108,9

* it is close to zero because residual municipal solid waste (RES) does not consist of any fossil-based carbon; therefore, no additional GHGs are produced.

The negative number in table 4.1 indicates how much benefit incineration has on the environment and saves greenhouse gas emissions.

The differences between the two studies for treatments are mainly resulting from different system scoping. The difference in the local conditions in the Czech Republic where the Pavlas et al study was done and the local conditions in Estonia for this study resulted in a difference in the amounts of carbon emission from transportation. Also, the consideration in this study of a different location for treatment plants while the other study presumed the same distance for both the composting and anaerobic digestion options.

Despite the apparent lower global warming potential from composting in Pavlas et al study, the Anaerobic digestion resulted in better net global warming potential after including the negative global warming potential from treatment products, as for the incineration the other study included only the incineration of waste residual which didn’t put focus on incineration as alternative treatment technology but more as a supplementary tool to support the first two technologies.

4.4.1 The effect of distance on climate change

Since it was concluded in the previous section that distance plays an important role in the global warming impact category, sensitivity scenarios with the shortest distance were calculated.

In previous calculations, the longest distance was taken into account—this time, the wase station is located in Kadrina Vald in Viru lääne county. Table 4.2 shows the distances from the waste station to treatment centers. Figure 4.8 shows the comparison of how much distance of transportation can be critical to climate change for composting, incineration, and anaerobic digestion, respectively.

Table 4.2 Distances from waste-collecting stations to waste treatment centers

Waste treatment center	Average distance (km)	Two-way trip distance (km)
Composting	22,4	44,8
Incineration	32,65	65,3
Anaerobic digestion	31,5	63

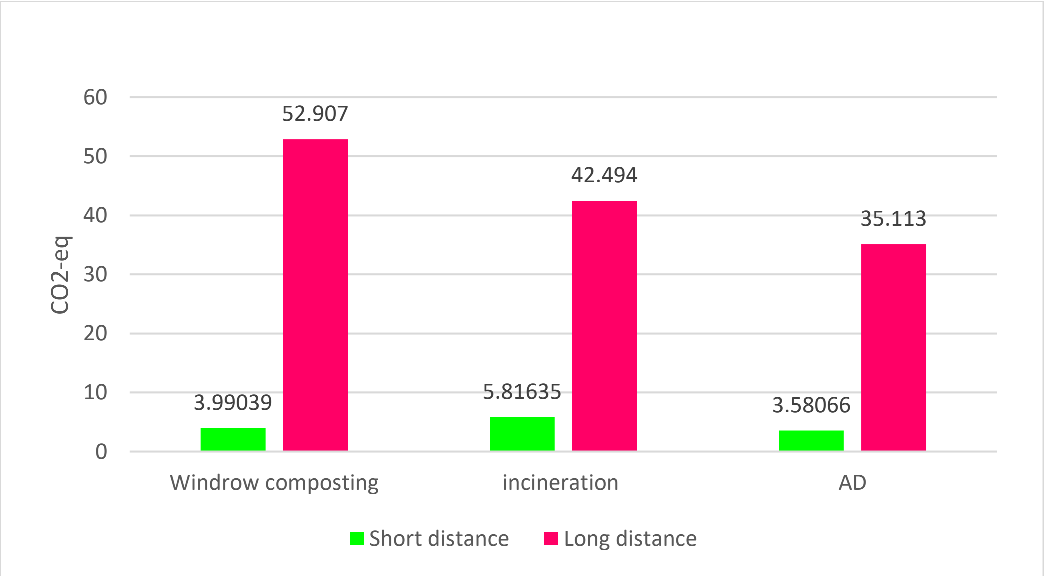

Figure 4.8 Impact of distance on global warming (CO2 kg-eq) for Three biowaste treatment technologies

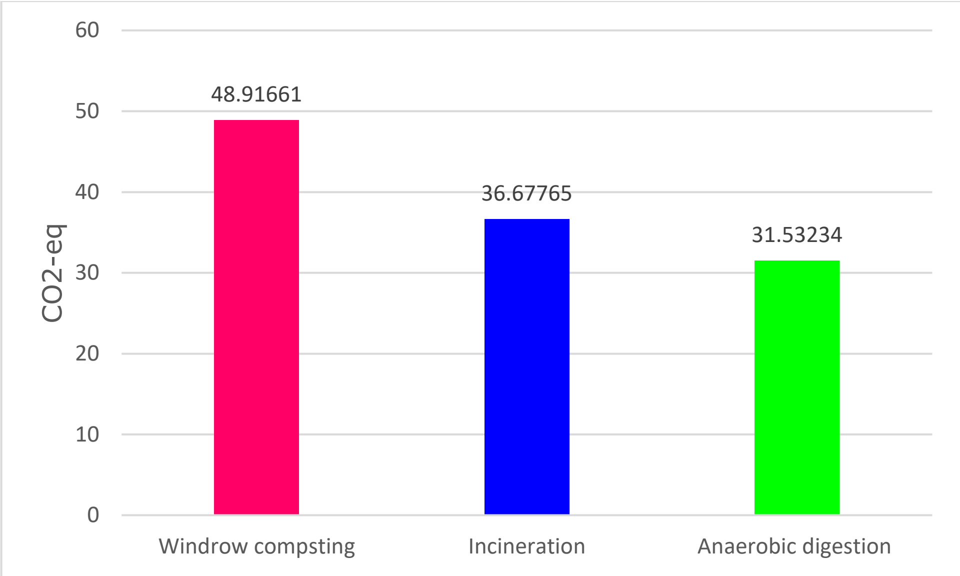

Figure 4.9 The difference of two distance scenarios for each biowaste treatment options

Figure 4.9 indicates the differences of each biowaste treatment technology for two different distances of biowaste transferring from waste station to biowaste treatment centers. The highest difference is for windrow composting that shows that if the biowaste is being sent from the waste station to treatment centers by a shorter distance, it will save more greenhouse emissions and less impact climate change.

4.5 A comparison among different avoided products

Avoided product is a feature in Open LCA. When there are two or more products as the outputs of a process, it would be possible to see how much the flows in the process can impact and contribute to different product outputs.

This study for biowaste incineration and biowaste anaerobic digestion technologies made it possible to avoid products.

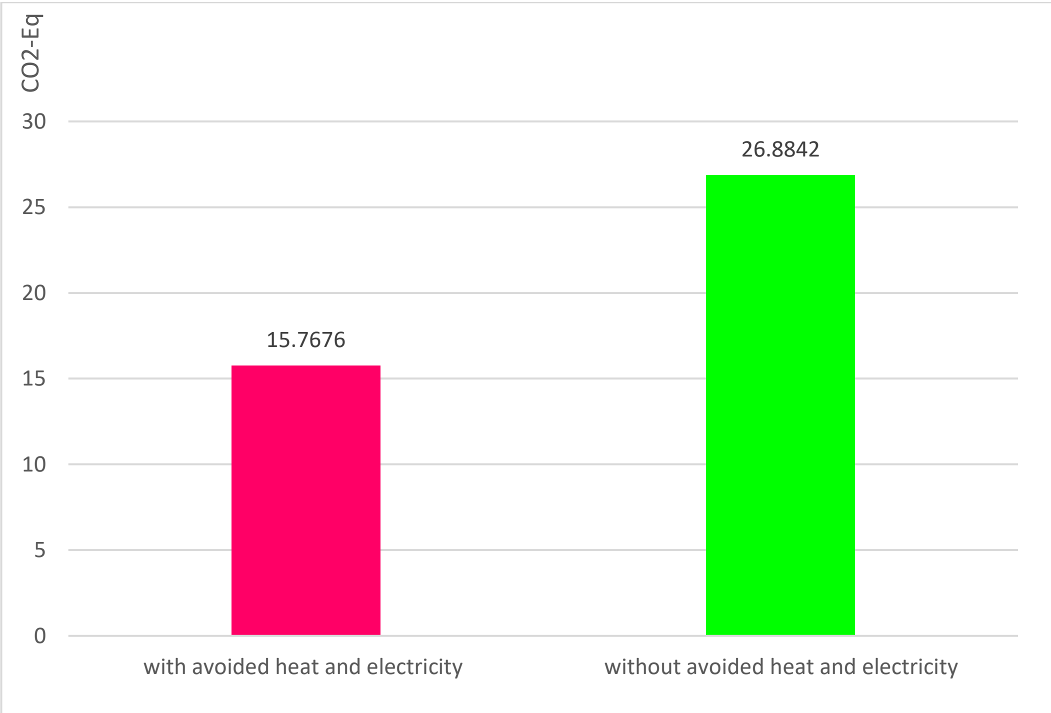

Figure 4.10 biowaste incineration with and without avoided heat and electricity production

In incineration, electricity and heat were two products from the process which could be recovered. Figure 4.10 shows that if heat and electricity are considered as avoided products, the biowaste treatment process would have less impact on climate change. It means the head and electricity will be produced elsewhere, and the heat and electricity will be substituted via the heat and electricity produced by the modelled product system. Thus, the biowaste incineration product system is credited with the avoided impact of the alternative heat and electricity processes from somewhere else. The climate change impact of that process will be subtracted from the overall climate change impact of the biowaste incineration process.

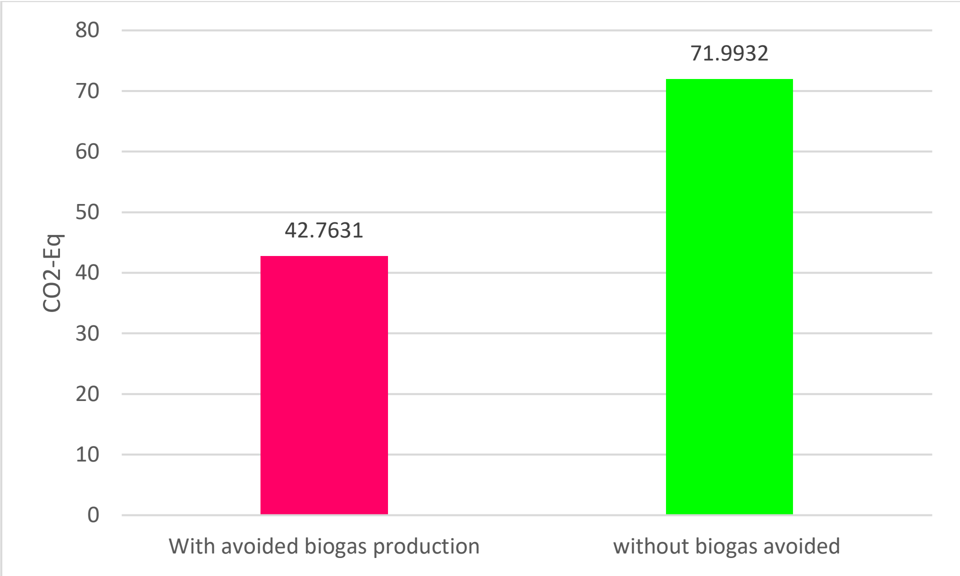

Figure 4.11 Biowaste anaerobic digestion with and without avoided biogas production

The explanation mentioned above can also be applied for the biowaste anaerobic digestion process, and the impact of the avoided product is shown in Figure 4.11. This time the avoided product in anaerobic digestion is biogas, which means biogas from anaerobic digestion can substitute natural gas used in electricity and heat generation and might be also utilized for the waste incineration process. Therefore, the climate change impact would be less in this process too. The result provided in Table 4.1 was considered biogas without avoided product in system boundary.

5. CONCLUSION

The analysis of the carbon footprint of three different biowaste treatment technologies scenarios in Estonia was done in this study. The carbon footprint calculation was done with open LCA and CML impact method for 100 years perspective climate change impact category.

This study showed that among these mentioned biowaste treatments, incineration with energy recovery had the least impact on climate change with 26.8842 Kg CO2- eq, followed by anaerobic digestion with 71.9932 Kg CO2-eq, and the most impact resulted from windrow composting with 94,9 Kg CO2-eq.

A comparison between the longest and the shortest distance was made for all the three treatment technologies scenarios to see the impact of transportation on climate change. And it resulted in saving greenhouse gas emissions 48.91661, 36.67765, and 31.53234 Kg CO2-eq for windrow composting, incineration, and anaerobic digestion, respectively.

There is a 41.34% CO2 reduction when heat and electricity are considered as avoided products. This result was almost the same for biogas in anaerobic digestion, which means the amount of CO2 equivalent is reduced by 40% when it is taken into account as an avoided product.

Despite the environmental performance of the waste incineration option having the least carbon footprint. The incineration process is still considered as waste disposal with no impact to national and regional recycling rates to reach 50% target. Also, incineration works in a counterproductive way to the modern waste hierarchy which targets higher waste recycling.

Anaerobic digestion has a higher carbon footprint in comparison with the incineration option, but with proper accounting of the compost material stream produced from the treatment process, it will be added to the recycling targets.

By evaluating the transportation impact on the different treatment technologies, the windrow option was found to be the most impacted by distance difference with a nearly. Local conditions suggest a priority of considering alternatives for the farthest locations in addition to a need for evaluation of expanding the windrow composting option to different areas to minimize the transportation impact.

Additional studies are required to account for recycling fly ash from the incineration process which might affect the potential of future investment in the incineration process and can be realized in national and regional targets by material extraction reduction.

SUMMARY

There is a global concern about waste generation growth with the rapid increases in development and population and its direct impacts on the environment. Alarming rates of global warming are connected to the increase in greenhouse gas emissions. A specific scope is set in this study to focus on the impact of biodegradable waste management technologies impact on climate change associated.

This study is set to investigate the carbon footprint of different biodegradable waste treatment technologies by accounting for the amount of emitted greenhouse gases from each. Based on the mass of CO_2 equivalent, it is possible to determine which treatment method can be implemented that has the best environmental performance concerning the climate change impact.

Legislative grounds for biodegradable waste management in Estonia were examined and it showed a governmental determination to meet the European Union targets for achieving sustainable development and lower the greenhouse gas emissions associated with biodegradable waste treatment.

Three biodegradable technologies were studied in detail windrow composting, incineration, and anaerobic digestion. Previous research showed a wide range of impacts from the aforementioned technologies, and an overview of the different impacts was illustrated in addition to the main focus on the climate change impact.

The life cycle assessment approach was found to provide the most comprehensive results in the assessment of impacts through the compilation of the inputs and outputs of treatment systems. A functional unit of 1 ton of separated biodegradable waste was considered as the base for different technologies comparison.

System boundaries were drawn to help the set focus on the treatment technologies by including mainly the main operations and the transportation of waste stream to treatment plants.

Certain assumptions had to be considered due to the limitation of data available regarding the selection of treatment plants under investigation that include locations, distances, and unobtainable or outdated data available.

Results were compiled for the treatment technologies and it was found that windrow composting had the most significant impact on climate change while the least impact came from incineration. The difference in distance of waste transportation from collection points and separation centers had a clear impact on the amount of CO_2 emitted. Also, the impact of the avoided products was evaluated to clarify the difference it makes on climate change and it was found that impacts had a significant reduction by including the avoided products in calculations as products of treatment technology.

Incineration showed great potential in comparison to other considered technologies by having the lowest emission due to including the energy recovery option, windrow composting was the most impacted treatment technology by transportation distance which suggest a further investigation and assessment for the potential of expanding windrow composting to different counties.

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APPENDIX

Table 0.1 Used providers for biowaste windrow composting

Composting		
Name of the flow	Provider	description
Electricity (Low voltage)	Market for electricity (Estonia)	- electricity inputs produced in this country and from imports and transformed to low voltage - the transmission network - direct emissions to air (SF6 from the insulation gas in the high voltage level switchgear are allocated to the electricity demand on medium voltage). - electricity losses during transmission
Municipal solid waste	heat and power co-generation, biogas (Estonia)	- This market dataset model the disposal mix for 1 kg of municipal solid waste in Estonia using country-specific data - The transport from the production site of the waste to the different treatment facilities where the waste is treated is accounted in this dataset
Machine operation, diesel	Market for machine operation, diesel	From cradle, i.e. including all upstream activities.

Table 0.2 used providers in biowaste incineration

Incineration		
Name of the flow	Provider	description
Electricity, for reuse in municipal waste incineration only	treatment of biowaste, municipal incineration (GLO)	- represents the activity of waste disposal of biowaste in a municipal solid waste incinerator - including all upstream activities
Heat, for reuse in municipal waste incineration only	treatment of biowaste, municipal incineration (GLO)	- represents the activity of waste disposal of biowaste in a municipal solid waste incinerator - including all upstream activities
Water, decarbonised	water production, decarbonized (ROW)	- represents the production of 1 kg of decarbonised water - From the intake of raw surface water into the plant - From cradle, i.e. including all upstream activities - It includes the use of chemicals and some emissions for the treatment of water used in power plants
Metalliferous hydroxide sludge	metalliferous hydroxide sludge to market for zinc concentrate (GLO)	- a proxy dataset which connects the "metalliferous hydroxide sludge to the market for zinc concentrate - The metalliferous hydroxide sludge is produced as a by-product of the incineration of different types of waste in incinerators - This sludge with its high concentrations of zinc is then sent as a secondary feedstock to the zinc smelting industry
spent activated carbon with mercury	treatment of spent activated carbon with mercury, underground deposit (ROW)	No emissions from waste material are inventoried.

waste cement, hydrated	treatment of waste cement, hydrated, residual material landfill. (Europe without Switzerland)	- Inventoried waste contains 100% cement hydrated - From the cradle, i.e., including all upstream activities
	heat, district or industrial, other than natural gas	Market for heat, district or industrial	- The shares of heat supplying activities from the different technologies - They amount to about 52% heat from coal and peat, 16% heat from oil, 18% heat from biofuels, 11% heat from waste and 2% heat from other sources

Table 0.3 Used providers in biowaste anaerobic digestion

Anaerobic digestion		
Name of the flow	Provider	description
Electricity (Low voltage)	Market for electricity (Estonia)	-electricity inputs produced in this country and from imports and transformed to low voltage - the transmission networks - direct emissions to air (SF6 from the insulation gas in the high voltage level switchgear are allocated to the electricity demand on medium voltage). - electricity losses during transmission
Heat	heat and power co-generation, biogas (Estonia)	the production of electricity and heat from a biogas mix from different sources (bio-waste, sewage sludge)
Tap water	Market for tap water (Europe without Switzerland)	This activity starts from tap water, under pressure, at tap water treatment plant and fed into the tap water distribution network
Digester, sludge	Market for digester sludge (GLO)	This market does not include any transport because it is assumed that the follow-up treatment occurs in the same location. From the cradle, i.e. including all upstream activities
Wastewater	Market for wastewater (Europe without Switzerland)	The wastewater, the average, is treated in the same place as it is produced. That is why regional market activities are, in this case, adequate from the cradle, i.e., including all upstream activities.