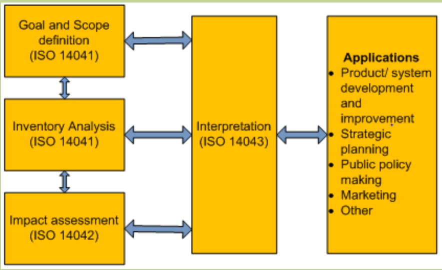
ISWM-TINOS:

Development and implementation of a demonstration system on Integrated Solid Waste Management for Tinos in line with the Waste Framework Directive

Deliverable 1-4:
LCA studies for composting and anaerobic digestion units



Action 1: Preparatory Activities

Activity 1-3: Literature review on success stories of applied Integrated Solid Waste Management systems for MSW and on evaluation methodologies of such systems. Assessment and evaluation of the key parameters for the successful implementation of best scenarios

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Background

This report entitled: ***"LCA studies for composting and anaerobic digestion units"*** was produced under co-finance of the European financial instrument for the Environment (LIFE+) as the forth Deliverable (D1-4) of Action 1 of Project "ISWM-TINOS" (LIFE10/ENV/GR/000610) during the implementation of Activity 1-3.

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1. Introduction

In Greece, according to the legislative framework each municipality has the responsibility for the management of Municipal Solid Waste (MSW). The methods used globally for the management of organic of MSW are [1]:

- composting
- anaerobic digestion
- gasification
- combustion, incineration with energy recovery
- mechanical biological treatment
- incineration without energy recovery
- disposal in landfills, both with and without energy recovery from generated methane.

The European approach to waste management is based on three principles, including: a) waste prevention, b) recycling and reuse and c) Improving final disposal and monitoring [2]. The European legislation [3], [4] is based on the above referred principles.

This study focuses on composting and anaerobic digestion method. In order to compare these methods and to obtain the environmental results of each method, the Life Cycle Analysis (LCA) is used. Life cycle analysis offers standardization and its level of sophistication makes it a reliable tool, well – known among scientists and in industry.

The aim of this report is to review LCA studies for composting and anaerobic digestion. Within ISWM-TINOS project (Action 5.1), in the frame of Environment (LIFE+) program [5], a LCA study will be conducted for the ISWM system both for composting and anaerobic digestion technology. Literature review, identification of good practices and methodology is a prerequisite for the proper and effective performance of the LCA studies within ISWM.

2. Aerobic and anaerobic treatment

2.1 Biological stabilization

The biological stabilization of the organic fraction of municipal solid waste (OFMSW) into a form stable enough for land application can be achieved via aerobic or anaerobic treatments.

2.2 Composting

Composting is an aerobic treatment method. The product of this method is the compost, an organic matter that has been decomposed, which can be used as a fertilizer and soil amendment in gardens, landscaping, horticulture and agriculture applications [6]. Specifically about the process of decomposition, microorganisms such as bacteria, fungi, and actinomycetes account for most of the decomposition that takes place in a pile [7]. In general, there are three methods for composting process: a) windrow composting with turning; b) aerated static pile and c) in-vessel composting [8].

Windrow composting has been the common practice for large scale composting globally. It is carried out in piles. The piles have the following dimensions: 3-5 meters in width, 2-3 meters in height and up to a hundred meters in length. These piles keep high temperature, while allow oxygen flow to the center core. The periodically turning of the windrows, by using special turning machines, is a significant factor which impacts to heat releasing and exposing anaerobic volumes to oxygen [9]. Usually, these turners [10] are equipped with watering attachments, which are used to adjust the moisture level [11]. The advantage of the windrow composting is the low investment cost in comparison with other technology. The main disadvantage is the fact that it not easy to control this specific process. The results are the uncontrolled and undesirable emissions and odors.

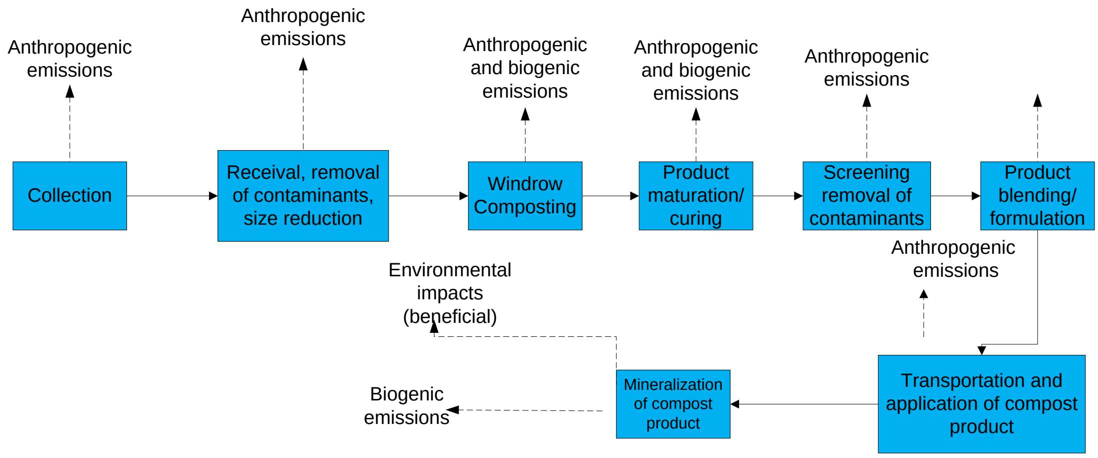

Figure 1: Windrow composting flow chart [12]

The second method for composting method is the aerated pile technology. This technology in contrast of the previous one, consists of a concrete foundation with horizontal aeration tubes on its surface through which air flows upward into the waste pile. The organic waste is usually shredded and then deposited on this floor, similarly to windrow composting. A special membrane cloth covers the pile. So by using this covering, the organics vapors and moisture are kept in the pile and gases as nitrogen, carbon dioxide and unused oxygen pass through this pile. The covers are kept in place by either sandbags, fire hoses or they are attached to bolts in small walls with rubber ropes. Moisture and oxygen levels are kept at the optimum level for degradation to take place. The biodegradation process consists generally of three parts and last for about 9 weeks:

- 1-4 weeks biodegradation under cover
- 2-4 weeks post-rotting under cover
- 2-3 weeks exposed curing

The third method is the vessel aerobic composting of organics. This method is appropriate for both yard waste and food wastes are suitable. In comparison with the two above methods, vessel aerobic composting method is considered as a high level controlled method, in function of emissions and odors. It resembles a chemical reactor where all parameters (oxygen and moisture levels) can be optimized for the highest conversion rates. In a typical facility, the system consists of a rotating drum, an air blower and an air filtration system consisting of wet scrubber and biofilter. The drum rotates at 1-10 rounds per minute. Typical dimensions of drum are: 3 meters in diameter and 56 meters in length.

2.3 Anaerobic digestion

Anaerobic digestion combines a series of processes in which microorganisms break down biodegradable material in the absence of oxygen. It is used for industrial or domestic purposes to manage waste and/or to produce energy [13], [14]. The anaerobic digestion of organic matter is a complex process. The four degradation steps are hydrolysis, acidogenesis, acetogenesis and methanogenesis [15]. The specific microorganisms that take part in the process have different requirements on environmental conditions and moreover coexist in synergetic interactions. The anaerobic digesters can be classified into three categories: single stage, multi stage and batch. Basic parameter for the selecting of reactor type is the temperature range. The temperature range can move in mesophilic or in thermophilic area. More specifically, the most common MSW Anaerobic digestion technologies are categorized as follows:

1. One-Stage continuous systems: Low-solids or Wet and High solid or Dry
2. Two-stage Continuous Systems: Dry-Wet and Wet-Wet
3. Batch Systems: One stage and Two stage

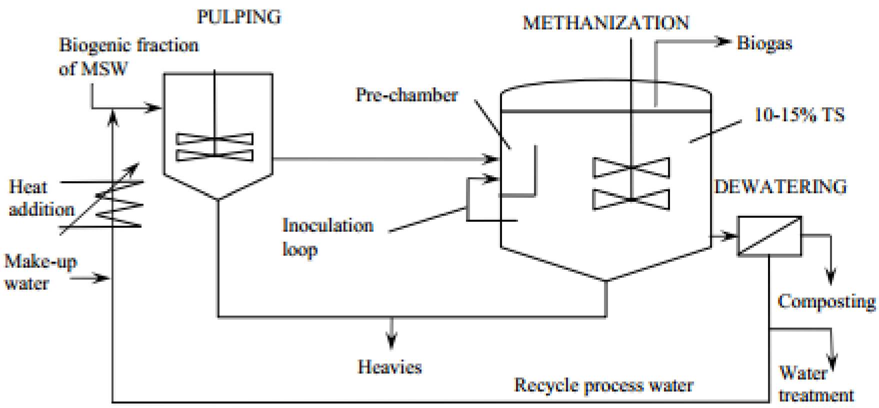

Figure 2: Schematics of the Waasa one-stage digestion process [16]

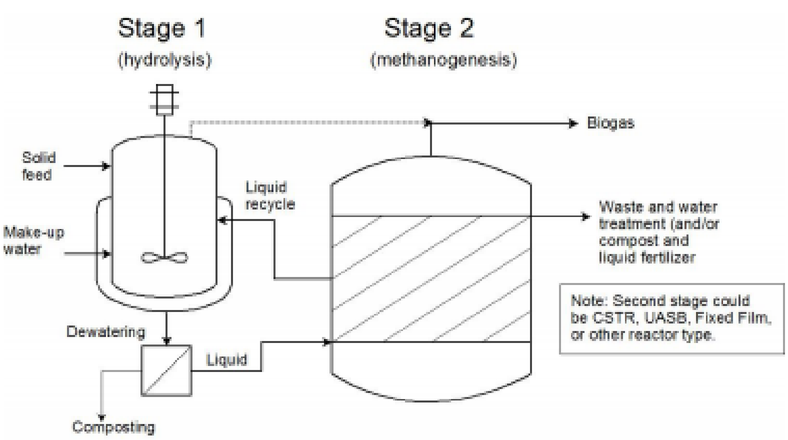

Figure 3: Schematic of a generalized two-stage anaerobic digestion [17]

Single-stage digesters are simple to design, build, and operate and are generally less expensive. The organic loading rate of single-stage digesters is limited by the ability of methanogenic organisms to tolerate the sudden decline in pH that results from rapid acid production during hydrolysis. Two-stage digesters separate the initial hydrolysis and acid-producing fermentation from methanogenesis, which allows for higher loading rates but requires additional reactors and handling systems. The most usual applications in Europe are the single stage systems (90% of the installed Anaerobic Digestion (AD) capacity), while the rest are two stage systems (10% of the installed AD capacity). Another important design parameter is the total solids (TS) concentration in the reactor, expressed as a fraction of the wet mass of the prepared feedstock. The remainder of the wet mass is water by definition. The classification scheme for solids content is usually described as being either high-solids or low-solids. High-solids systems are also called dry systems and low-solids systems may be referred to as wet systems.

Table 1: Summary of Single Stage-Wet systems digester technology [17]

Criteria	Advantages	Disadvantages
Technical	Derived from well developed waste-water treatment technology Simplified material handling and mixing	Short circuiting Sink and float phases Abrasion with sand Complicated pre-treatment
Biological	Dilution of inhibitors with fresh water	Sensitive to shock as inhibitors spread immediately in reactor VS lost with removal of inert fraction in pre-treatment
Economic and Environmental	Less expensive material handling equipment	High consumption of water and heat Larger tanks required

Table 2: Summary of Single Stage-Dry Systems digester technology [17]

Criteria	Advantages	Disadvantages
Technical	No moving parts inside reactor Robust (inert material and plastics need not be removed) No short circuiting	Not appropriate for wet (TS<5%) waste streams
Biological	Less VS loss in pre-treatment Larger OLR (high biomass) Limited dispersion of transient peak concentrations of inhibitors	Low dilution of inhibitors with fresh water Less contact between microorganisms and substrate (without inoculation loop)
Economic and Environmental	Cheaper pre-treatment and small reactors Very small water usage Smaller heat requirement	Robust and expensive waste handling equipment required

Table 3: Summary of two Stage systems digester technology [17]

Criteria	Advantages	Disadvantages
Technical	Operational flexibility	Complex design and material handling
Biological	Higher loading rate Can tolerate fluctuations in loading rate and feed composition	Can be difficult to achieve true separation of hydrolysis from methanogenesis
Economic and Environmental	Higher throughput, smaller footprint	Larger capital investment

Table 4: Summary of Batch systems digester technology [17]

Criteria	Advantages	Disadvantages
Technical	Simplified material handling Reduced pre-sorting and treatment	Compaction prevents percolation and leachate recycling
Biological	Separation of hydrolysis and methanogenesis Higher rate and extent of digestion than landfill bioreactors	Variable gas production in single reactor systems
Economic and Environmental	Low cost Appropriate for landfills	Less complete degradation of organics (leach bed systems

It should be underlined that the three principal products of anaerobic digestion are biogas, digestate, and water [18].

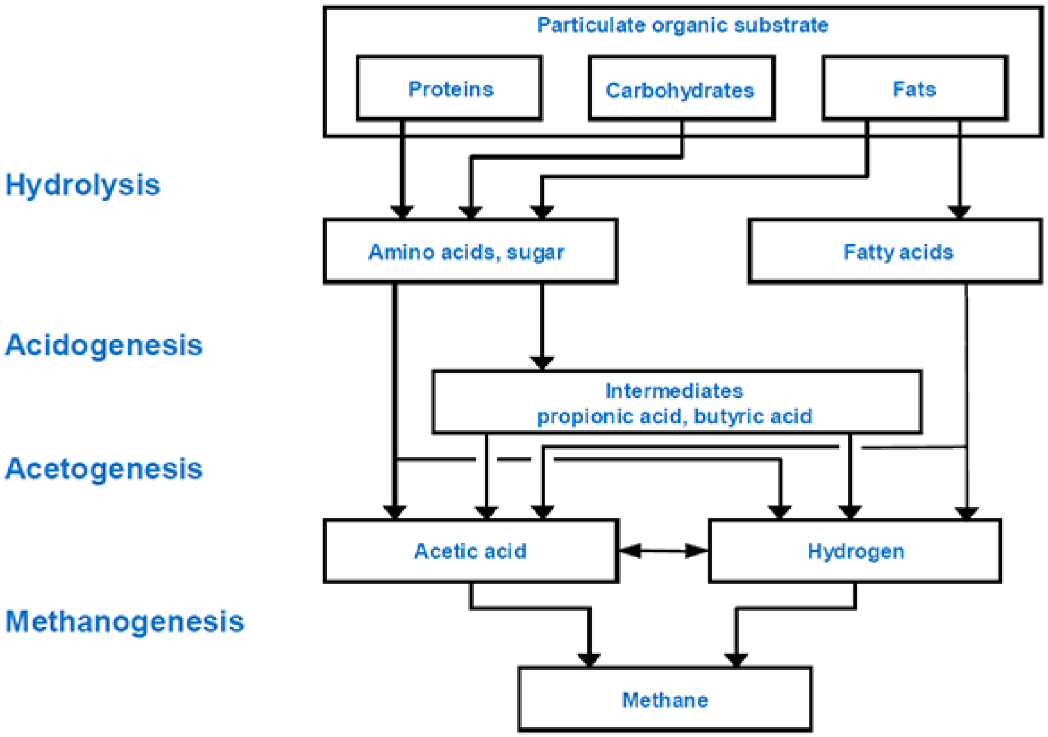

Figure 4: Degradation steps of anaerobic digestion process [19]

2.4 Quality protocols for compost and anaerobic digestion

The Quality Protocols set out criteria for the production of quality outputs from composting and anaerobic digestion of material that is biodegradable waste (biowaste) [20], [21]. These protocols have been applied in England [22], Wales and Northern Ireland. The relation between the two protocols is shown in Figure 5.

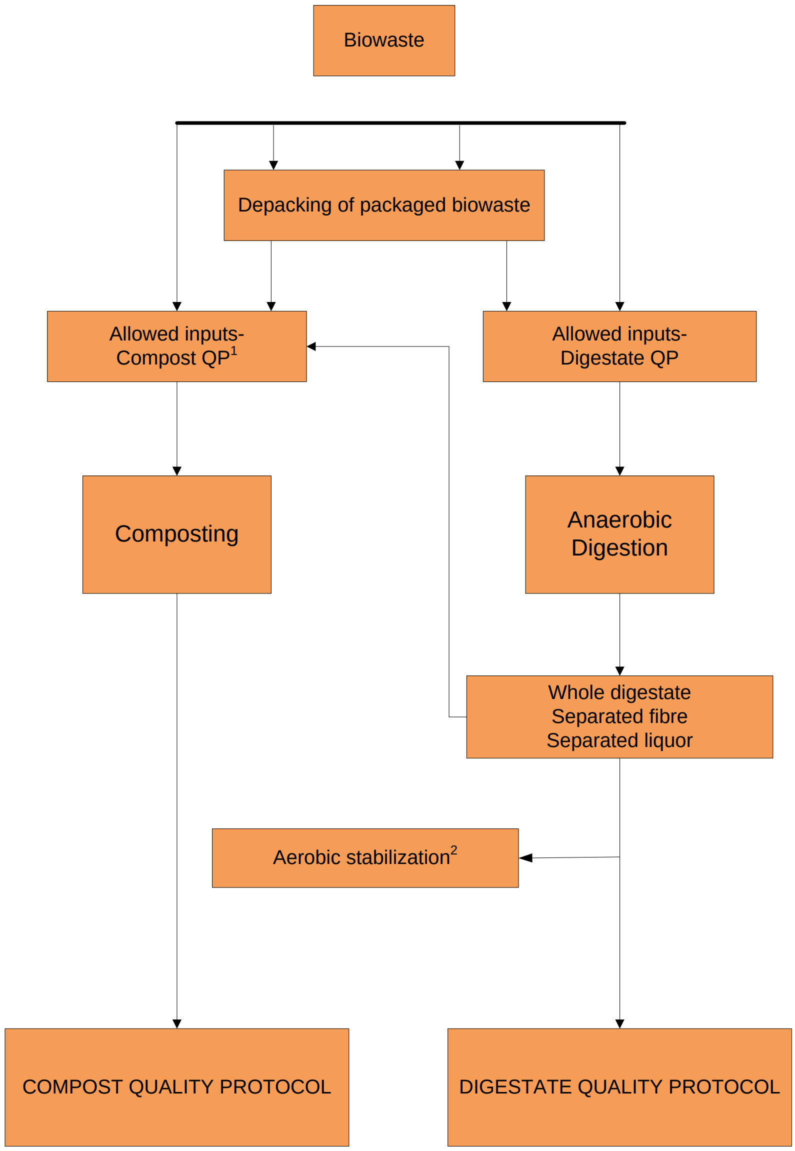

Figure 5: Relationship between the two Quality Protocols [20]

[1]If digestate is used as an input, it must have been produced using Anaerobic Digestion Quality Protocol Acceptable inputs

[2]Separated fibre with no further material added

2.5 Advantages-Disadvantages

Both composting and anaerobic digestion have their own specific advantages and disadvantages, with composting generally accepted as being a more rapid process than anaerobic treatment. In addition, anaerobic method is considered as an energy production process. However, based on an energy balance, anaerobic digestion has an advantage over composting, incineration, a combination of composting and digestion or land-filling, with anaerobic digestion capable of being energy sufficient if only one quarter of the biogenic waste is digested to biogas. A well – known disadvantage of anaerobic digestion is the fact that the solids produced are not typically suitable for direct land application as they tend to be odorous, too wet and too high in volatile fatty acids (VFA) concentration, which are phytotoxic. In addition, if the digestion is not performed under thermophilic conditions, the solids are not sanitized. Consequently, a post treatment of these solids is required with composting providing an appropriate management solution [23]. It is important to refer that organic waste and municipal solid waste usually contain considerable amounts of different nitrogen compounds, which may inhibit anaerobic degradation processes and cause problems in the downstream and peripheral devices. This refers particularly to the different process stages of anaerobic digestion, to wastewater treatment, and to exhaust air treatment [24]. The advantages and disadvantages of each method are summarized in Table 5.

Table 5: Advantages and Disadvantages of Composting and Anaerobic Digestion [23]

Composting		Anaerobic Digestion	
Advantages	*Disadvantages*	*Advantages*	*Disadvantages*
Simple			More Complex
Inexpensive			More expensive
	Larger area	Smaller area	
	Odour pollution	Reduced odour via biogas combustion	
	Uncontrolled leachate pollution		High strength wastewater formed
	Uncontrolled CH4 production		
	Net energy consumer	Net energy producer	

3. Life Cycle Analysis

3.1 Methodology

Generally, Life Cycle Management (LCM) is an integrated concept for managing the total life cycle of goods and services towards more sustainable production and consumption.

LCM uses various procedural and analytical tools for different applications and integrates economic, social and environmental aspects into an institutional context. LCM is applicable for industrial and other organizations demanding a system-oriented platform for implementation of a preventive and sustainability driven management approach for product a service systems [25].

Life cycle analysis (LCA) can be defined as a method that studies the environmental aspects and potential impacts of a product or system from raw material extraction through production, use and disposal [26]. The general categories of environmental impacts to be considered include resource use, human health and ecological consequences [27], [28].

Waste management strategies taking place in LCA should aim at maximizing energy and material recovery, while minimizing the final amount of waste delivered to landfill and the pollution related to all treatment and collection steps. The suitable scenario is estimated after the consideration of a large range of scenarios as it is realized in reference [29].

The first effort for LCA study is realized for Coca-Cola by Harry E., Teastley Jr., in 1969. The study revealed the plastic bottle as better choice than glass bottle, contrary to all expectations. The study has never been published in its complete version. Only was a summary in April 1976 in Science Magazine. In the period 1997-2000, ISO standard determined the stages of LCA [30]. It is noted that the typical LCA methodology [31], initially was proposed by SETAC [32].

A typical LCA study consists of the following stages:

a) Goal and scope definition;

b) Life cycle inventory (LCI) analysis, incorporating data for energy and material flows and for emissions, throughout the life cycle of the case study (ISO 14041);

c) Assessment of the potential impacts (Life Cycle Impact Analysis, LCIA) associated with the identified forms of resource use and environmental emissions (ISO 14042);

d) Interpretation of the results from the previous phases of the study in relation to the objectives of the study (ISO 14043) [33].

Specifically, the quantification of inputs and outputs of a system is called Life Cycle Inventory (LCI). At this stage, all emissions are reported on a volume or mass basis (e.g., kg of CO_2, Kg of cadmium, cubic meter of solid waste). Life Cycle Impact Assessment (LCIA) converts these flows into simpler indicators.

The impact assessment methods, which are used in LCA can be divided into two categories: those that focus on the amount of resources used per unit of product (upstream methods), and those which estimate the emissions of the system (downstream methods) [34]

To allow a consistent comparison between the different scenarios, it is necessary to define a common reference in order to express the results for the same output: this common reference is called the «functional unit». The functional unit, which is usually chosen in waste management scenarios, refers to 1 t input MSW [35].

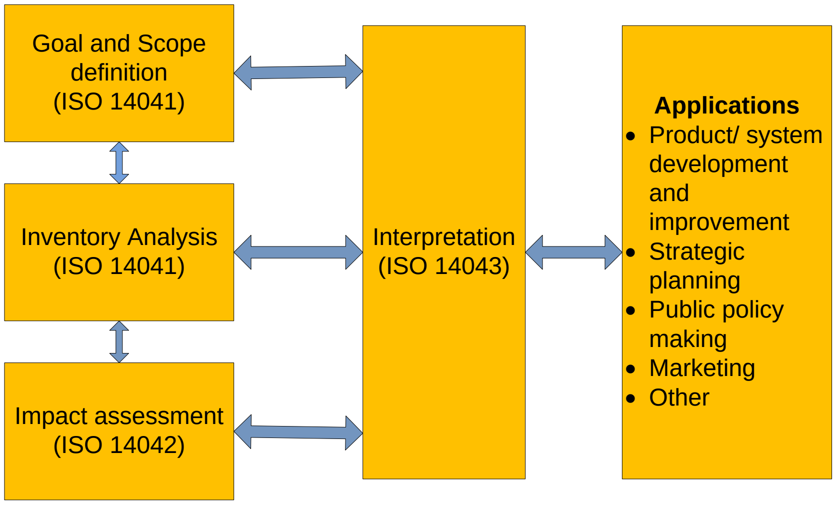

Figure 6: Stages of an LCA study

Examples of environmental impacts that may be covered by an LCA, and that may result from a particular organic waste management method, include:

- Climate change
- Human respiratory health decrement from particulates
- Human health decrement from toxics
- Human health decrement from carcinogens
- Acidification
- Eutrophication
- Ecosystem toxicity
- Ozone depletion
- Smog formation
- Habitat alteration
- Biodiversity decrease
- Resource depletion
- Water consumption
- Land use and/or land use change

The usual indicators which represent the above categories of impact are:

- Gross energy requirement (GER)
- Global warming potential (GWP_{100})
- Ozone depletion potential (ODP)
- Acidification potential (AP)

- Photochemical ozone creation potential (POCP)
- Photochemical oxidation
- Eutrophication
- Human toxicity

Global warming refers to the increase in the average temperature of the Earth's surface, due to an increase in the global warming potential, caused by anthropogenic emissions of global warming gases (carbon dioxide, methane, nitrous oxide, fluorocarbons (e.g. CFCs and HCFCs), and others). These global warming gases are defined according to references [36], [37]. Carbon sequestration is the opposite of GHG emissions. Specifically, carbon is removed from the carbon cycle (or from the atmosphere) and added to a carbon sink, where carbon is stored for a long period of time. It is mentioned that there is no impact to the greenhouse effect for the period time of storage. The more representative characteristic examples of carbon sinks are soils, forests and oceans [12].

Table 6: Global warming potential and related carbon equivalents of GHGs of 1 kg of greenhouse gas [38]

Greenhouse gas	Global warming potential ($CO_{2\ eq.}$)	Carbon equivalent (kg of carbon)
Carbon dioxide	1	0.27
Methane	21	5.67
Nitrous oxide	310	83.7

Acidification consists of the accumulation of acidifying substances (e.g. sulphuric acid, hydrochloric acid) in the water particles in suspension in the atmosphere [39]. Deposited onto the ground by rains, acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings).

Eutrophication is a process whereby water bodies, such as lakes or rivers, receive excess chemical nutrients – typically compounds containing nitrogen or phosphorus – that stimulate excessive plant growth (e.g. algae) [40]. Sources for nutrients are the following: a) fertilizers applied to agricultural fields, b) deposition of nitrogen from the atmosphere, c) erosion of soil containing and d) sewage treatment plant discharges.Human activities resulting in anthropogenic nutrient enrichment encompass inputs from point sources (e.g. sewage plants or industry) and from diffuse sources (e.g. agriculture, households not connected to sewerage, overflows, and atmospheric inputs as reported by reference [41]).

Table 7: EP for characterising eutrophying releases to water [12]

Substance (g)	EP (g O_2 depletion) P-limited	EP (g O_2 depletion) N-limited
Ammonia (air)	3.8	19.8
Ammoniun (water)	3.6	18.6
Nitrate (water)	0	4.4
COD (water)	1	1
Nitrogen (dioxide)	0.13	-
Nitrogen (monoxide)	0.2	-
Nitrogen oxides (air)	0	6
Phosphorus (water)	140	0
Phosphorus (V) oxide P_2O_5	1.34	-

Photochemical oxidants are trace species that are formed during the photo-oxidation of volatile organic compounds (VOCs), carbon monoxide (CO) and oxides of nitrogen (NO_x). Examples include ozone (O_3), which is the most significant, hydrogen peroxide (H_2O_2) and peroxy acetyl nitrate ($CH_3C(O)OONO_2$, PAN). The prevalence of tropospheric photochemical oxidants is of major international concern, because of their adverse effects on human health and the environment [42].

Table 8: POCPs for characterising photo-oxidant forming releases to air [12]

Substance (kg)	POCP at high NO_x background (ethylene eq)
Carbon monoxide	0.027
Nitrogen Dioxide	0.028
Sulphur Dioxide	0.048
Ethylene	1.0
Methane	0.006

Human and Eco-toxicity refers to toxic substances released during production and application of compost, fertilizers, pesticides, biocides etc. These may be toxic to humans and the environment. Human exposure to these chemicals through food, air, water and soil causes health problems. Two indicators used for the quantification of this impact. The first one is the the human toxicity potential (HTP) and the second is ecotoxicity potential (ETP). HTP and ETPs are usually based on the impact of a reference chemical on human and ecosystems.

A life cycle assessment (LCA) includes the steps as shown in

Figure 7. A description of each process includes the evaluation of the infrastructure needed, such as buildings, asphalt surfaces, machines, infrastructure for pre- and post-treatment etc.

(investment of materials and energy). The materials needed to provide the treating infrastructure is divided by the span of their life time in order to obtain the yearly amounts of cement, metals, asphalt etc. necessary to treat a defined amount of waste. In an LCA all processes, such as raw material extraction, distribution and manufacturing could be included up to the moment of building, running and breaking down the plants. About the operation of examined plant, it is mentioned that LCA includes energetic and material parameters based on energy fluxes, parts replaced because of attrition, transports etc. Generally the emissions can be categorized in three distinct categories: savings, avoided and direct emissions. A positive number shows emissions to the atmosphere, while a negative number indicates avoidance of emissions. This usually takes place in the evaluation of CO_{2eq} emissions. CO_2 savings refer to the GHG emissions avoided by not having to reproduce the recovered materials (recycling method) [43]. CO_2 avoided emissions refer to avoided GHG emissions that, otherwise would be emitted, if an another treatment method has been realized [44]. CO_2 direct emissions are GHG emissions, emitted directly in the environment from the processes that take place [45], [46].

Materials and energy consumption cause *indirect* environmental impacts: The emissions to produce materials and energy for constructing, running and breaking down the plants are quantified by taking data from the respective data base tool used. These impact factors show effects on the impact categories. All impacts caused by the different activities of a waste treating process are first sorted and attributed to the relevant categories. For each damage category, a reference substance has been defined. The impacts are brought to a comparable size by multiplying with a factor corresponding to their relative damage potential. The damages caused by the reference substances of each impact category are weighted for causing mortality, damage to health and ecosystem impairment. For damage weighting factors, subjective weighting is possible.

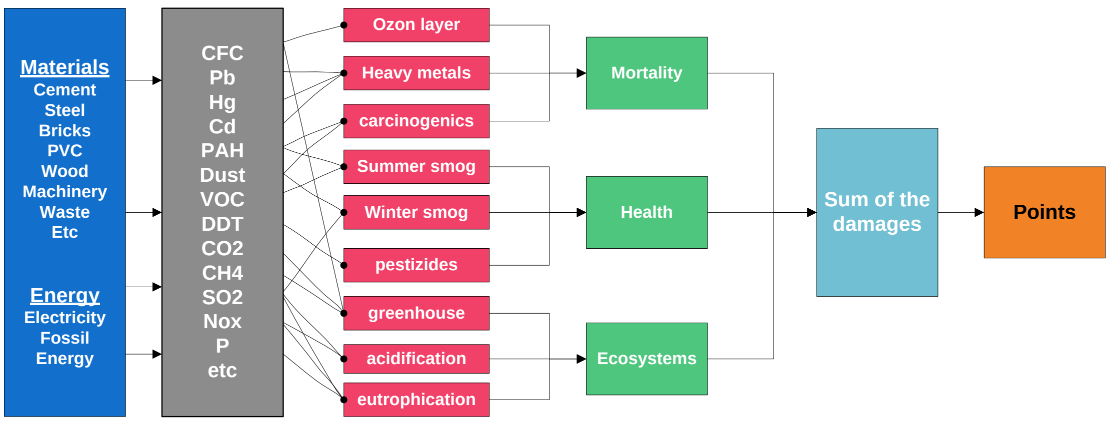

Figure 7: LCA steps for the estimation of total results [47]

The LCA studies are categorized in four types [48]:

a. Screenings
b. Short studies
c. Extensive Studies

d. Continuous LCA operations

The main parameter for this distinction is the budget indication. The budget indication is based on the days are demanded for the LCA study.

More specifically, the screenings LCA studies are more suitable for the cases where the speed and budget are more important than precision. The short LCA studies are used in the cases, where the decision has a significant influence on the product development process or communication strategy, while LCA report itself is not applied for external communication. The extensive LCA are applied for making detailed environmental claims and using the LCA report on public debate. About the continuous LCA operations, the ISO standards and many LCA specialists consider LCA studies implicitly as an ad-hoc activity. A study is done to support a decision and after this, the activity stops until a new decision needs to be supported. Nowadays a clear trend away from this ad-hoc approach has been identified, as more and more organisations tend to see LCA as a continuously maintained Environmental Lifecycle Management Information System (ELMIS). In such a system, the aim is to gradually develop and improve an LCA database.

3.2 LCA software

In order to apply the aforementioned methodology by a reliable and standardized way, LCA should be performed by a commercial software. There are many suppliers of LCA software tools on the market. The available software tools are intended for different types of users and designed for different types of LCA applications [49]. The main differentiations of LCA software is in the database and in the methodology adopted. There are several methods of LCA: Recipe [50], Impact 2002+, Edip2003, Stepwise2006 (combination of Impact2002 and Edip2003) [51]. Impact 2002+ and Edip 2003 methods are second-generation methods, building on previous work (Ecoindicator 1999 [52] and EDIP1997, respectively). A list of LCA tools is available in reference [53].

The most commonly used LCA packages are: Simapro [54], Easewaste [55], Umberto [56], Gabi [57], Gemis [58], Boustead [59]

In ISWM-TINOS project the LCA study will be performed by the Simapro software. Simapro is the most widely used LCA software. It is standardized, so the results are considered reliable and universal. Moreover, it is the most suitable software for analysis of complex waste treatment and recycling scenarios, as it has unique features such as parameterized modeling, interactive results analysis and weak point analysis using process tree. It is based on Ecoinvent database [60]. This database is the outcome of a large effort undertaken by Swiss institutes, in order to update and integrate the well-known ETH-ESU 96, BUWAL250 and several other databases. The database covers a broad range of parameters. Also it provides a consistent specification of uncertainty data, as lognormal distribution with standard deviation.

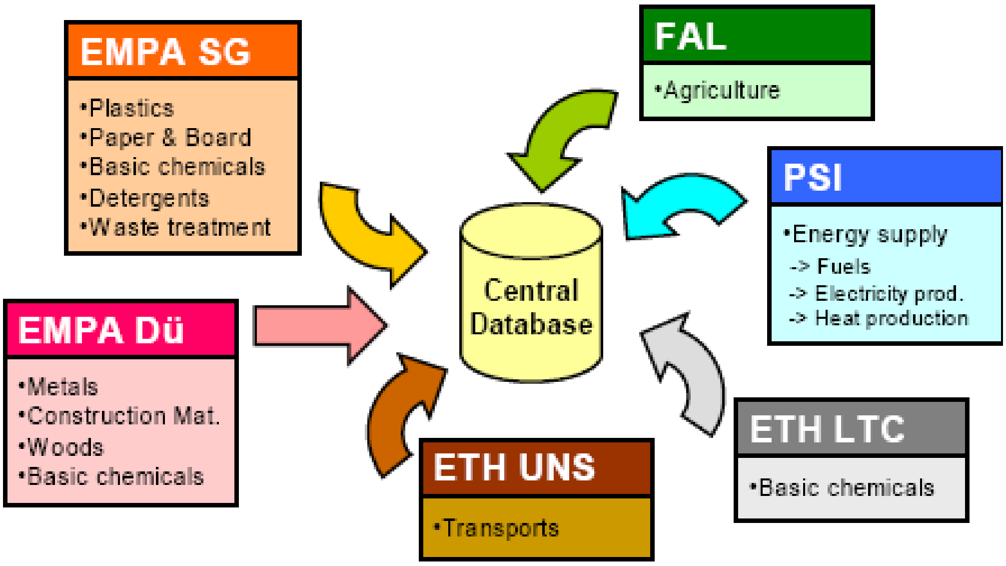

Figure 8: Swiss organizations that joined forces to create the Ecoinvent database [60]

Product stages are used to describe the composition of the product, the use of phase and the disposal route of the product. Each product stage refers to processes. In SimaPro, there are five different product stages, all with their own structures [54].

a) *Assemblies,* which contain a list of materials and subassemblies and a list of production or transport or energy processes. The assembly is equal to the definition of a product. For the examined case the assembly will be the quantity of MSW. Because of the complexity of the product, the assembly can be linked to other subassemblies as paper, plastic etc.
b) *Life Cycles* are the central product stages. Specifically in this stage, the life cycle examined scenario is built by using the created assembly, the existed use processes (energy use), the disposal or waste scenario and if it is necessary, an additional life cycle of a product.
c) *Disposal scenarios,* which describe the the end-of-life route of entire products that may still be reused or disassembled. They contain: a number of processes, representing the environmental load connected to the scenario, a number of links to disassemblies, disposal scenarios, waste scenarios or reuse records, that specify to which destinations the product flow. SimaPro also has waste scenarios that describe waste streams in terms of materials, and not in terms of products.
d) *Disassemblies,* which describe the disassembly of components. It is mentioned that this stage contains a reference to the assembly that is being disassembled. Also a number of processes representing the environmental load connected to the disassembly operations, a number of destinations of dismantled parts (subassemblies), and the disassembly efficiency and a destination for the remains, usually a disposal scenario or a waste scenario are included in this stage
e) *Reuse*, which describes the way products, can be reused. This stage contains a number of processes representing the environmental load connected to the reuse operation and a reference to the assembly that is being reused.

3.3 LCA of aerobic composting

The environmental impacts of aerobic composting are very sensitive to compost facility management practices for maintaining aerobic conditions. Variations from aerobic conditions can result in releases of methane and/or nitrous oxide, both of which are greenhouse gases. Results for an aerobic composting LCA depend on offsets. For example, when peat is the product which compost replaces, the carbon offset is much larger than for replacing synthetic fertilizer. In addition the offset changes depending on the type of fertilizer (N,P,K). In Table 9, Life Cycles Burdens and Benefits of LCA for Composting treatment are shown.

Table 9: Burdens and Benefits of Life Cycle Analysis of composting [61]

Life Cycle Burdens	Life Cycle Benefits
Energy and emissions associated with separate collection	Diversion of organics/MSW from landfills
Energy and emissions associated with compost operation and compost construction facility	Potential beneficial offsets of other products (fertilizer, etc.)
Energy and emissions associated with transportation of compost product and residuals	Potential soil carbon sequestration associated with application of compost product

3.4 LCA of anaerobic digestion

LCA data for anaerobic digestion are sensitive to the amount of methane which is produced for use as energy offset [62]. This can depend on both the actual composition of the organic waste inputs and the specific digestion technology. The magnitude of the benefit from energy offsets also depends on the energy fuel displaced. For example, if the displaced fuel is coal, the climate benefit is much larger than if the displaced fuel is natural gas. If the displaced energy is one that is close to carbon neutral such as renewable energy, then the energy offset will be small no matter how much methane is generated during the digestion process. For this case, it is mentioned that the total energy offset depends on the respective boundaries of life cycle analysis of the displaced energy. Finally, because anaerobic digestion specifically attempts to maximize methane production, any system deficiencies with respect to best practices may result in fugitive emission releases that will substantially degrade this technology‘s environmental performance.

More specifically, the anaerobic digestion of municipal solid waste is, technically, perfectly feasible. There are two options for collecting organic waste: By source separately and by mechanical segregation of the mixed waste. Source segregation does not mean that the waste does not contain any unwanted materials. The source separation, which is implemented, involves new containers and vehicles for the collection, thus, the costs are always higher than the traditional single collection vehicle methods, except if it is part of an integrated source segregated collection system. It is important that the purity of the waste stream should be defined with respect to the purpose of the AD plants. If the plant is intended to maximize the output of methane, mixed collection is suitable. If the purpose is to produce a high quality digestate, then the purity of the waste is very important. Thus, the final product of anaerobic digestion is a significant parameter [63].

4. LCA studies of aerobic and anaerobic treatment methods

4.1 Introduction

In this section, a variety of studies for aerobic and anaerobic treatment are presented. Each study corresponds to a specific case. The two general categories of studies are: Studies for composting and studies for anaerobic treatment. These categories analyzed by themselves and compared with other waste management as landfill, incineration regarding to LCA principles. In each following LCA study, the boundaries of system and the inputs are given in order to find the benefits and the burdens of each method using the appropriate LCA indicators.

4.2 Aerobic Treatment

4.2.1 Comparison between composting and landfill

In study in the reference [64], a LCA study for comparison between composting and landfill in Asti District in Northern Italy is accomplished. About the collection system used, a separate collection of municipal solid waste has overcome the 50% threshold, according to EU waste directives. Nearly one-third being composed of household and green organic waste. The study area covers 1513km^2, involving 114 municipalities, with a population of approximately 210,000 inhabitants, presently producing around 89,000 t/year of municipal solid waste. It is noted that during the year 2004, 16,000 t of input wet bio-waste were turned into 4500 t of high quality compost and then delivered to farmers. The systematic quality control at each process step resulted in an overall mass yield that is lower than the Italian average (0.28 t of mature compost per ton of input bio-waste), but, on the other hand, this allowed a better compost quality. It is considered that the emissions are 156 kg of biogenic carbon dioxide and 0.6 kg of ammonia per 1 t of input bio-waste. Composting of 1 t bio-waste is estimated to avoid production of 8.4 kg N, P, K synthetic fertilizers and allow recycling of 1.12 kg of steel, while the carbon dioxide sequestration potential is 48 kg. The differences between the impacts of composting and landfilling are shown in Table 10. It is noted that the overall net balance of greenhouse emissions from composting is 130 g/kg, corresponding to only 14% of greenhouse emissions caused by landfill. The phases of LCIA refer to collection (production waste bags and transportation), waste processing (country's mix electricity, diesel use, biogenic emissions) and avoided products (substitution of fertilizers and recycling of steel).

Table 10: Life Cycle Impacts of organic waste disposal (impact per 1 t input biowaste) [64]

LCIA step	Impact category	Unit	Composting	Landfill
Characterisation	Energy resources	MJ	0.959	0.800
	Global warming	Kg CO_{2equiv}	0.130	0.951
	Ozone depletion	mgCFC11$_{equiv.}$	0.027	0.021
	Acidification	molH^+	0.018	0.023
	Eutrophication	gO_{2equiv}.	3.635	21.397
	Photochemical smog	mg$C_2H_{4equiv.}$	0.578	184.788
Weighting		mPt	4.225	8.360

4.2.2 Environmental impact of two aerobic composting technologies

The environmental impacts depend on the technology of the composting plant. According to reference [65], two composting facilities using different technologies- tunnels (CT) and confined windrows - are examined. These facilities are located in Catalonia (Spain) and were evaluated during 2007. The composting tunnels (CT) facility is located in Girona province. This plant treats around 6,000 t OFMSW/year using wood chips as bulking agent. The second plant is located in Barcelona province (Catalonia, Spain). This plant uses a composting technology based on confined windrows (CCW) treating around 91 t OFMSW/year using pruning waste as bulking agent.

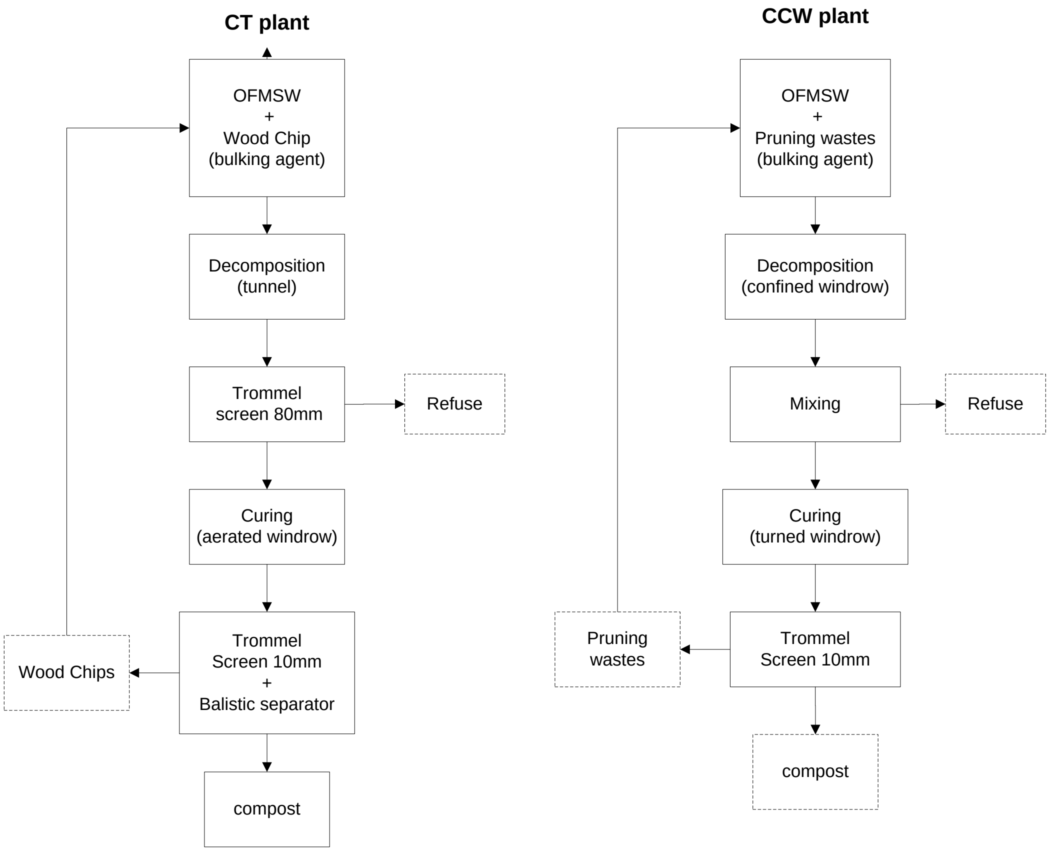

Figure 9: Flowchart of the studied composting processes. Composting in tunnels (CT) and composting in confined windrow (CCW) [65]

According to the results of this work, total energy consumption required for composting OFMSW depends on the technology used (ranging from 130 for CT plant to 160 kWh/t OFMSW for CCW plant). About water consumption required for the composting method, this is estimated from 0.02 for CCW plant to 0.33 m^3 of water/t OFMSW for CT plant. The total environmental impacts are summarized in

Table 11.

Table 11: Total Impact potential according to the type of composting technology used [65]

Impact potentials	Tunnel composting plant (CT)	Confined windrows composting plant (CCW)
Global warming ($kg\ CO_{2\ eq}/t$ OFMSW)	63.90	63.15
Acidification ($kg\ SO_{2\ eq}/t$ OFMSW)	7.13	3.7
Photochemical oxidation ($kg\ C_2H_{4\ eq}/t$ OFMSW)	0.13	3.11
Eutrophication ($kg\ PO_4^{3-}{}_{eq}/$ t OFMSW)	1.51	0.77
Human toxicity ($kg\ 1.4\text{-}DB_{eq}/$ t OFMSW)	15.86	14.54
Ozone layer depletion ($kg\ CFC^{-11}{}_{eq}/t$ OFMSW)	$1.66*10^{-5}$	$2.77*10^{-5}$

4.2.3 Life cycle assessment of the use of compost from municipal organic waste for fertilization of tomato crops

The aim of the LCA study presented in reference [66] is to determine the environmental impacts associated to the use of compost, from the moment of collection of organic municipal solid waste until its application to tomato crops, and to compare these results with mineral fertilizer application. The use of compost in horticulture demonstrated to be a treatment with fewer impacts than mineral fertilizer, if the avoided loads of using compost instead of fertilizer are considered. The avoided loads refer to the avoided emissions from the process activities for the production of compost instead of the production of fertilizer.

When comparing the impacts of the three treatments (*Compost*, *Compost* + *Mineral* and *Mineral*), it must be underlined that composting, as well as providing fertilizer, is a form of waste management of organic MSW, which is not the case in the production of mineral fertilizer. In order to make these three systems comparable and to include the extra function of composting, the boundaries of the system should be expanded, considering a form of managing organic MSW alternative to composting. The method selected was dumping, with the environmental burdens subtracted from those treatments that include composting so that only the fertilizing function of the three treatments is compared.

The results of the LCA indicated that the production of a tone of tomatoes using compost (C) consumes 2,584 MJ eq. with 136 kg CO2 eq emitted. The stage with the major impact is compost production, with between 53% and 98% of the total impact, depending on the impact category, mainly due to gas emissions generated and energy consumption at the composting facility. The yield stage also contributes substantially to the total impact.

Composting Treatment has 33–95% more impact than treatment with mineral fertilizer, depending on the category of impact and excluding Photochemical Oxidation (PO), as a consequence of compost production. It is also considered an expanded system that integrates the burdens avoided by not depositing the composted organic MSW and pruning waste in landfill. For the expanded scenario, treatment with compost has similar or less impact than treatment with mineral fertilizer for all the categories apart from PO, for which treatment with compost has 32 times more impact than treatment with mineral fertilizer. In this case, compost can possibly be an environmentally better option than mineral fertilization for all categories except PO. The application of compost as a fertilizer for tomato crops apparently not has a negative effect on harvest or product quality. Quite the opposite, non-commercial production is significantly lower for treatment with compost although commercial production is similar between treatments.

4.2.4 Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery

In reference [67], the composting method for the treatment of food waste is compared with the processes of dry feeding, wet feeding and landfill. All stages of disposal involved in the systems such as separate discharge, collection, transportation, treatment, and final disposal, were included in the system boundary and evaluated. Global Warming Potential generated from 1 t of food waste for each disposal system was analyzed by the life cycle assessment method. The quantity of waste food examined accounts for 13,372 t, which are generated per day in Korea. The examined composting treatment process includes shredding, sorting, adding sawdust, fermentation and maturing. The functional unit used is 1 t of food wastes for each scenario. The results are shown in

Figure 10. As it can be seen, the composting system is more environmental method from the others, except wet feeding method.

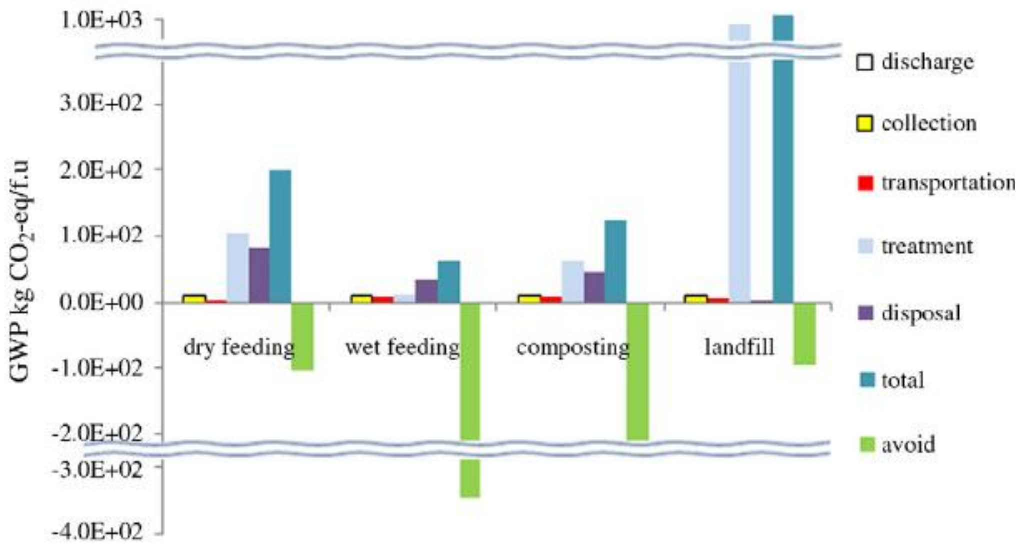

Figure 10: GWP of four methods waste treatment: dry feeding, wet feeding, composting, landfill [67]

4.2.5 BMT-based integrated municipal solid waste management

In reference [68] life cycle assessment is employed to compare the environmental impact potential (EIP) of three Biological and Mechanical treatment (BMT)-based [69] waste treatment strategies (BMT-compost, BMT-incineration and BMT landfill) with traditional landfill and incineration in Pudong New Area of Shanghai. The amount of MSW generated in Pudong New Area is about 2200 t/day, which almost reaches one fifth of the total amount produced in Shanghai. The great mass of MSW is directly treated by incineration and landfill without any pretreatment, except for compost. Meanwhile, only 4% of MSW generated from Pudong are recycled by separation. MSW in Pudong is of high moisture content (50–60%) and low calorific value (1000 kcal/kg), containing a large percent of organic garbage. 2190 t/day of MSW in Pudong are collected and treated by three disposal facilities: the incineration plant, the biological compost factory and the landfill yard. The daily handling capacity of each site is 1000 t, 1000 t and 1000–1500 t, respectively.

The results of life cycle assessment for the five different alternative waste treatment strategies (landfill, incineration, BMT-compost, BMT-incineration and BMT-landfill) show that the incineration process of MSW presents the highest acidification potential while the landfill presents both the highest global warming potential and eutrophication potential. For the calculation of total environmental impact potential (TEIP), the respective weighting factors are used. The weighting factor accounts for 0.82 for global warming, 0.73 for acidification and 0.74 for eutrophication.

As far as the TEIP of the five different alternative waste treatment strategies is concerned, the TEIP of landfill is 0.017, 1.5 times larger than that of BMT-landfill (0.011). Moreover, the TEIP of incineration is 0.012, 1.5 times larger than that of BMT-incineration (0.0078). The TEIP of BMT-compost is the lowest, only 0.00049. Therefore, it can be assumed that BMT-based integrated MSW management model is environmentally more preferable than the current MSW management model in Pudong.

4.2.6 Home composting

Except of the methods for large scale systems, composting can be implemented at a smaller scale at home. Home composting, or backyard composting, which means the composting of biowaste as well as the use of the compost in a private garden presents some potential benefits in comparison to composting in large scale facilities. Home composting avoids the collection of an important part of MSW, thus reducing the economic, material and energetic investments in infrastructures. It requires less land use and, finally, it allows for a better control of the composting process and the organic input material. According to reference [70], it is calculated that the home composting entailed the consumption of 468 MJ eq. The functional unit used is a tone of leftovers of raw fruits and vegratables (LRFV). So the indicator of GWP is equal to 83 kg of CO_2 eq/t of LRFV. However, the scenario of assessment performed indicated that the emission of CO_2 equivalents can vary from 30 kg of CO_2 eq/t of LRFV for the best-case scenario considered to 148 kg of CO_2 eq/t of LRFV for the worst-case scenario.

4.2.7 Life cycle assessment of four municipal solid waste management scenarios in China

Composting, landfill and incineration as methods of waste management are examined in reference [71]. China is considered a significant researching area for waste management, because of its too large population. More specifically, four scenarios mostly used in China are compared: (1) landfill, (2) incineration, (3) composting plus landfill, and (4) composting plus incineration. In all scenarios, the technologies significantly contribute to global warming and increase the adverse impact of non-carcinogens on the environment. The function unit chosen is 1 t dry MSW. The boundaries of the systems included the infrastructure of composting, incineration, and landfill, the road transport of slag to landfill and of composted MSW to land application, the leachate treatment, the direct emissions generated from composting, incineration, and landfill scenarios, the material and energy production and finally the electricity recovery from landfill and incineration scenarios.

Two methods which were used for the assessment included: the recipe method [50] and the impact 2002+ method. The results are shown in Table 12 and Table 13, respectively. It is noted that for the recipe method the results has the mid-point format, while for the impact 2002+ methods, the results has the end-point format. The results from the estimations based on the two methods, are the same.

Table 12: Recipe mid-point results (per t dry waste) [71]

	Landfill	Incineration	Composting + Landfill	Composting + Incineration
Climate change (kg CO_2 eq.)	$1.66*10^3$	$-6.19*10^2$	$1.33*10^3$	38.40
Ozone depletion (kg CFC-11 eq.)	$7.47*10^{-6}$	$5.73*10^{-6}$	$8.31*10^{-6}$	$4.98*10^{-6}$
Human toxicity (kg 1,4-DB eq.)	$-5.26*10^2$	$-2.31*10^3$	$3.33*10^2$	$1.19*10^3$
Photochemical oxidant formation (kg NMVOC)	-0.13	-1.39	$1.28*10^{-2}$	0.68
Particulate matter formation (kg PM10 eq.)	$-6.48*10^{-2}$	-0.37	$-1.19*10^{-2}$	0.29
Ionizing radiation (kg U235 eq.)	2.76	2.18	3.95	3.59
Terrestrial acidification (kg SO_2 eq.)	-0.32	-1.37	-0.13	1.13
Freshwater eutrophication (kg P eq.)	$-6.34*10^{-3}$	$-3.28*10^{-2}$	$-4.09*10^{-3}$	$2.35*10^{-3}$
Marine	$-2.98*10^{-2}$	-0.23	$-1.22*10^{-2}$	$7.65*10^{-2}$

	Landfill	Incineration	Composting + Landfill	Composting + Incineration
eutrophication (kg N eq.)				
Terrestrial ecotoxicity (kg 1,4-DB eq.)	$2.08*10^{-2}$	1.88	0.14	1.60
Freshwater ecotoxicity (kg 1,4-DB eq.)	-0.37	-1.77	-0.20	0.32
Marine ecotoxicity (kg 1,4-DB eq.)	$-8.36*10^{2}$	$-3.85*10^{3}$	$-5.26*10^{2}$	$5.38*10^{2}$
Agricultural land occupation (m^2a)	0.13	0.12	3.59	3.63
Urban land occupation (m^2a)	6.72	1.02	5.72	1.78
Natural land transformation (m^2)	$3.83*10^{-2}$	$2.63*10^{-2}$	$4.50*10^{-2}$	$2.53*10^{-2}$
Water depletion (m^3)	0.86	0.53	0.87	0.62
Metal depletion (kg Fe eq.)	1.25	3.28	2.75	4.48
Fossil depletion (kg oil eq.)	-14.13	$-1.37*10^{2}$	-2.88	14.70

Table 13: Impact 2002+ endpoint results (per t dry waste) [71]

Categories	Landfill	Incineration	Composting + landfill	Composting + incineration
Human health (DALY)	$-1.88*10^{-5}$	$-1.50*10^{-4}$	$5.96*10^{-4}$	$7.05*10^{-4}$
Ecosystem quality(PDF*m^2*y)	7.25	79.44	95.02	167.95
Climate change (kg CO_2 eq)	$1.52*10^{3}$	-618.466	$1.22*10^{3}$	38.59
Resources (MJ primary)	-557.10	$-5.73*10^{3}$	-73.58	657.73

Apart from the important role of GHG emissions, it is noted that direct emissions from incineration, landfill, and land application processes represented the dominant contribution to the global warming and non-carcinogens scores. Electricity recovery from methane gas and waste incineration can significantly reduce the non-renewable energy and global warming scores of landfill and incineration scenarios, respectively, thereby reducing as well the overall environmental impact. As a general conclusion, in the global warming, and non-renewable energy categories, incineration had the lowest value due to the electricity recovery from waste incineration, and therefore, incineration is a good choice for MSW treatment in China.

The flow diagram which shows the relation between the three methods and how they can be parts of a full waste management scenario is presented in
Figure 11 [72].

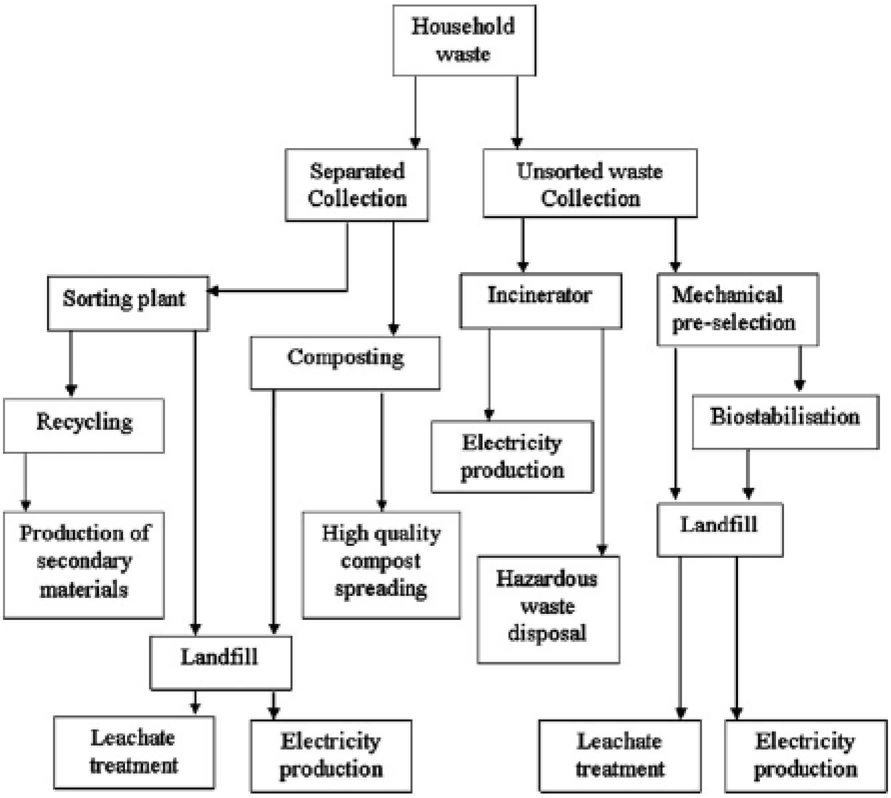

Figure 11: MSW management system in Bologna [72]

4.2.8 Composting as part of MSW management system in Lithuania

The goal of study [73], is to compare different waste management options for the MSW in the region of Alytus, Lithuania. The scope of the study included 5 different scenarios: Scenario 1 was based on landfilling (L-1); scenario 2 included recycling, composting and landfilling (RLC-2); scenario 3 was based on recycling, composting, MBT and incineration (RCMI-3); scenario 4 was based on recycling and incineration (RI-4) while scenario 5 included recycling, MBT and incineration (RMI-5). The functional unit used is the MSW generated in one year (2005): 45,150 tones MSW. It is noted that the waste composition data were extracted from empirical studies in the region of Alytus for the life cycle inventory. Data were also extrapolated from official Lithuanian statistics, while the data on incineration processes are based on the average operation of Swedish technologies. The time boundary of the study was set at 10 years. Assumptions are made for all the waste management options (incineration, landfilling, composting, recycling) of the study. The results of this LCA study are based on four impact categories: global warming, acidification, eutrophication and photo-oxidant formation. The software used is the WAMPS. The results are summarized in Table 14 and are shown in the following respective figures.

Table 14: Results obtained in five scenarios of waste management in Alytus region [73]

Impact category	L-1	RLC-2	RCMI-3	RI-4	RMI-5
Global warming (t CO_2-equiv)	51,230	36,445	8226	4617	8187
Acidification (t SO_2-equiv)	236	155	49	24	48
Eutrophication (t O_2-equiv)	2286	1580	537	319	536
Photo-oxidants (t C_2H_4)	37	25	-7	-11	-7

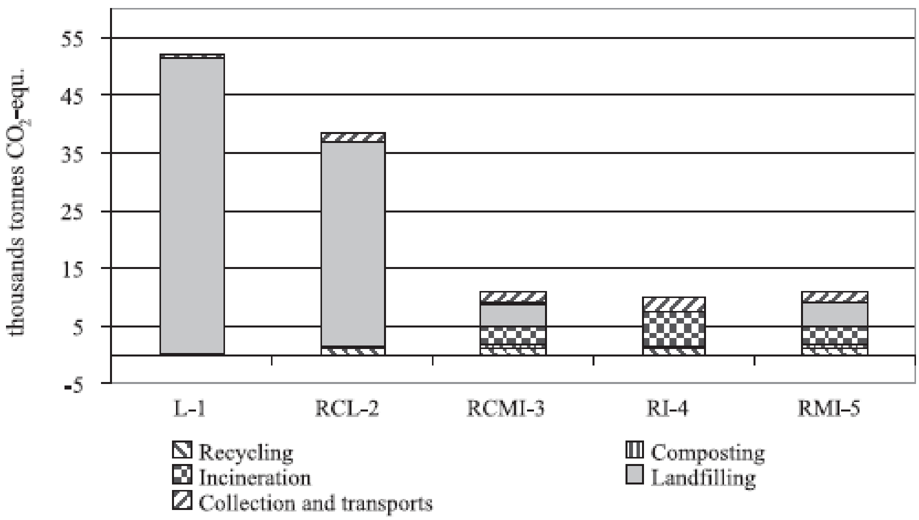

Figure 12: Results for impact category global warming [73]

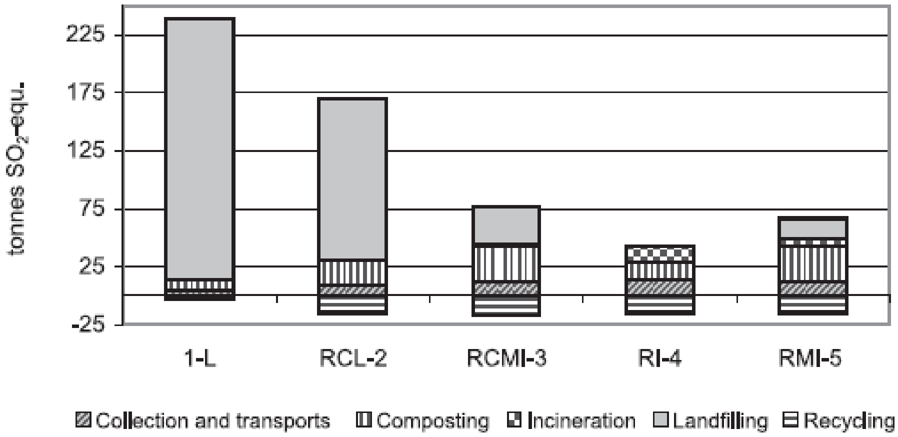

Figure 13: Results for impact category acidification [73]

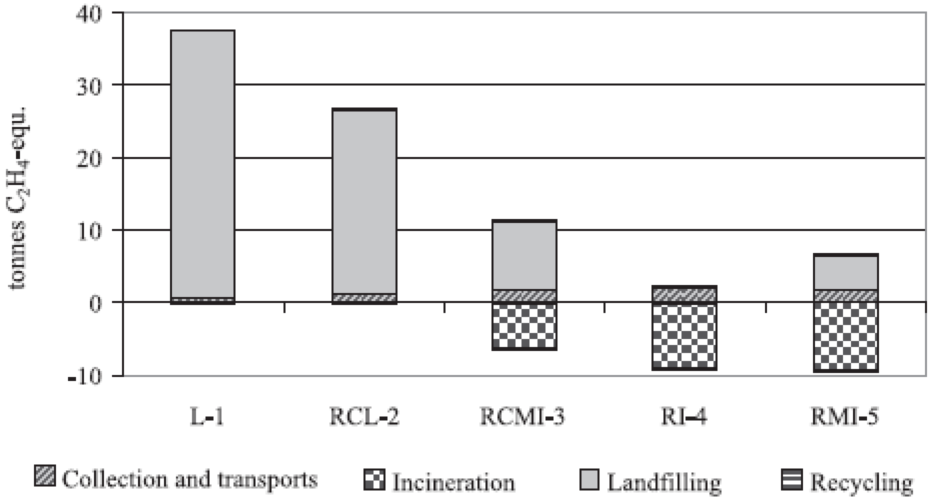

Figure 14: Results for impact category photo-oxidant formation [73]

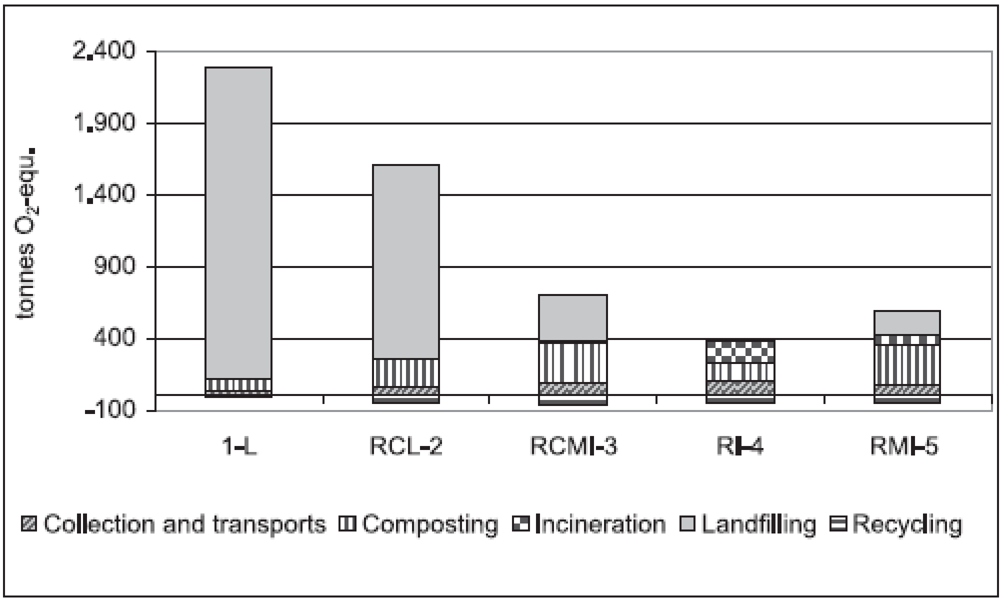

Figure 15: Results for impact category eutrophication [73]

According to the results of this study, the landfilling gives the worst environmental results compared to the other waste management options. Furthermore, with regard to the biodegradable waste fraction, aerobic composting is not a better option compared to incineration with energy recovery in all impact categories.

4.3 Anaerobic Treatment

4.3.1 Comparison between incineration and anaerobic digestion

In study [74], Life cycle assessment is performed to evaluate environmental impacts of two scenarios for municipal solid waste (MSW) to energy schemes in Thailand: incineration and anaerobic digestion. The functional unit used is 1 t of MSW managed. For the anaerobic digestion scheme, processes of separation, slurry preparation, anaerobic digestion, biogas production, fertilizer production, electricity production, and disposal of solid residues to landfill are included in the boundaries of the examined system, as is shown in

Figure 16. It is noted that transportation, construction and maintenance of the plants, and recycling were not included in this study.

The results of the LCA study are presented to the Table 15 and
Table 16. The negative global warming impact, which includes the global warming potential avoided due to both fertilizer and electricity productions, was greater than that produced by the anaerobic digestion activities.

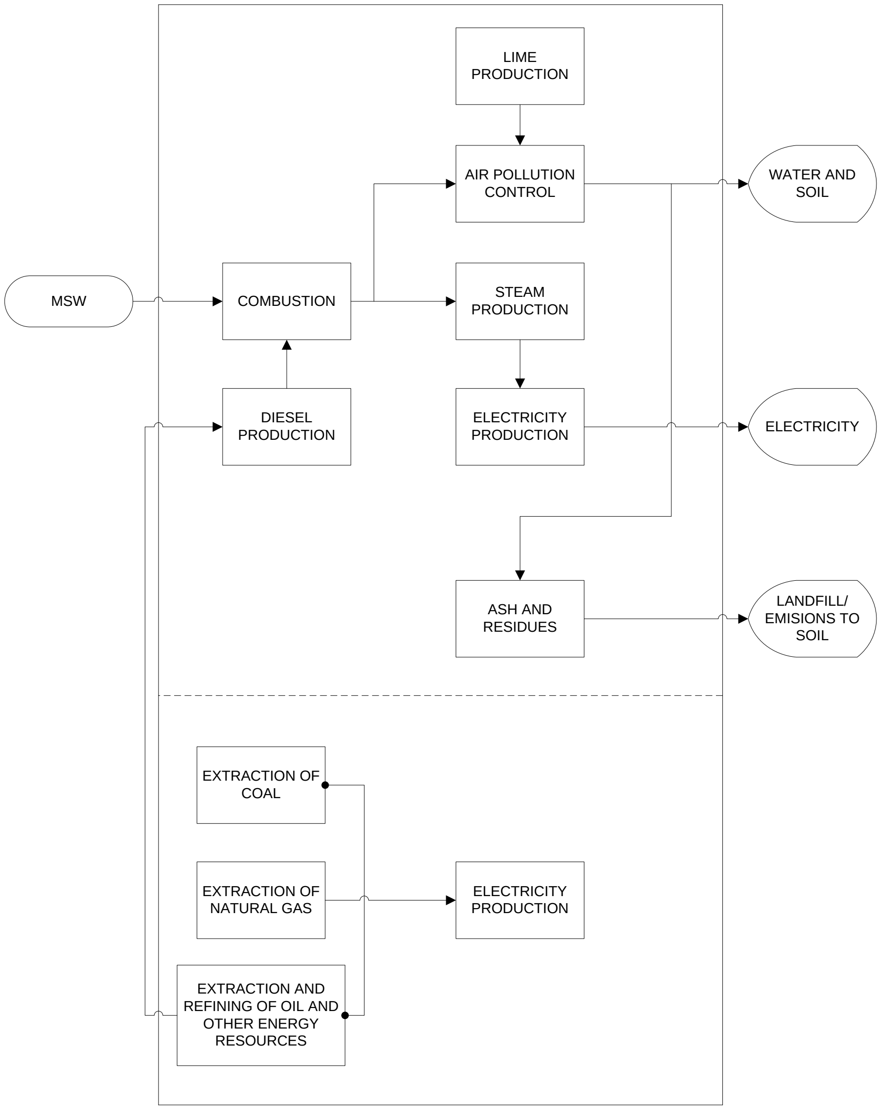

Figure 16: Boundaries of MSW incineration system [74]

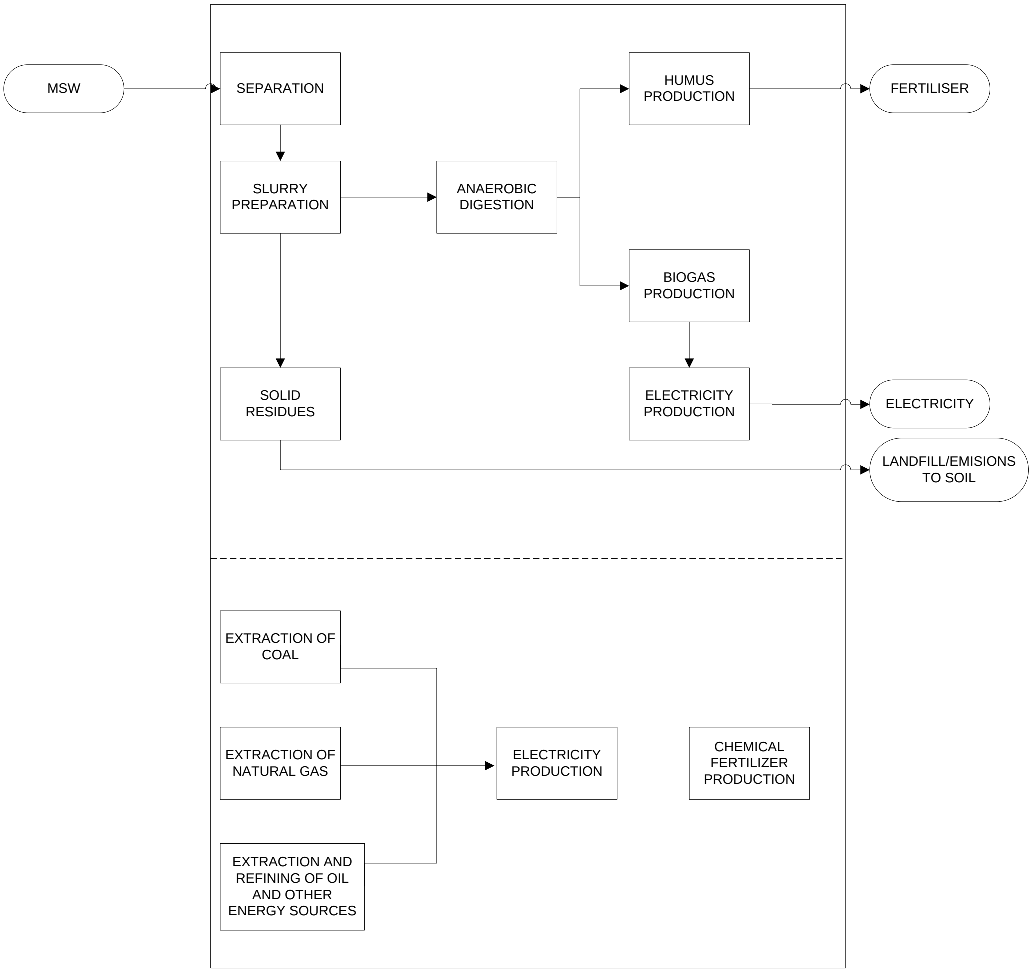

Figure 17: Boundaries of MSW anaerobic digestion system [74]

Table 15: Impact Assessment Results for MSW incineration [74]

Impact category	Unit	Total impact	Combustion	Diesel production	Lime production	Electricity production
Global warming	Kg $CO_{2\ eq.}$	273	307	0.594	14.3	-48.4
Acidification	Kg $SO_{2\ eq.}$	2.37	2.54	0.00491	0.0291	-0.207
Nutrient enrichment	Kg PO_{4eq}	0.354	0.372	0.000433	0.0015	-0.0202
Photo-oxidant formation	Kg C_2H_{4eq}	-0.00826	-	0.00391	0.00111	-0.0133
Stratospheric ozone depletion	Kg CFC11 eq.	$-3*10^{-06}$	-	$7.22*10^{-06}$	$1.1*10^{-06}$	$-1.1*10^{-05}$
Heavy metals	Kg $Pb_{eq.}$	$3.04*10^{-05}$	$1.18*10^{-5}$	$6.72*10^{-06}$	$4.79*10^{-05}$	$-3.6*10^{-05}$
Consumption of energy resourses	MJ LHV	-563	-	53.2	65	-681
Generation of solid waste to landfill	kg	582	582	-	-	-0.0363

Table 16: Impact Assessment Results for MSW Anaerobic digestion [74]

Impact category	Unit	Total Impact	Anaerobic Digestion	Electricity production	Fertilizer production
Global warming	Kg $CO_{2\ eq.}$	-276	-	-76	-200
Acidification	Kg $SO_{2\ eq.}$	-1.57	0.00951	-0.324	-1.25
Nutrient enrichment	Kg PO_{4eq}	7.37	11.2	-0.0317	-3.77
Photo-oxidant formation	Kg C_2H_{4eq}	-0.0253	$9.31*10^{-07}$	-0.0208	-0.00444
Stratospheric ozone depletion	Kg CFC11 $_{eq.}$	$^{-}1.9*10^{-5}$	-	$-1.8*10^{-05}$	$-1.1*10^{-06}$
Heavy metals	Kg $Pb_{eq.}$	-0.00358	$4.85E^{-08}$	$-5.7*10^{-5}$	-0.00352
Consumption of energy resourses	MJ LHV	-3580	-	-1070	-2510
Generation of solid waste to landfill	kg	372	374	-0.057	-1.54

A second study [75] examines the treatment of separated organic waste. Two possible treatments are the anaerobic digestion and the mass burn incineration. The results are based on Danish data [76]. The two processes are shown in following figures (Figure 18 and Figure 19).

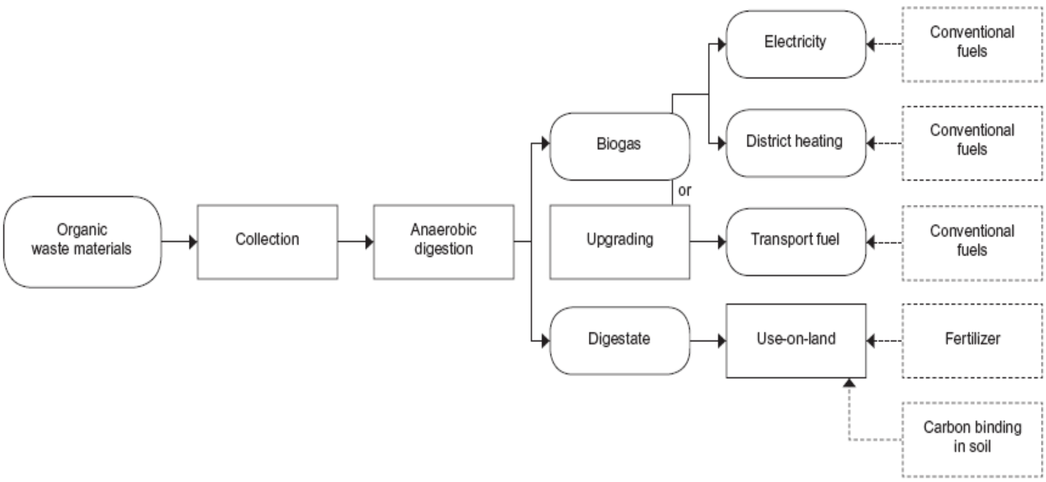

Figure 18: Flow of Anaerobic digestion [75]

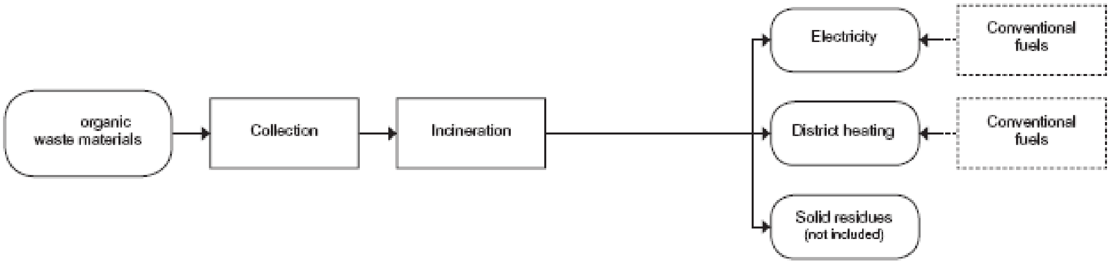

Figure 19: Flow of Incineration [75]

The composition of organic waste for anaerobic digestion depends on the source of waste, the collection system and the final processing of the waste. Biogas production from household waste is usually found in the range 80–130 Nm^3/t of waste received at the AD facility with methane constituting 45–65% of the gas volume. Organic waste was assumed originating from households with food waste constituting the majority of the waste. The scenarios presented in Figure 20 are: waste incineration without energy recovery, waste incineration with energy recovery, anaerobic digestion-produced biogas is utilized in CHP production and anaerobic digestion-produced biogas utilized as transported fuel. For the scenario SENS4, a coal substitution is considered instead of natural gas substitution.

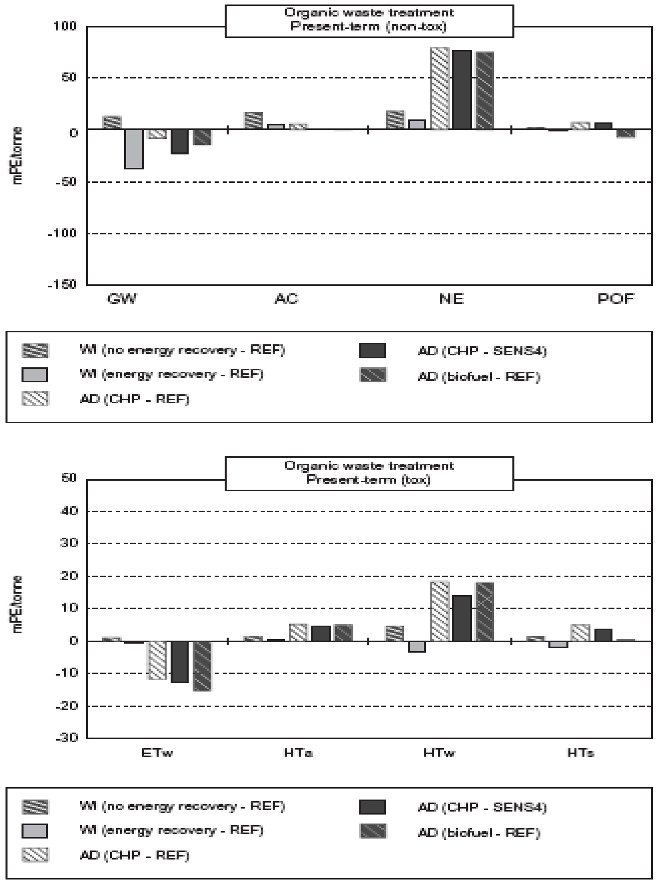

Figure 20: Results of LCA for the different scenarios [75]

For treatment of organic waste, incineration with energy recovery proved to be a better alternative than anaerobic digestion for the majority of impact categories, regardless whether the produced biogas was utilized for CHP production or as transportation fuel.

Utilization for CHP production was slightly worse than use for transportation, however, only in a present-day perspective. Especially nitrate and Hg emissions from utilizing digestate on farmland caused significant loads, whereas avoided emissions of Cd and Cu due to replacement of inorganic fertilizer induced savings. The higher energy conversion rate of the waste incinerator compared with the rate of the anaerobic digestion plant was significant, as well. Overall, waste incineration with efficient energy recovery proved to be a very environmentally competitive solution.

4.3.2 Environmental aspects of the anaerobic digestion of the organic fraction of municipal solid wastes.

In study [77], different processes to treat biogenic waste in plants with a treating capacity of 10,000 t of organic household waste per year as well as agricultural codigestion plants are compared by life cycle assessments (LCA), using the tool EcoIndicator. From the results of the study, it seems that anaerobic digestion shows to be advantageous as compared to composting, incineration or combination of digestion and composting, mainly because of a better energy balance.

Six different technologies are compared in order to treat 10,000 t of biogenic waste per year. These are: open windrow composting (OC) as well as fully automated, enclosed tunnel composting (EC), anaerobic digestion with aerobic post-treatment (DP), combinations of digestion with open (DO) and enclosed composting (DE) as well as incineration in an incineration plant including exhaust gas scrubbing (IS; incinerating 10,000 t of biogenic wastes together with a corresponding amount of “gray” waste in a plant with a treating capacity of 100,000 t/a). The functional unit is 10,000 t of fresh substance of biogenic waste per year.

Figure 21 shows as an example the results of CO_2 and CH_4 emissions caused by composting and by the aerobic post-treatment while digesting, respectively. In digestion plants there is a considerable potential of methane emission during the "aerobic" post-treatment, even if just a small percentage of the organic breakdown takes place outside the digester. (The methane produced within the digester will be burnt to CO_2; CH_4 refers only to the amount generated after digestion). About the percentages of processes in each method, the EC is 100% Enclosed automated Composting, the OC is 100% Open windrow Composting, the DE is combination 40% Digestion with 60% Enclosed composting, the DO is combination 60% Digestion with 40% Open composting and finally DP is 100% Digestion with aerobic Post treatment.

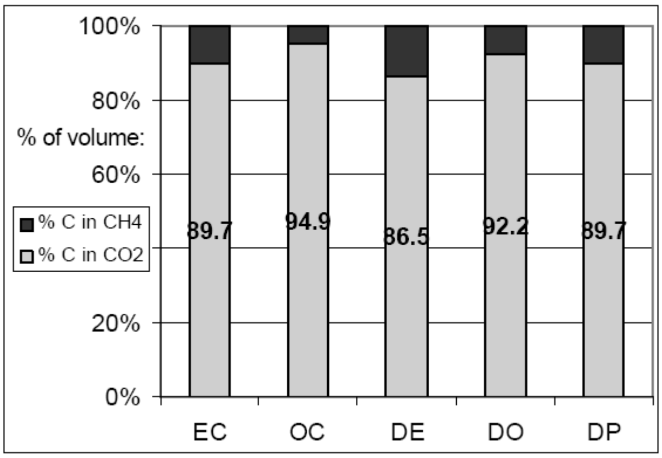

Figure 21: Ratio of CO_2 to CH_4 emissions of the composting (% of volume weighted mean values of 3 campaigns [77]

The effects of all greenhouse gas emissions during construction, plant running, demolition and ash dumping (IS) are shown in Figure 22. The negative effect on global warming decreases only after 100 (default value) and 500 years respectively to values significantly better than incineration, because of slow photo-oxidation and biological degradation of methane within the atmosphere. The final result for the above different treatment methods is shown in Figure 22 according to the sensitivities of Ecoindicator tool. From an ecological point of view, anaerobic digestion with an aerobic post-treatment shows by far the best performance, followed by digestion combined with enclosed composting and digestion combined with open composting. Pure open composting shows environmental impacts similar to incineration. Highest impacts with most of the sensitivities are caused by fully enclosed tunnel composting.

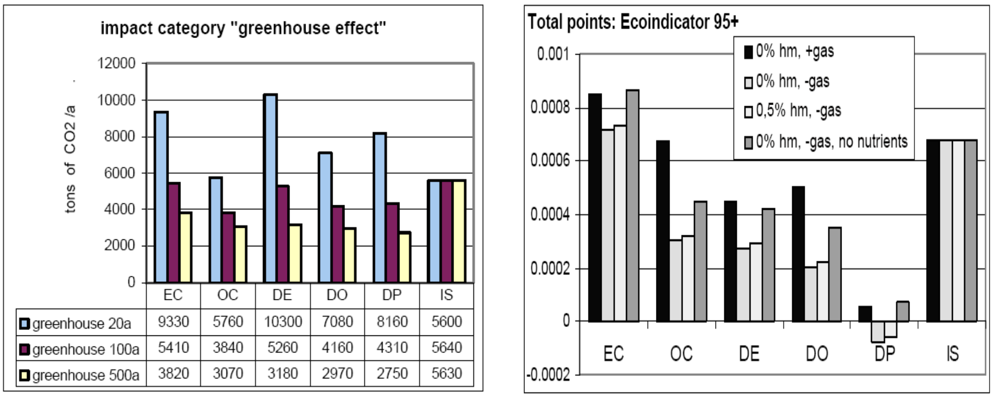

Figure 22: Greenhouse effect and total results of each waste management method applied [77]

4.3.3 Comparison between anaerobic digestion and open windrow composting – landfilling without energy recovery

In the Canadian LCA study presented in reference [78], Anaerobic Digestion is compared with the open windrow composting, and landfilling of MSW where landfills with and without energy production were considered. The study concluded that Anaerobic Digestion results in less air and water pollution than any of the other technologies, as shown in Table 17. The study also found that over the life of the project, anaerobic digestion had a positive net energy balance, while the other technologies including landfilling with gas collection, consumed net energy.

However, the boundaries of the LCA system don't include the sectors of construction and transportation. For example, additional transportation would be required for an AD facility located at a centralized site some distance from the landfill. A centralized digester, however, would serve multiple landfills. The costs and benefits of centralized OFMSW treatment would have to be evaluated for the entire region.

The model also assumed that excess electricity could be sold to the local power grid. The study includes emissions from post-digestion treatment of residuals, and the reductions in emissions due to AD are high, as mentioned in the Table 17. Interestingly, open windrow composting led to an increase in air and water pollution for most pollutants as compared with landfilling. This would most likely change if in-vessel composting was considered.

Table 17: Comparison of the energy use and emissions* from anaerobic digestion (AD), open windrow composting (WC) and landfilling without energy recovery [78]

	AD vs LF	AD vs. WC	WC vs LF
Energy consumption (GJ/y)	-400,000	-430,370	+32,228
GHG Emissions ($tCO_{2\,eq}/y$)	-134,379	-93,470	42,075
NO_x (t/y)	-53.8	-55.4	+1.7
SO_x (t/y)	-75.4	-82.2	+6.83
PM-10 (t/y)	-64.4	-56.0	-8.4
VOC (t/y)	-9.5	-4.2	-5.2
Lead (kg/h)	-88.3	-93	+4.72

*All emissions are air emissions with the exception of lead, which is a water pollutant

4.3.4 MSW management treatment with: anaerobic digestion, composting, incineration, material recycling

The main cases examined in the study [79], are anaerobic digestion, composting, incineration and material recycling. More specifically the scenarios examined are the following:

- Incineration: Incineration of all waste
- Landfilling: Landfilling of all waste
- Anaerobic digestion-bus: Anaerobic digestion of biodegradable waste. The biogas is used as fuel for busses. The rest of the waste is incinerated.
- Anaerobic digestion-heat/electricity: Anaerobic digestion of biodegradable waste. The biogas is used for production of district heat and electricity. The rest of the waste is incinerated.
- Composting: Composting of biodegradable waste in open windrows. The rest of the waste is incinerated.
- Plastic recycling: Sorting out 70% of high density polyethylene (HDPE) from households and 80% of HDPE and low density polyethylene (LDPE) from business for material recycling. The rest of the waste is incinerated.
- Cardboard recycling: Sorting out 70% of cardboard from households and 80% cardboard from business for material recycling. The rest of the waste is being incinerated.

The amounts and compositions of the waste are shown in Table 18**.**

Table 18: Amount and Composition of waste (t/year) [79]

	Detached houses	Flats	Rural houses	Domestic waste, sum	Waste from business	Total waste
Degradable waste	5642	9490	2655	17787	5645	23432
Non-combustible residue	549	924	258	1732	1408	3140
Combustible residue	1930	3246	908	6085	7370	13455
Diapers	831	1398	391	2621		2621
Rubbers, textiles	401	674	189	1264		1264
Dry paper	2762	4645	1300	8706	3678	12384
Cardboard	787	1324	370	2481	1096	3577
Plastic sheets & bags	327	549	154	1030	488	1518
Plastic containers	223	375	105	702	340	1042
Laminate	163	275	77	515		515
Glass	950	1598	447	2996	340	3335
Metals	282	474	133	889	1592	2481
Sum	14848	24972	6988	46809	21957	68765

*Exclusive construction and demolition wastes

Figure 23 presents the results for global warming (emissions of greenhouse gases). Landfilling gives the worst impact due to methane emissions from the landfill. It should be noted that the landfill has a landfill gas recovery system and produces electricity from the landfill gas. Recycling of plastic and anaerobic digestion show lower impact than incineration, because fossil fuels are saved when plastic is recycled, as well as fossil fuels are replaced when utilizing the biogas.

Emissions of acidifying substances are presented in
Figure 24. Landfilling gives the highest emissions of acidifying gases, due to emissions from the landfill gas combustion, and from district heat production in the compensatory system. Composting gives high emissions due to ammonia releases from the compost process. Anaerobic digestion with production of heat and electricity gives high NO_x-emissions from the combustion engine.

The emissions of eutrophicating substances are given in
Figure 25. Landfilling gives the highest eutrophication impact depending on N- and P-compounds in the leachate water. Anaerobic digestion and composting causes emissions from spreading of the digestion residue respectively compost. The spreading model is based on new spreading technique where the material (digestion residue or compost) is cultivated into the soil and immediately covered with soil to decrease the release of ammonia. Recycling of materials gives just slightly lower impact than incineration.

Photooxidant formers have been divided into VOC (volatile organic compounds) and NOx. The VOC emissions are shown in
Figure 26 and the NOx emissions in Figure 27.

Methane is included in VOC but has another weighting than other VOCs. Landfilling gives the highest emissions due to the methane emissions. Anaerobic digestion gives higher emissions than incineration, depending on emissions from the biogas use.

Landfilling gives the highest NOx emissions depending on emissions both from the landfill gas combustion and from the district heat production in the compensatory system. The two anaerobic digestion alternatives give different results. Using the biogas as bus fuel gives lower emissions of NOx than using the biogas for electricity and heat production in a gas engine.

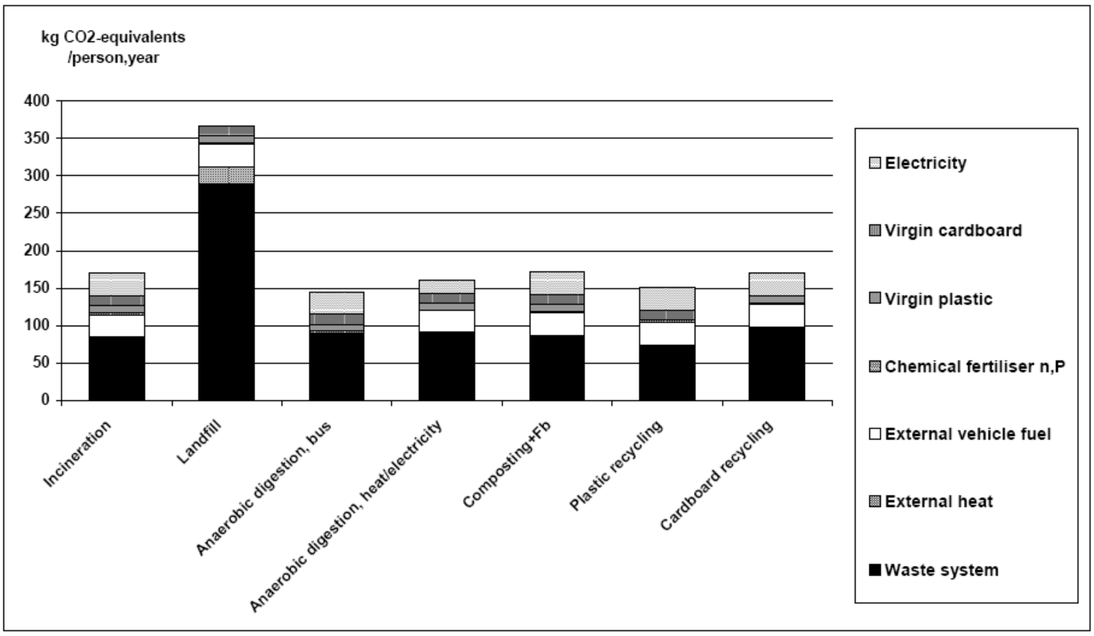

Figure 23: Emissions of greenhouse effect [79]

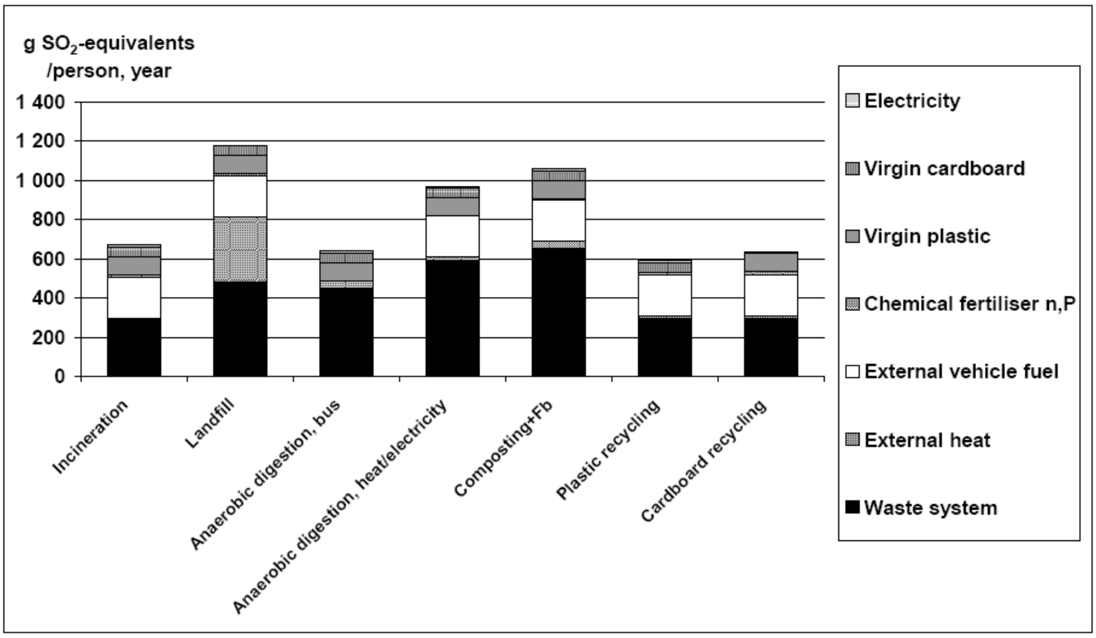

Figure 24: Emissions of Acidifying substances [79]

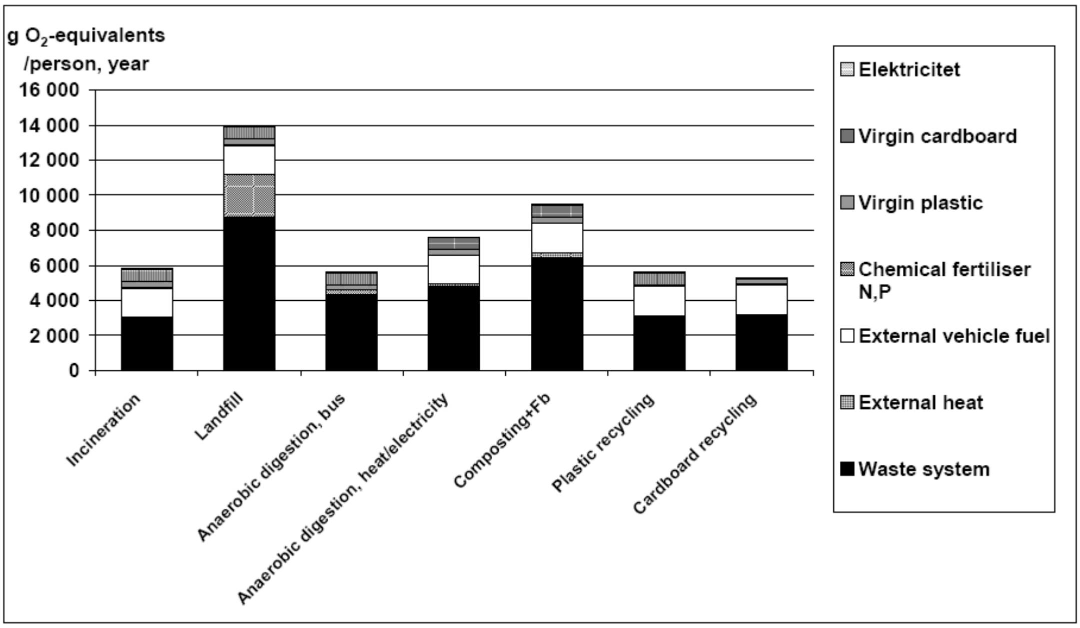

Figure 25: Emissions of eutrophicating substances [79]

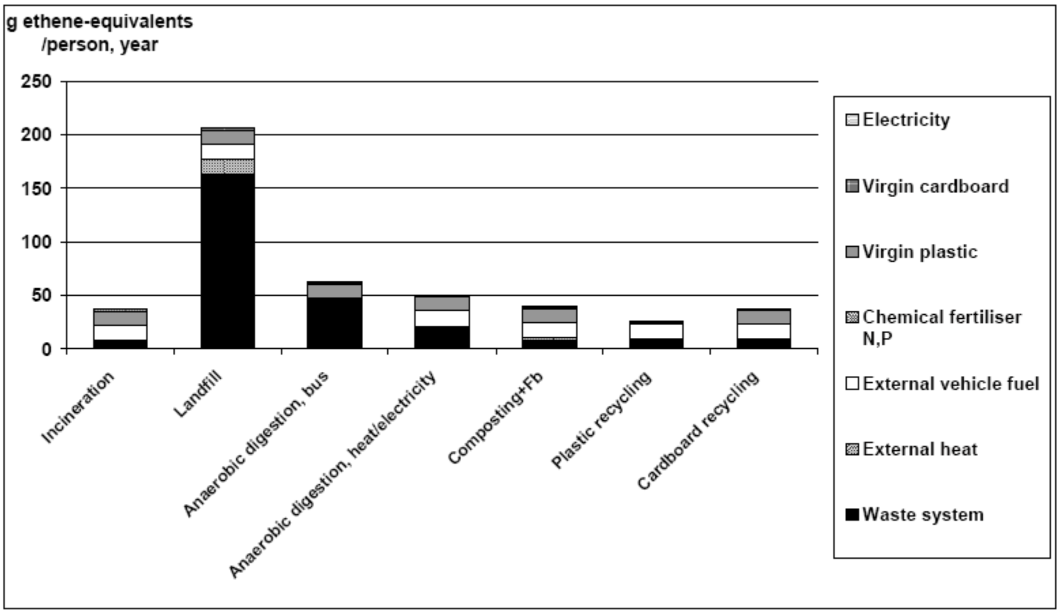

Figure 26: Emissions of photooxidants-VOC [79]

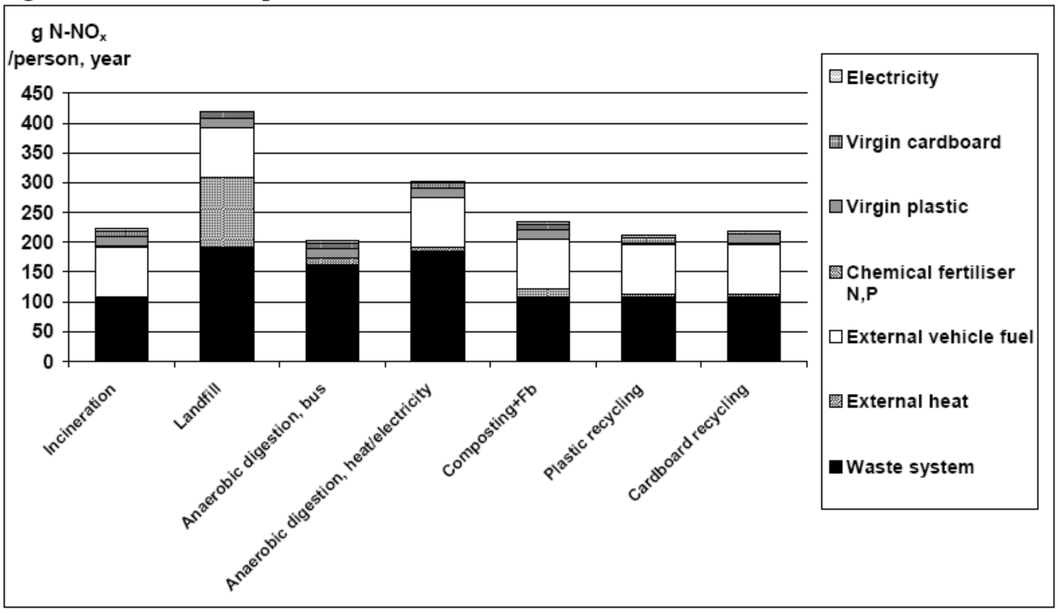

Figure 27: Emissions of photooxidants-NOx [79]

The energy consumption for the different scenarios is shown in the following figures. There is a net consumption of energy for the whole system (including the compensatory system). In general the differences in energy consumption between the scenarios are small except for the landfill scenario which consumption of energy resources is much higher. This is because of the production of district heating, fuels fertilizers, plastics and cardboard in the compensatory system. The lowest total consumption can be seen for recycling of plastic package waste. Another result from the study, not shown in the diagram, is that the energy consumption for collection and transports of waste is small compared to the energy consumption of the other processes in the studied system.

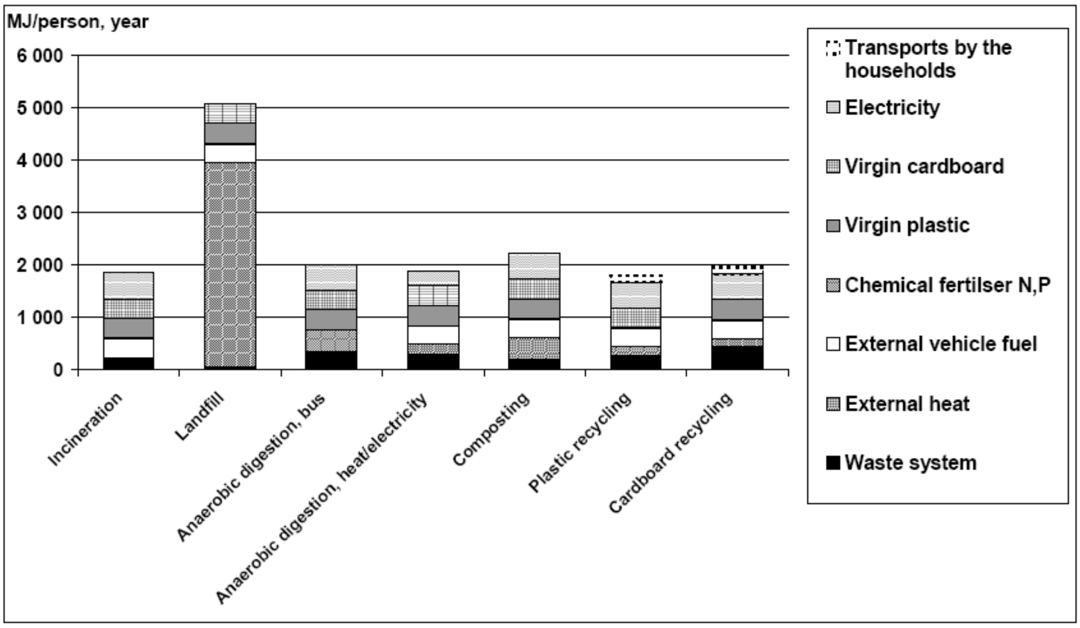

Figure 28: Consumption of primary energy carriers-total consumption for different processes [79]

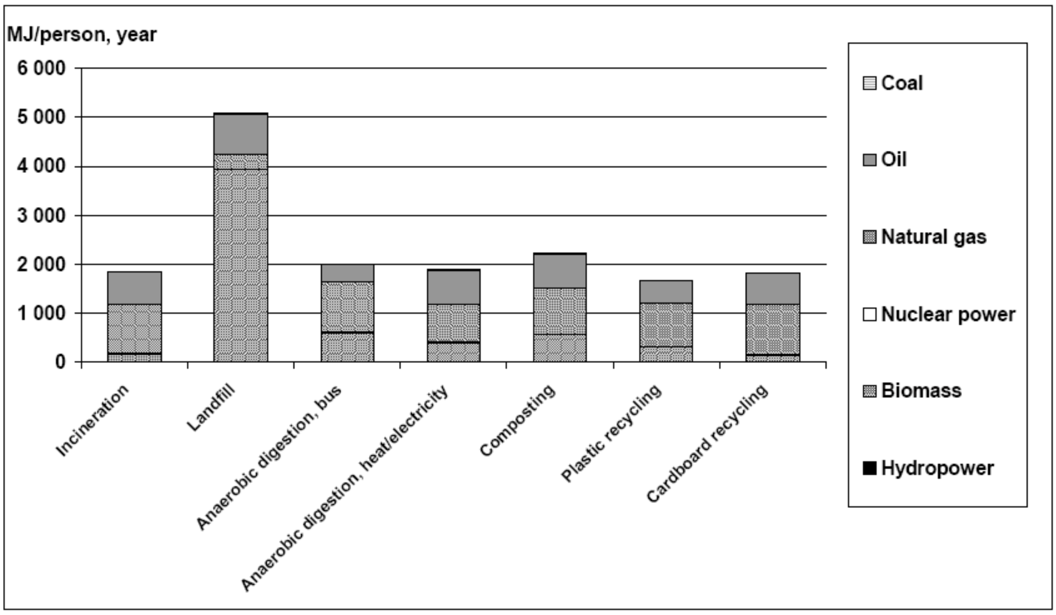

Figure 29: Consumption of primary energy carriers of different primary energy carriers [79]

4.3.5 Biogas utilizations

The best method to use the biogas of anaerobic digestion of organic fraction of MSW is estimated by using LCA method. In study [80], a comparison based on utilization of biogas regarding LCA principles has been accomplished. The Table 19 has all the information about the uses of biogas and the respective substances of this specific study.

Table 19: Biogas utilizations [80]

<table>
<tr><th rowspan="2">Procedure</th><th colspan="2">Utilisation method</th><th colspan="2">Substituted systems</th></tr>
<tr><th>Nm^3 of used biogas</th><th>Production of raw biogas</th><th>Avoided function</th><th>Avoided process</th></tr>
<tr><td>Heat (fuel oil)</td><td rowspan="2">Combustion of 0.82 Nm^3 of crude biogas in a boiler of 2 to 20 MW_{th}</td><td rowspan="2">• Digestion of 8.3 kg of biodegradable waste with digestate composting and the utilization of 3 kg of metha-compost
• Combustion of 0.08Nm^3 of crude biogas in a boiler in order to satisfy the requirements of the site
• Consumption of 0,83 kW_h taken from the network
• Combustion of 0,1 Nm^3 of crude biogas at the flare</td><td rowspan="2">Generation of 3,9 kWh_{th} / (in case of heat utilization of 100%)</td><td>Production and combustion of 0,45 litres of fuel oil in an industrial boiler of 1 MW_{th}.</td></tr>
<tr><td>Heat (natural gas)</td><td>Production and combustion of 0,45 Nm^3 of natural gas in an industrial boiler with the power of > 100 kW_{th}.</td></tr>
<tr><td>Electricity</td><td>Combustion of 0,46 Nm^3 of crude biogas in a generator of 650 kW</td><td rowspan="3">• Digestion of 8,3 kg of biodegradable waste with digestate composting and the utilization of 3 kg of metha-compost
• Combustion of 0,44Nm^3 of crude biogas in a boiler in order to satisfy the heating and electricity requirements of the site
• Combustion of 0,1 Nm^3 of crude biogas at the flare</td><td>Generation of 0,85 kWhe</td><td>Generation of 0,85 kWhe according to the average model of electricity production in the examined country.</td></tr>
<tr><td>Cogeneration (fuel oil)</td><td rowspan="2">Combustion of 0,46 Nm^3 of crude biogas in a cogeneration unit of 2 to 20 MW_{th}</td><td rowspan="2">Generation of :
• 0,85 kWh_e
• 1,9 kWh_{th}
(in case of Heat utilization of 100%)</td><td>Generation of 0,85 kWhe according to the average model of the electricity production in the examined country.
Production and combustion of 0,22 litres of fuel oil in an industrial boiler of 1 MW_{th}.</td></tr>
<tr><td>Cogeneration (natural gas)</td><td>Generation of 0,85 kWh_e according to the average model of electricity production in the examined country
Production and combustion of 0,21 Nm^3 of natural gas in an industrial boiler with the power of > 100 kWth.</td></tr>
</table>

<table>
<tr><th rowspan="2">Procedure</th><th colspan="2">Utilisation method</th><th colspan="2">Substituted systems</th></tr>
<tr><th>Nm^3 of used biogas</th><th>Production of raw biogas</th><th>Avoided function</th><th>Avoided process</th></tr>
<tr><td>Fuel (diesel)</td><td rowspan="3">Combustion of 0,47 Nm³ of biogas as fuel in a bus, car or waste trucks
This biogas as fuel is produced from 0,82 Nm³ of crude biogas with 57% of methane</td><td rowspan="3">• Digestion of 8,3 kg of biodegradable waste with digestate composting and the utilization of 3 kg of metha-compost
• Combustion of 0,08 Nm³ of crude biogas in a boiler in order to satisfy the heating requirements of the site
• Consumption of 0,99 kWhe taken from the network
• Combustion of 0,1 Nm³ of crude biogas at the flare</td><td rowspan="3">Journey of :
• 0,64 km by bus
• 6,8 km by car
• 0,40 km by waste truck</td><td>Production and consumption of diesel fuel :
• 0,38 litre for a bus
• 0,39 litre for a car
• 0,34 litre for a waste truck</td></tr>
<tr><td>Fuel (petrol)</td><td>Production and consumption of petrol:
• 0,54 litre for a car</td></tr>
<tr><td>Fuel (natural gas for vehicles)</td><td>Production and consumption of natural gas for vehicles
• 0,48 Nm³</td></tr>
</table>

The LCA results are shown in Table 20. The negative figures show that the emissions from the biogas production are lower than those emissions avoided due to the combustion of non-renewable energies. The positive figures show that the emissions from the biogas production are higher than those emissions avoided due to the combustion of non-renewable energies.

It is noted that the functional unit is the Utilization of 1 Nm^3 of crude biogas (Net Calorific Value 5,7 kWh/Nm^3).

Table 20: Impacts for different utilizations of biogas [80]

Biogas use (Substituted procedure)	Primary energy non-renewable MJ	Global warming potential (100 years) in g eq CO_2	Air acidification in g eq SO_2	Eutrophication in g eq PO42-
Heat (Fuel Oil)	-13	-1390	1.5	0.59
Heat (Natural gas)	-8.6	-1141	4.0	0.74
Electricity	-9.8	-327	3.8	0.76
Cogeneration (Fuel oil)	-20	-920	3.2	0.72
Cogeneration (Natural gas)	-18	-800	4.4	0.80
Carburant (Bus with diesel fuel)	-7.0	-1176	-4.7	0.11
Carburant (Bus with natural gas)	-7.8	-1297	3.0	0.70
Carburant (Waste truck with diesel)	-5.1	-1020	-4.9	0.10
Carburant (Waste truck with natural gas)	-7.8	-1299	3.0	0.70
Carburant (Car with diesel)	-7.4	-1241	1.2	0.54
Carburant (Car with petrol)	13	-1566	0.88	0.56
Carburant (Car with natural gas)	7.8	-1336	3.0	0.70

As it is observed, for both different energy uses (heat and fuel), the utilization of biogas shows an advantage in terms of the consumption of non-renewable primary energy and the global warming potential (for 100 years). Also the utilization of biogas shows an advantage in terms of the air acidification only if it substitutes diesel fuel for a bus or a waste truck. The utilization of biogas energy does not provide an advantage in terms of eutrophication whatever the biogas utilization.

The utilization of biodegradable waste as biogas is potentially more interesting than composting in terms of the global warming potential and primary energy balance, whatever the energy utilization method use. This is related to the fact that the avoided emissions of global warming gases and the avoided consumption of primary energy due to the substitution of the classic energy generation procedures are higher for the utilization of biogas method than for composting.

Regarding the eutrophication category, biogas production has a higher impact than the composting method because of the large amounts of liquid discharge during the anaerobic process except for its utilization as fuel with diesel oil substitution in busses or waste trucks.

In regard to the air acidification category, anaerobic digestion is preferable to the direct composting of biodegradable waste for the utilization method of biogas as fuel with diesel or petrol substitution and for biogas utilization for heat production with fuel oil substitution. The other biogas utilization (electricity, or the substitution of natural gas or natural gas for vehicles) bring about the same amount of acid emissions (for the utilization of biogas as fuel substituting natural gas for vehicles) or slightly higher than the direct composting of the biodegradable waste. The ranking of some procedures is sensitive to the rate of the air emissions of ammoniac from the composting pad.

5. LCA of ISWM-TINOS system

5.1 Introduction

The ISWM composting system will be applied in Pyrgos Village and will cover the needs for the treatment of Pyrgos and of Ormos of Panormos. Pyrgos is located at the north part of Tinos island [81] and it is the capital of the Municipal Unit of Panormou (Figure 30) [82]. Pyrgos was a major marble carving center, and it's still home to a major art academy.

Figure 30: Tinos Island

5.2 Parameters-Boundaries

The average production of MSW per person per year accounts is 450 kg according to reference [84]. The production of MSW is a basic parameter for the LCA planning, which depend on the season. Tinos Island is a touristic area, so in summer months, its population increase so MSW production changes.

The literature review suggests GHG emissions from waste decomposition are greatly higher for landfills than for composting unit [85]. This is because anaerobic decomposition facilitates the production of CH_4 which has a GWP 25 times that of CO_2. Energy recovery and appropriate landfill capping strategies can help to reduce this impact, but composting still remains a simpler and effective method of reducing GHG emissions. In this point, it is noted that illegal landfill is the present solution of MSW in Tinos Island. Illegal landfill does not follow the standards of a typical landfill. So the aim of LCA is to show the obvious benefits of composting method instead of illegal landfill and to quantify them.

The boundaries of the defined system play a significant role, for the option of the suitable waste management method. For example in the study [86], the anaerobic digestion is more favorable for biodegradable materials than industrial composting, home composting in temperate climates and waste incineration, because it combines energy recovery with the production of digestate, which can be used as a soil conditioner. Home composting is roughly equal to incineration with energy recovery, with small differences across materials; industrial composting is worse than home composting because lower credits are assigned to the resulting compost. Home and industrial composting differ in terms of methane and especially nitrous oxide emissions and the choice of perspective. Carbon credits for the use of compost as a soil conditioner significantly improve the carbon and energy footprints for both types of composting [87]. The temperature under which home composting is carried out also has a large effect on methane and nitrous oxide emissions and thus on the carbon footprint. All biological waste treatment options have the additional benefit of producing a soil conditioner that supports humus formation, which cannot be achieved artificially. This means that if soil carbon becomes a limiting factor in the future, then biological waste treatment options should be chosen to safeguard it.

In LCA of ISWM-TINOS system, boundaries must be determined. Pyrgos and Ormos of Panormos will participate in the activities of the composting treatment, so the sector of transportation will be included in the LCA boundaries, in order to present the environmental impact regarding to the transportations accomplished between the two places. The transportation may receive in the total consideration of the project regarding the management of recycling materials in the place out of the borders of the island.

Apart from boundaries, the culture of the people in the study area, is another parameter which affect the final result [88]. If the culture is according to Biodegradable and compostable (B&C) materials, then composting is a suitable recycling treatment. If the culture is according to non-B&C materials, then composting is not applicable and only waste treatments without material recycling can be adopted (i.e., landfill and incineration).

As it is already mentioned above, the culture may be change because of tourism. But the low population of town allows affecting more easily to the culture of those persons, so the parameter of tourism affect as little as possible.

Finally, for the evaluations, the applied method (Impact2002+, Recipe) database have a leading role to the final results, because of the different parameters using in each method.

5.3 Summary of Expected Results

The final results of the ISWM-TINOS LCA expected to be into the range of values of the literature. In study [89], typical values for several waste management methods, included aerobic composting and anaerobic method, are given. These values determine the range of climate change impact of the organic waste management methods. The results are given in

Table 21.

Table 21: Comparison of Climate Change Impacts of Organic Waste Management Methods, (Metric tons of Carbon dioxide equivalents/metric ton organic waste) [89]

Management Method	minimum	maximum	median	mean
Anaerobic Digestion	-0.74	-0.06	-0.14	-0.25
Aerobic Composting	-0.76	0.22	0.04	-0.07
Mass Burn WTE	-0.24	0.63	-0.02	0.02
Home Aerobic Composting	-0.69	0.29	0.14	0.05
LFGTE	-0.31	1.00	0.11	0.16
LF flaring	-0.06	-0.05	-0.06	-0.06

According to reference [90], composting and anaerobic digestion comparing with waste to energy plants and recycling facilities present advantages and disadvantages. The following figures show the impact indicators calculated with the LCA approach for the mechanical recycling of packaging materials, the composting and anaerobic digestion of the biowaste and the energy recovery from the residual waste. The impact indicators are expressed per tone of material sent to the treatment and each of them varies in a range of values according to the different assumptions made during the assessment [90]. A negative value indicates that the avoided impacts are higher than the added ones, thus meaning a benefit for the environment.

As it is presented in the figures, composting of bio-waste is advantageous only for Global warming Potential and Cumulative Energy Demand (CED) indicators, but the latter only when the energy feedstock of the avoided peat is included in the analysis. The electricity consumption is another parameter, which influences the CED indicator.

The results are better when considering anaerobic digestion instead of composting, due to the fact of net production of energy. In this case CED, Global warming Potential and Photochemical Ozone Creation Potential indicators are always negative, meaning a benefit for the environment. Acidification Potential and Human Toxicity Potential indicators can be either negative or positive depending on the assumptions made. The parameters of biogas production rate and its utilization affect the final results in this case.

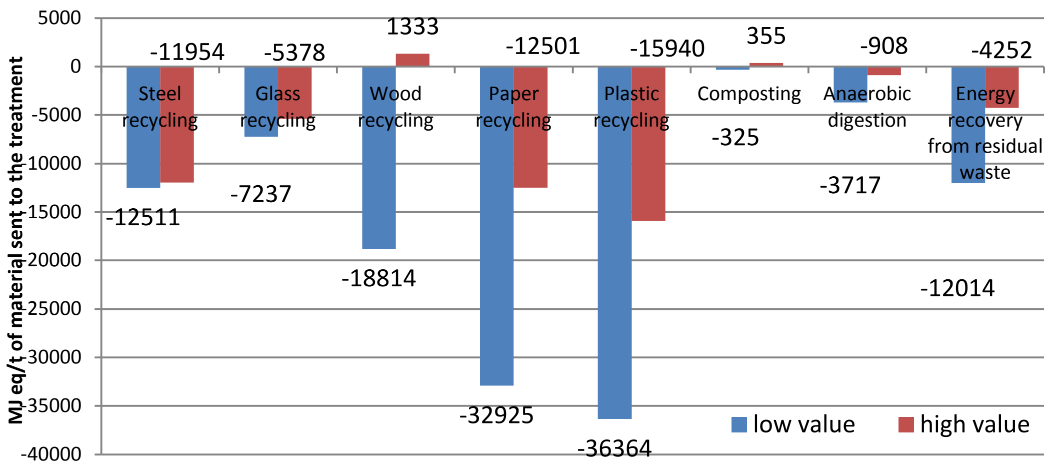

Figure 31: Range of values of the cumulative energy demand [90]

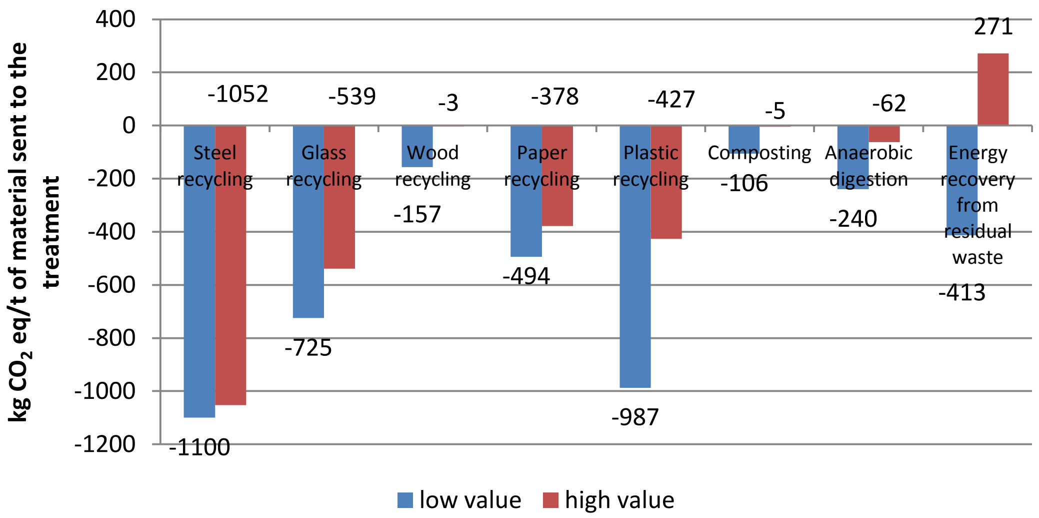

Figure 32: Range of values of the global warming indicator [90]

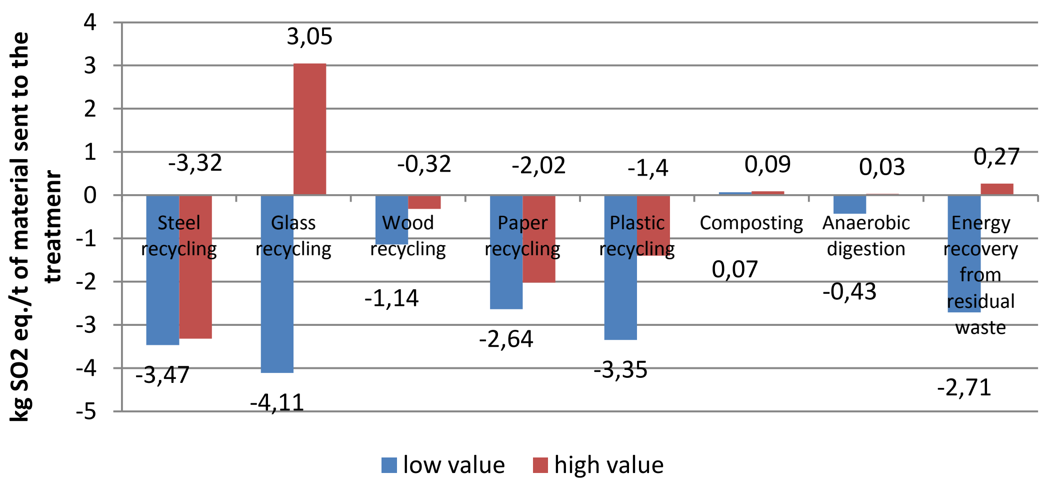

Figure 33: Range of values of the acidification indicator [90]

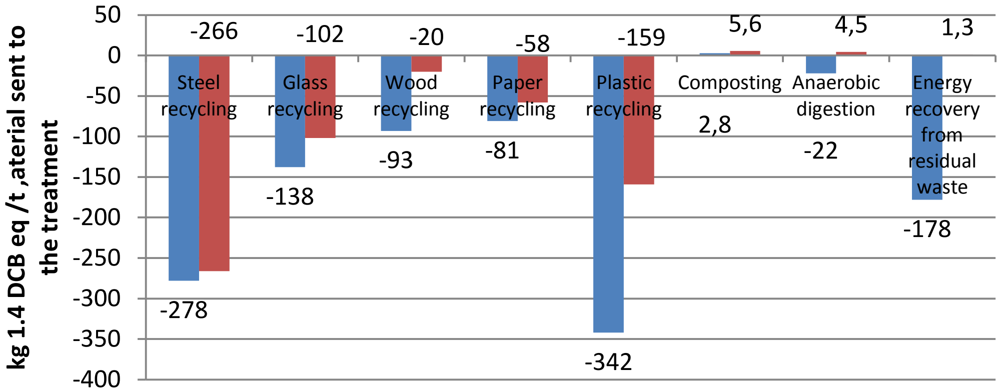

Figure 34: Range of values of the human toxicity indicator [90]

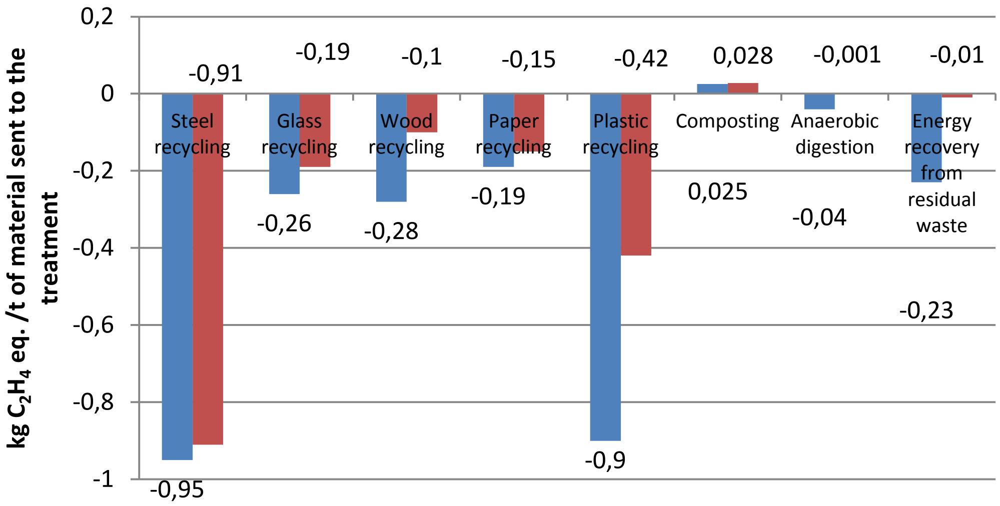

Figure 35: Range of values of the photochemical ozone indicator [90]

5.4 Conclusions

Literature review, identification of good practices and methodology is a prerequisite for the proper and effective performance of the LCA studies within ISWM-TINOS project. More specifically, the scope of this work was to find similar LCA studies with the LCA studies of ISWM-TINOS project, in order to collect appropriate information for the execution of LCA in the ISWM-TINOS system and to compare the future results with other relative. To this end, 51 internet sites and 39 bibliographic references (papers of scientific magazines, reports etc) were examined in order to investigate the results of LCA studies for composting method and anaerobic digestion. Moreover the comparison between the examined methods (composting and anaerobic) and other applied methods as landfilling or incineration was investigate in order to find the advantages of each method.

The most significant points from the reviewed literature are:

Information about anaerobic digestion and composting

- Anaerobic digestion is more complex and expensive than composting process.
- Composting process demands larger area than anaerobic digestion
- In composting method, it is observed odour pollution, uncontrolled leachate pollution and uncontrolled CH_4 production in contrast to anaerobic digestion.
- Composting process is a net energy consumer, while the anaerobic digestion process is a net energy producer.

LCA results about composting and anaerobic digestion

- The environmental impacts of aerobic composting are very sensitive to compost facility management practices for maintaining aerobic conditions
- Results for an aerobic composting LCA are also very dependent on offsets
- LCA data for anaerobic digestion are sensitive to the amount of methane which is produced for use as energy offset.
- Composting treatment and anaerobic digestion have less emissions of greenhouse effect than landfills. This fact affects the CO_2 trade market, so there are financial profits for these management treatments.
- The best method to use the biogas of anaerobic digestion of organic fraction of MSW is estimated by using LCA method.
- SimaPro software covers the analysis of complex waste treatment scenarios, through its database and its evaluation methods.

5.5 Future work

In Figure 36, it is shown the total methodology for the MSW management. Specifically the proposed paths presented are two. The first one concerns mixed bag collection, while the second one concerns the separate collection. The proposed treatments for the mixed bag collection are relevant to thermal treatments, while for separate collection the proposed treatments are biological (composting and anaerobic) which are the study objectives of the existed project. The management of recycling material is included in the examined processes.

In ISWM-TINOS project, two scenarios will be examined: the scenario for composting treatment and the scenario for the anaerobic digestion. Due to the fact that the transfer of MSW is not allowed outside of the boundaries of the island, the disposal residues scenarios take place at the land of island. The recycling materials are not considered as residues of the process, but as recovery materials, which have the potential to be transferred out of island.

Thus, two studies will be realized:

- Life Cycle analysis for composting treatment. The necessary data will be derived through the results of Actions 4.1 and 4.2

- Life Cycle analysis for anaerobic digestion. The boundary and operating conditions as well as the anaerobic digestion methodology that will be considered for this study will be derived through the results of Action 4.1 and 4.3.

Finally, it was concluded that Life Cycle Analysis will be performed by the Sima Pro software due to the fact that it is the most suitable software for analysis of complex waste treatment and recycling scenarios. The method for the evaluation of LCA will be selected among the wide variety methods according to the options in the Sima Pro software. Sima Pro is a standardized software , so the results are considered reliable and universal. Also this software is based on Ecoinvent database, which covers a broad range of parameters. Also it provides a consistent specification of uncertainty data, as lognormal distribution with standard deviation. Generally it is a widely used software, which provides standardized results by a performance through trees and bar charts, which provide to the researcher the complete control of all process treatment and to the reader the understanding of the examined process (composting and anaerobic method).

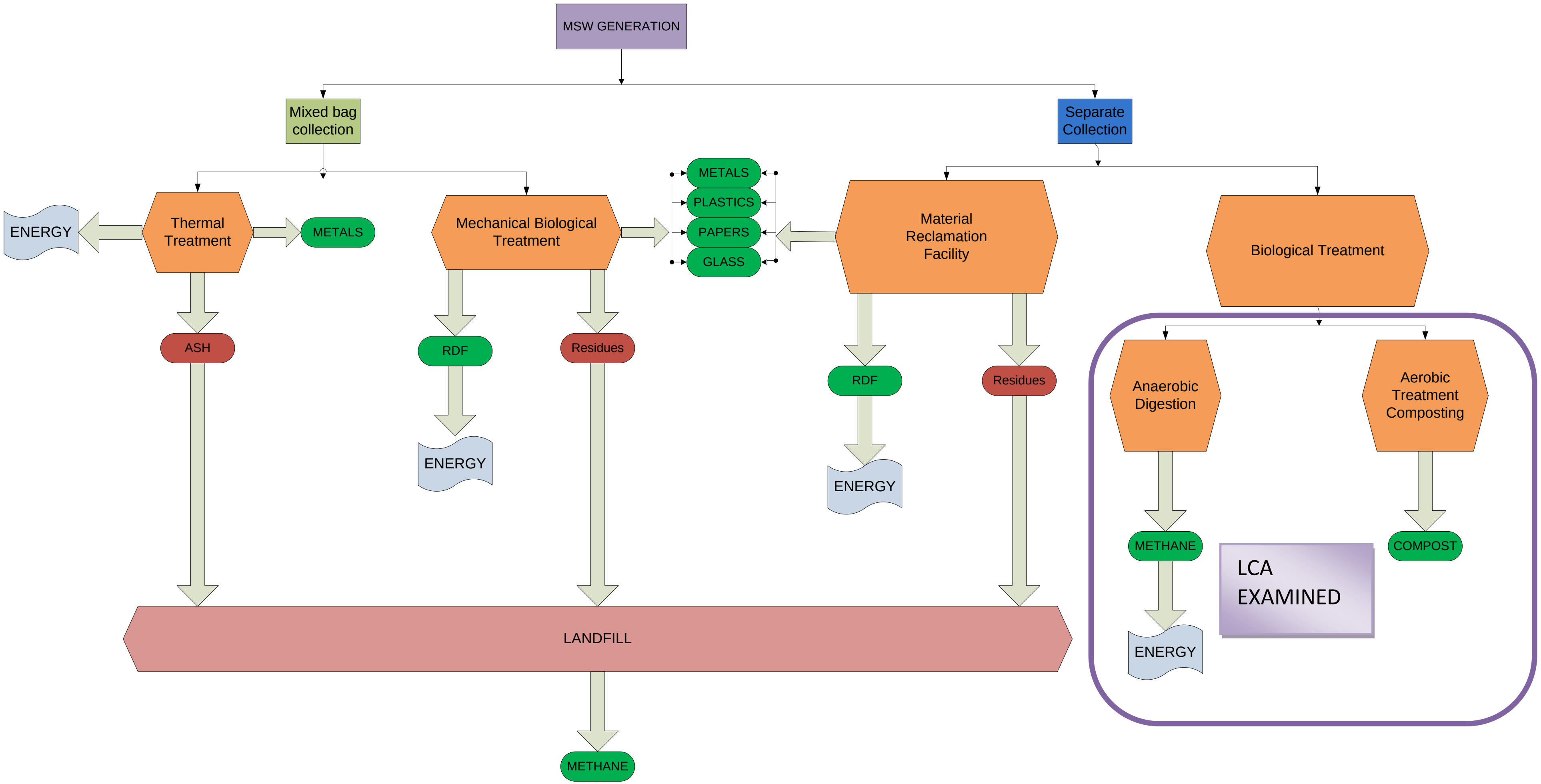

Figure 36: MSW treatment methodology

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