AMERICAN UNIVERSITY OF BEIRUT

AHP APPROACH: A DECISION MAKING ANALYSIS FOR ASSESSING AN INTEGRATED SUSTAINABLE SOLID WASTE MANAGEMENT SYSTEM FOR AUB CAMPUS AND ITS NEIGHBORHOOD

by
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AN ABSTRACT OF THE THESIS OF

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Applications of energy recovery from solid wastes are widely practiced; however, the utmost economic and environmental benefit for Lebanon would be reducing the amount of waste production and reusing unpreventable wastes as part of the waste management strategy. In an effort for the American University of Beirut to become a leader in sustainability in the Middle East, this project aims to implement an integrated sustainable solid waste management system to treat the wastes produced on campus and its neighborhood. The adoption of a sustainable waste management strategy would provide an additional renewable energy source, besides mitigating the greenhouse gas emissions associated with Lebanon's current waste treatment strategy. This report represents the first initiative towards potential waste management facilities on college campuses in Lebanon and the Middle East. The implementation of a sustainable solid waste management is a complex process. Thus, this dissertation presents the viable options available in order to reduce the environmental impact of wastes and to exploit the produced wastes as an energy resource. The analysis is conducted using Analytical Hierarchy Process (AHP), which allows decision makers to make simple pairwise comparison judgments throughout the hierarchy to arrive at overall priorities for alternatives. The decision problem involved environmental, sociocultural, technical, and economic factors. The results of this analytical process revealed that anaerobic digestion should be the first choice for MSW treatment, given that clear and efficient policies are made available to encourage waste reduction, reuse, and recycling. This vision is based upon the waste hierarchy, and would definitely contribute to expanding renewable energy sources on the university campus.

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CHAPTER I

INTRODUCTION

The American University of Beirut (AUB) has been always devoted to implementing initiatives and projects which target the reduction of its negative impacts on the environment while using these initiatives to raise environmental awareness to students and Lebanese citizens at large. This paper encourages an initiative towards a more sustainable campus through the adoption of an integrated waste management plan, and thus it looks at various solid waste management (SWM) options and decides which one ranks the best in accordance with a combined environmental, sociocultural, technical, and economic criteria. Proficient management, reduction and recycling of the solid wastes resulting from the university's campus and the neighborhood in its proximity are crucial factors for achieving a sustainable campus.

1.1 Sustainable Solid Waste Management (SSWM)

A sustainable solid waste management system (SSWM) could pose "net carbon savings and a resource efficient contribution to the economy." (Williams, 2013) It would also contribute to the economy through inspiring resource independence. The waste management sector has a major role to play in promoting a green economy through a balance in meeting the 3 basic elements of sustainable development (social, environmental and economic sustainability) - represented in Venn diagram below.

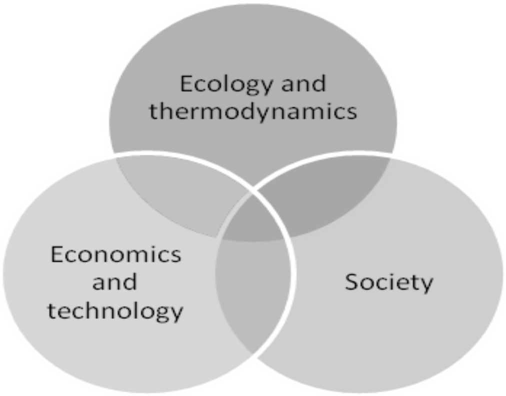


Figure 1: Sustainability Venn Diagram (Parkin, 2000)

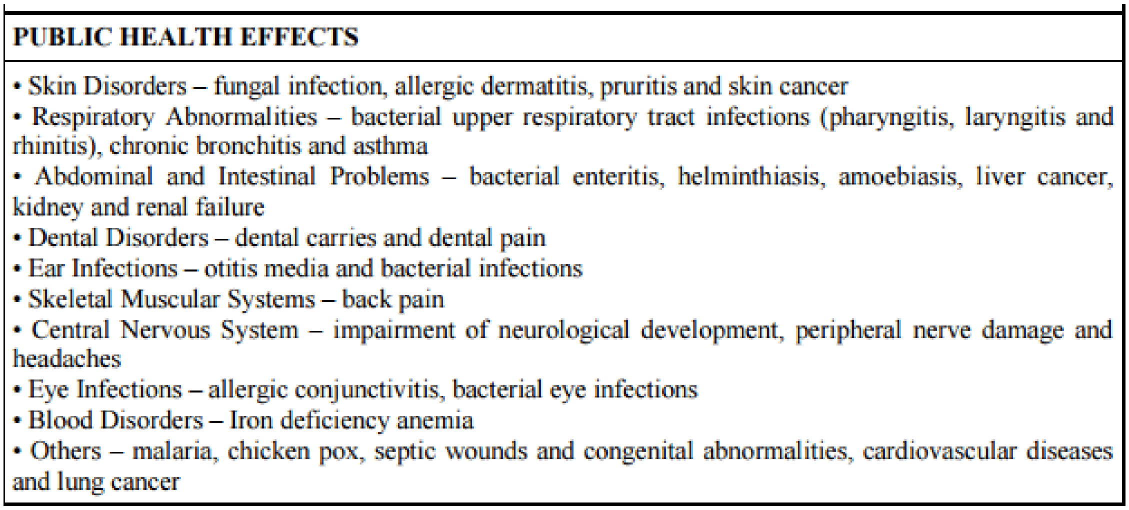
Social sustainability

The waste management plan should ensure meeting minimum social conditions, characterized by providing safe working environment for the human resources and setting health and safety regulations and principles.

Public health: The most essential stimulant for solid waste management is securing public health protection. Improper waste collection imposes threats on the public health due to the rise of several diseases resulting from the increase of vectors. Besides, waste itself imposes threats on public health due to the possibility of injuries and transmittance of blood diseases resulting from direct contact with hazardous waste. (Lindell, 2012)

Nonetheless, waste treatment could also impact negatively the public health, either through water contamination resulting from sub-par landfills that lack the adequate leachate control systems, or through the high VOC (Volatile Organic Compounds) emissions resulting from poor incineration processes. These emissions are identified as carcinogenic at high concentrations. (Cointreau, 2006)

Figure 2 below serves as an example to reflect the severe health effects triggered due to improper waste management in Nairobi, Kenya. Table 1 further demonstrates the effects on the public health of residents nearby the municipal dumpsite in Nairobi upon exposure to high levels of heavy metals.

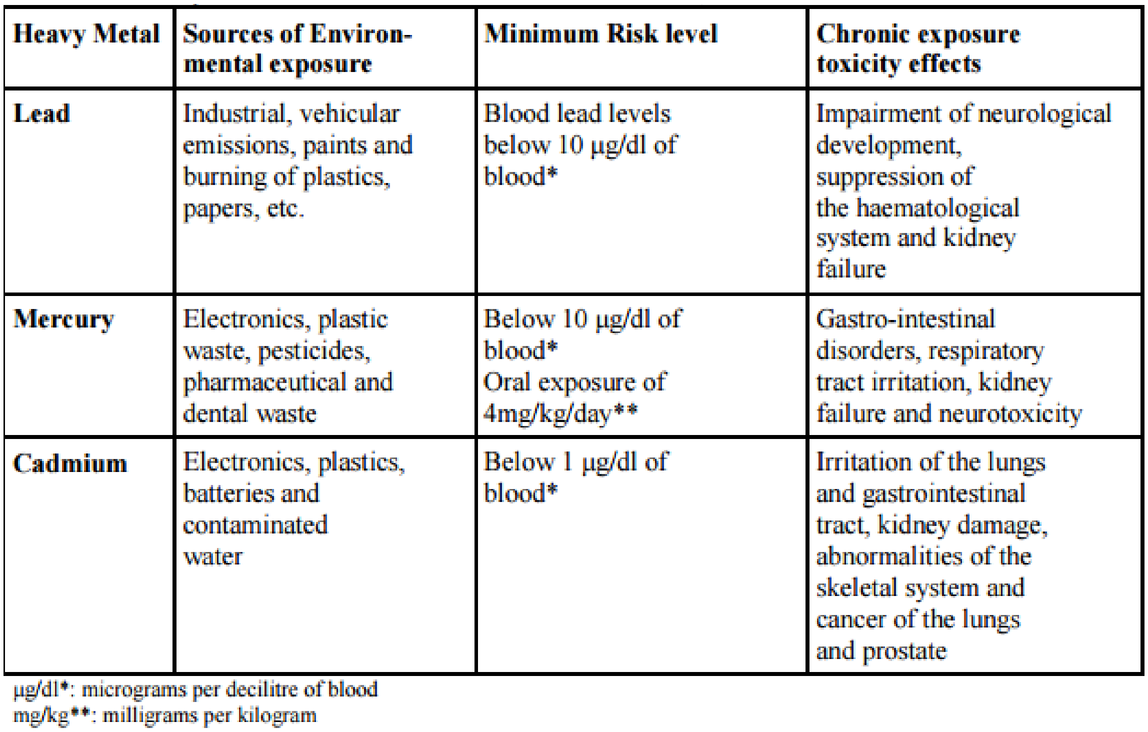


PUBLIC HEALTH EFFECTS

- Skin Disorders – fungal infection, allergic dermatitis, pruritis and skin cancer
- Respiratory Abnormalities – bacterial upper respiratory tract infections (pharyngitis, laryngitis and rhinitis), chronic bronchitis and asthma
- Abdominal and Intestinal Problems – bacterial enteritis, helminthiasis, amoebiasis, liver cancer, kidney and renal failure
- Dental Disorders – dental carries and dental pain
- Ear Infections – otitis media and bacterial infections
- Skeletal Muscular Systems – back pain
- Central Nervous System – impairment of neurological development, peripheral nerve damage and headaches
- Eye Infections – allergic conjunctivitis, bacterial eye infections
- Blood Disorders – Iron deficiency anemia
- Others – malaria, chicken pox, septic wounds and congenital abnormalities, cardiovascular diseases and lung cancer

Figure 2: The Public health effects arisen from a municipal waste-dumping site in Nairobi (UNEP, 2007).

Table 1: Toxic heavy metals with established health effects (UNEP, 2007)



Heavy Metal	Sources of Environ-mental exposure	Minimum Risk level	Chronic exposure toxicity effects
Lead	Industrial, vehicular emissions, paints and burning of plastics, papers, etc.	Blood lead levels below 10 µg/dl of blood*	Impairment of neurological development, suppression of the haematological system and kidney failure
Mercury	Electronics, plastic waste, pesticides, pharmaceutical and dental waste	Below 10 µg/dl of blood* Oral exposure of 4mg/kg/day**	Gastro-intestinal disorders, respiratory tract irritation, kidney failure and neurotoxicity
Cadmium	Electronics, plastics, batteries and contaminated water	Below 1 µg/dl of blood*	Irritation of the lungs and gastrointestinal tract, kidney damage, abnormalities of the skeletal system and cancer of the lungs and prostate

µg/dl*: micrograms per decilitre of blood
mg/kg**: milligrams per kilogram

<ins>Workers health</ins>: High risks of injuries and health problems arise due to handling wastes. Common health issues resulting from waste handling are: (Cointreau, 2006)

- Respiratory diseases upon the ingestion of particulates especially at open dumps
- Infections upon direct contact with wastes
- Puncture wounds that might cause tetanus, hepatitis, and even HIV

"In Mexico it is reported that the average life expectancy of a waste worker is 39 years while the normal life expectancy is 69." (UNHABITAT, 2010) However a life span of 53 years was estimated by a later study performed by the World Bank. (Bernstein, 2004)

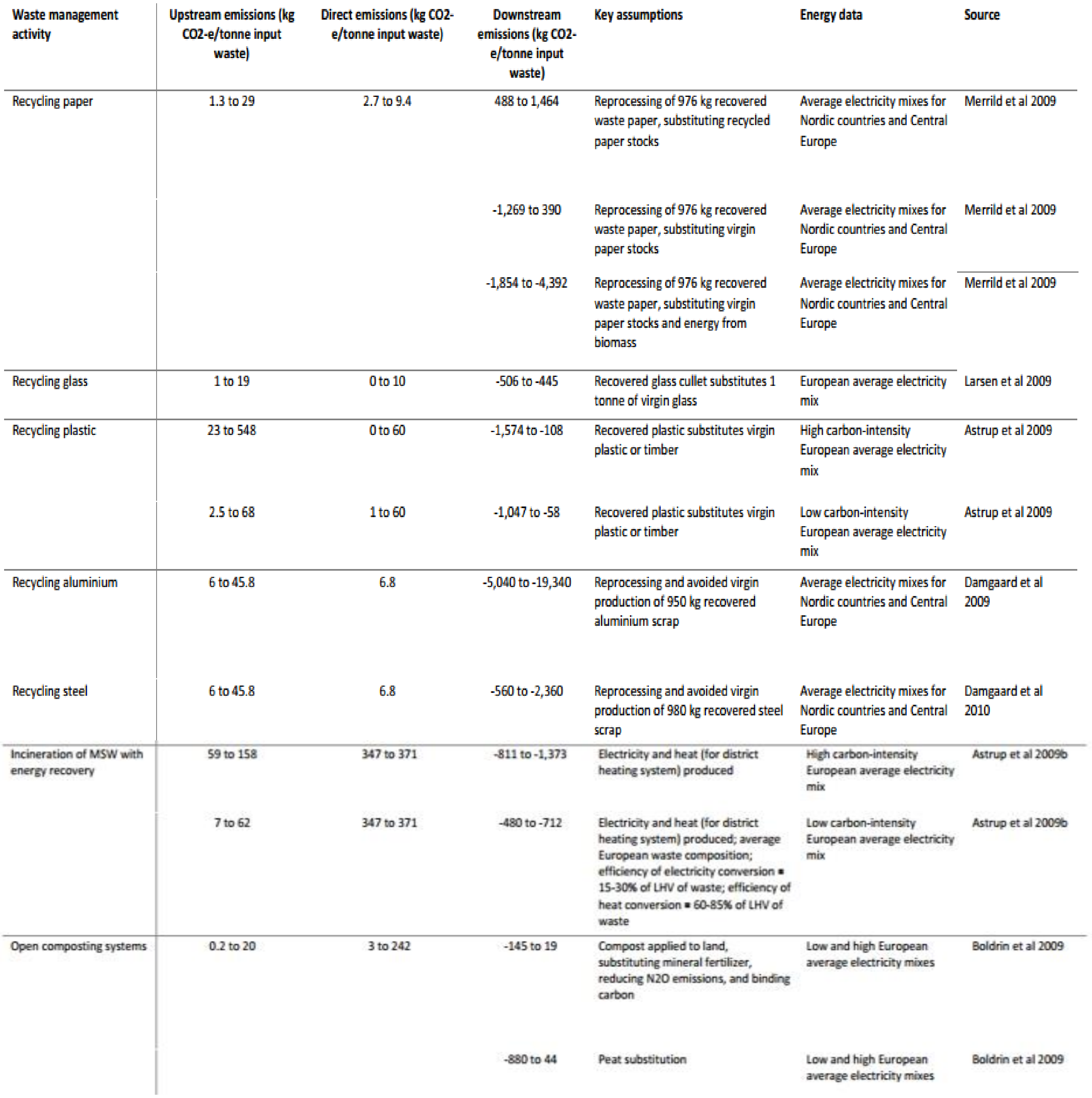
Environmental sustainability

Hazardous waste: Improper handling of hazardous waste leads to environmental pollution. Mixing hazardous waste with solid wastes augments pollution due to leaching occurring at dump sites or at sub-standard landfills, or due to burning wastes. Hazardous wastes are classified as either medical wastes or chemical wastes. (Lindell, 2012)

Exact estimates are not available, however, on average 0.5-3 kg of healthcare waste per capita per year (including hazardous and non-hazardous wastes) are generated by low-income countries. Whereas, high-income countries were held accountable for the generation of up to 6 kg of hazardous waste per person per year resulting from healthcare activities. (WHO, 2010)

GHG emissions: The waste sector is responsible for generating GHG emissions, mostly carbon dioxide (CO_2) and methane (CH_4). CO_2 is generated mainly from the transportation process intended for the collection of wastes, waste burning and incineration, and anaerobic digestion throughout the composting process. Methane emissions mainly stem from digesting organic wastes in anaerobic conditions at landfills. (UNEP, 2010) Table 2 below shows the GHG emissions resulting from the different waste management activities in Europe.

Table 2: Summary of GHG emissions from waste management practices in Europe (negative values indicate GHG savings and positive values indicate GHG emissions; data sources are noted in table).



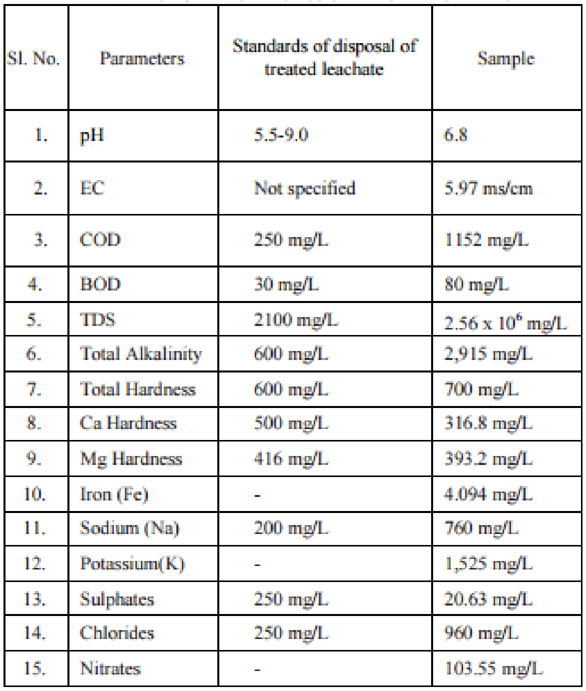
Waste management activity	Upstream emissions (kg CO2-e/tonne input waste)	Direct emissions (kg CO2-e/tonne input waste)	Downstream emissions (kg CO2-e/tonne input waste)	Key assumptions	Energy data	Source
Recycling paper	1.3 to 29	2.7 to 9.4	488 to 1,464	Reprocessing of 976 kg recovered waste paper, substituting recycled paper stocks	Average electricity mixes for Nordic countries and Central Europe	Merrild et al 2009
			-1,269 to 390	Reprocessing of 976 kg recovered waste paper, substituting virgin paper stocks	Average electricity mixes for Nordic countries and Central Europe	Merrild et al 2009
			-1,854 to -4,392	Reprocessing of 976 kg recovered waste paper, substituting virgin paper stocks and energy from biomass	Average electricity mixes for Nordic countries and Central Europe	Merrild et al 2009
Recycling glass	1 to 19	0 to 10	-506 to -445	Recovered glass cullet substitutes 1 tonne of virgin glass	European average electricity mix	Larsen et al 2009
Recycling plastic	23 to 548	0 to 60	-1,574 to -108	Recovered plastic substitutes virgin plastic or timber	High carbon-intensity European average electricity mix	Astrup et al 2009
	2.5 to 68	1 to 60	-1,047 to -58	Recovered plastic substitutes virgin plastic or timber	Low carbon-intensity European average electricity mix	Astrup et al 2009
Recycling aluminium	6 to 45.8	6.8	-5,040 to -19,340	Reprocessing and avoided virgin production of 950 kg recovered aluminium scrap	Average electricity mixes for Nordic countries and Central Europe	Damgaard et al 2009
Recycling steel	6 to 45.8	6.8	-560 to -2,360	Reprocessing and avoided virgin production of 980 kg recovered steel scrap	Average electricity mixes for Nordic countries and Central Europe	Damgaard et al 2010
Incineration of MSW with energy recovery	59 to 158	347 to 371	-811 to -1,373	Electricity and heat (for district heating system) produced	High carbon-intensity European average electricity mix	Astrup et al 2009b
	7 to 62	347 to 371	-480 to -712	Electricity and heat (for district heating system) produced; average European waste composition; efficiency of electricity conversion ■ 15-30% of LHV of waste; efficiency of heat conversion ■ 60-85% of LHV of waste	Low carbon-intensity European average electricity mix	Astrup et al 2009b
Open composting systems	0.2 to 20	3 to 242	-145 to 19	Compost applied to land, substituting mineral fertilizer, reducing N2O emissions, and binding carbon	Low and high European average electricity mixes	Boldrin et al 2009
			-880 to 44	Peat substitution	Low and high European average electricity mixes	Boldrin et al 2009

Waste management activity	Upstream emissions (kg CO2-e/tonne input waste)	Direct emissions (kg CO2-e/tonne input waste)	Downstream emissions (kg CO2-e/tonne input waste)	Key assumptions	Energy data	Source
Enclosed composting systems	1 to 60	5 to 81	-145 to 19	Compost applied to land, substituting mineral fertilizer, reducing N2O emissions, and binding carbon	Low and high European average electricity mixes	Boldrin et al 2009
			-880 to 44	Peat substitution	Low and high European average electricity mixes	Boldrin et al 2009
Anaerobic digestion	3 to 46	20 to 76	-414 to -49	Sophisticated AD systems; combustion of biogas (substituting heat or electricity); land application of digestate substituting fertilizer and binding carbon in soil	Low and high European average electricity mixes	Moller et al 2009
Dump (unmanaged landfill)	0	561 to 786	0	Average European waste composition; approx 46% of original biogenic C in waste assumed to remain as stored C and credited as GHG savings	n/a	Manfredi et al 2009
Landfill with flared LFG	2 to 12	-71 to 150	0	Average European waste composition; LFG capture efficiency over 100 yrs ■ 50-80%; 48% of original biogenic C assumed stored	n/a	Manfredi et al 2009
Landfill with LFG capture and utilisation	2 to 16	-71 to 150	-5 to -140	Average European waste composition; LFG capture efficiency over 100 yrs ■ 50-80%; 48% of original biogenic C assumed stored	Low and high European average electricity mixes	Manfredi et al 2009
Low organic waste landfill	2 to 10	-50 to -13	0	Low organic waste (30-40% biogenic C); LFG capture efficiency over 100 yrs ■ 30-50%	Low and high European average electricity mixes	Manfredi et al 2009

<u>Protection of local environment:</u> Improper disposal of wastes could lead to the contamination of soil and surface water. This should be a motive for enhancing the waste management sector, especially in countries that suffer from scarce natural resources, like drinkable water and fertile land. (Wilson, 2007)

To elaborate soil samples taken from the Municipal Solid Waste disposal site for the city of Thrissur, in Kerala, India, were analyzed. Table 3 below shows a comparison between the chemical properties of the sample and the standards of disposal of treated leachate.

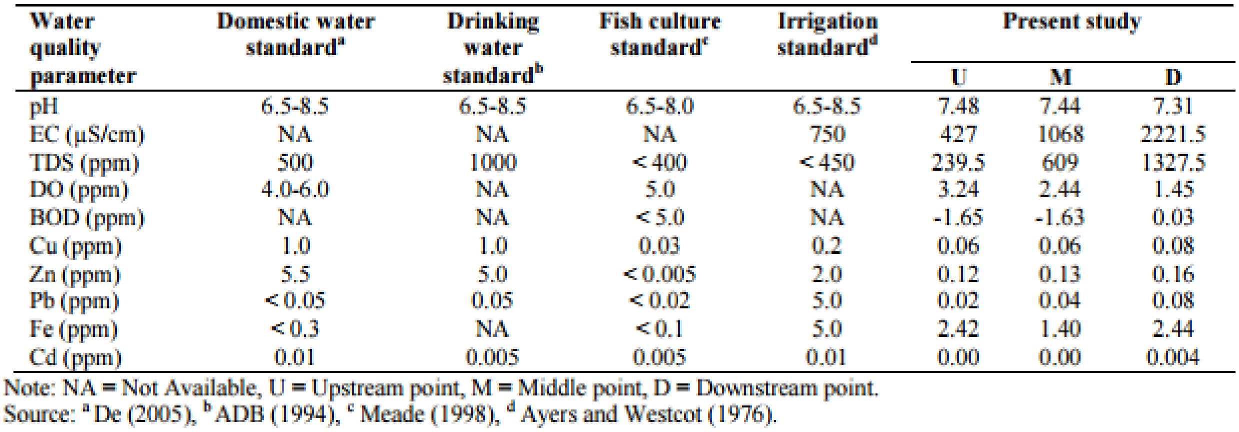
Table 3: Chemical properties of soil samples from MSW disposal site in India vs the standards of disposal of treated leachate (Sruti, et al., 2014)



Sl. No.	Parameters	Standards of disposal of treated leachate	Sample
1.	pH	5.5-9.0	6.8
2.	EC	Not specified	5.97 ms/cm
3.	COD	250 mg/L	1152 mg/L
4.	BOD	30 mg/L	80 mg/L
5.	TDS	2100 mg/L	2.56×10^6 mg/L
6.	Total Alkalinity	600 mg/L	2,915 mg/L
7.	Total Hardness	600 mg/L	700 mg/L
8.	Ca Hardness	500 mg/L	316.8 mg/L
9.	Mg Hardness	416 mg/L	393.2 mg/L
10.	Iron (Fe)	-	4.094 mg/L
11.	Sodium (Na)	200 mg/L	760 mg/L
12.	Potassium(K)	-	1,525 mg/L
13.	Sulphates	250 mg/L	20.63 mg/L
14.	Chlorides	250 mg/L	960 mg/L
15.	Nitrates	-	103.55 mg/L

Water samples collected from the Turag River at Konabari Industrial Area, Gazipur, Bangladesh were analyzed, and Table 4 summarizes and compares the water quality parameters with the standards.

Table 4: Comparison of water quality parameters from various sampling points of the Turag River and the standards (Islam, et al., 2012)



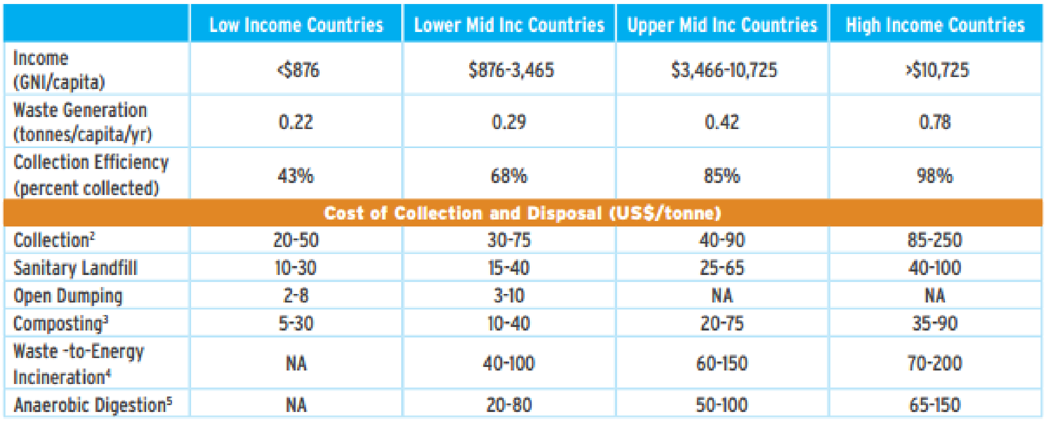
Water quality parameter	Domestic water standard[a]	Drinking water standard[b]	Fish culture standard[c]	Irrigation standard[d]	Present study		
					U	M	D
pH	6.5-8.5	6.5-8.5	6.5-8.0	6.5-8.5	7.48	7.44	7.31
EC (µS/cm)	NA	NA	NA	750	427	1068	2221.5
TDS (ppm)	500	1000	< 400	< 450	239.5	609	1327.5
DO (ppm)	4.0-6.0	NA	5.0	NA	3.24	2.44	1.45
BOD (ppm)	NA	NA	< 5.0	NA	-1.65	-1.63	0.03
Cu (ppm)	1.0	1.0	0.03	0.2	0.06	0.06	0.08
Zn (ppm)	5.5	5.0	< 0.005	2.0	0.12	0.13	0.16
Pb (ppm)	< 0.05	0.05	< 0.02	5.0	0.02	0.04	0.08
Fe (ppm)	< 0.3	NA	< 0.1	5.0	2.42	1.40	2.44
Cd (ppm)	0.01	0.005	0.005	0.01	0.00	0.00	0.004

Note: NA = Not Available, U = Upstream point, M = Middle point, D = Downstream point.
Source: [a] De (2005), [b] ADB (1994), [c] Meade (1998), [d] Ayers and Westcot (1976).

Economic sustainability

Public finances: Approximately 3-15% of the developing countries' budget is reserved for the waste management sector, where waste collection alone sometimes comprises 60-75% of the total expenditures, whereas the expenditures for disposal and treatment fluctuate depending on the methods of treatment as shown in Table 5 below. (Wilson, et al., 2013; Nemerow, et al., 2009)

Table 5: Costs of different disposal methods in low, lower middle, upper middle and high income countries (The World Bank, 2012)



	Low Income Countries	Lower Mid Inc Countries	Upper Mid Inc Countries	High Income Countries
Income (GNI/capita)	<$876	$876-3,465	$3,466-10,725	>$10,725
Waste Generation (tonnes/capita/yr)	0.22	0.29	0.42	0.78
Collection Efficiency (percent collected)	43%	68%	85%	98%
Cost of Collection and Disposal (US$/tonne)				
Collection[2]	20-50	30-75	40-90	85-250
Sanitary Landfill	10-30	15-40	25-65	40-100
Open Dumping	2-8	3-10	NA	NA
Composting[3]	5-30	10-40	20-75	35-90
Waste -to-Energy Incineration[4]	NA	40-100	60-150	70-200
Anaerobic Digestion[5]	NA	20-80	50-100	65-150

Value of waste: Resource recovery could be stimulated due to the value of some waste streams. Resource recovery is characterized by recycling, energy recovery and composting. In most developing countries, recycling is restricted to collecting, separating and cleaning the recyclables due to the absence of recycling infrastructure. Thus, recyclables have to be further brought to recycling plants. Hereby, the value of recyclables is assessed based on costs of transportation and the availability of a market for the recovered wastes. The economic advantage of composting is mainly preventing the presence of organic wastes in landfills. This in turn minimizes the required capacity of the landfill, besides cutting down methane (CH_4) emissions. The compost obtained can be sold for the fertilization of soil. (Henry, et al., 2006)

1.2 Research Objectives

In light of the challenges the Lebanese government is encountering to solve the solid waste crisis, the aim of this study is to facilitate the decision-making process on the investment in a waste treatment facility by the American University of Beirut, as a plan to indulge in an integrated sustainable solid waste management system. It is crucial that the cost and affordability of the proposed waste treatment technology wouldn’t be the only focal point for the decision makers, but also the intention to reduce the environmental impact of wastes and to exploit the produced wastes as an energy resource.

1.3 Preview on AUB’s Proposed Waste Management System

AUB generates daily seven and a half tons of trash, which calls for immediate action (Beaini, 2015). After the shutdown of the Naameh landfill, and the government’s incompetence in dealing with the garbage crisis, at least at the meantime, AUB might be forced to seize the initiative to manage their own wastes. To ensure proper waste management, the types, quantities, and sources of wastes disposed should be identified, and possible practices and methods for waste reduction and recycling should be considered.

The waste management policy at AUB would then be a series of strategies that, in conjunction, would eventually make the AUB campus more sustainable. To rectify the waste management crisis, the preliminary initiative would be curbing the growth of waste production at AUB. The reduction and minimization of the produced wastes should be the initial focus, before investigating best methods of waste treatment. Moreover, wastes should be beheld as a valuable resource, especially in terms of energy recovery, rather than a burden. Therefore, the target of AUB’s waste management strategy should be maximizing the efficiency of this resource through the endorsement of a sustainable waste management system.

According to Farouk Merhebi, director of the Environment, Health, Safety and Risk Management (EHSRM) department at AUB, more than half of the generated waste from AUB is organic. “55 percent of our trash is organic, 35 percent is recyclables, and 10 percent is other types.” (Merhebi, 2015)

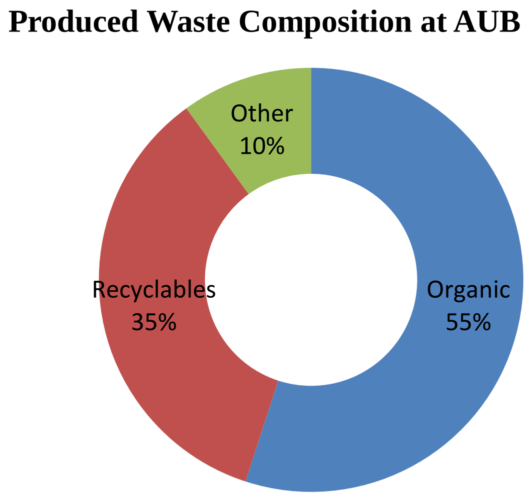


Figure 3: Produced Waste Composition at AUB

The designed system must be able to handle the different waste compositions and sources. Thus, AUB's waste management strategy should be designed based upon the below hierarchy which fosters the adoption of activities that best accomplish cost savings and environmental benefits. This strategy would lead to the reduction of the environmental emissions; however, there will be a trade-off between the cost and the environmental impact. The balance would be through reducing the environmental impact to the most possible extent, within a tolerable and acceptable cost (Johnson, 2011).

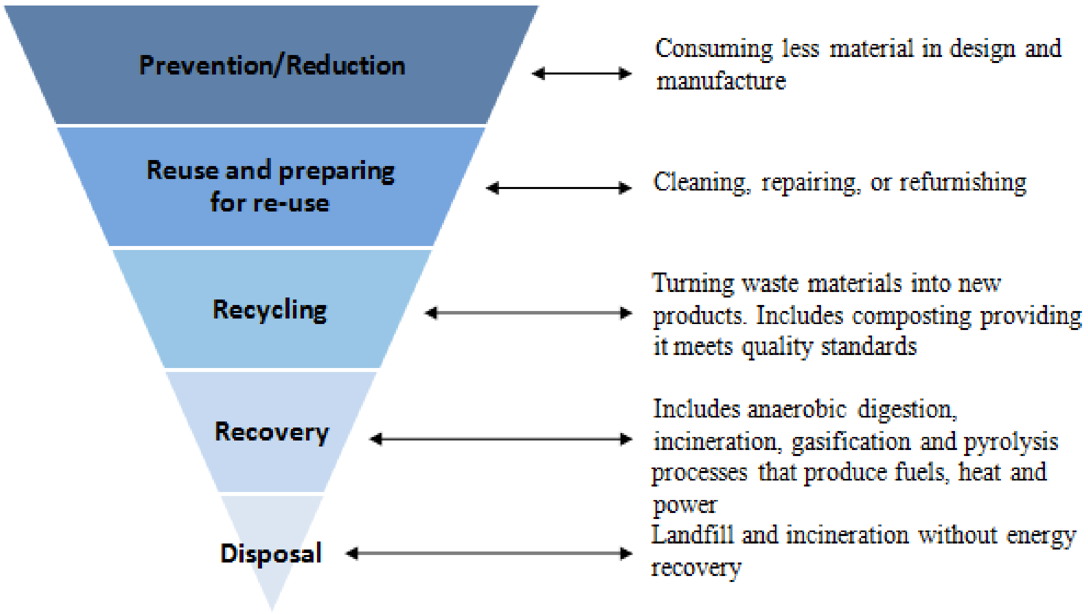


Figure 4: Waste Management Hierarchy (Johnson, 2011)

The crucial point is combining these options in an optimal way as a single strategy, rather than adopting as many options. Besides there is no one size fits all solution since conditions vary, and thus it is important that practices and options vary to meet these conditions (Johnson, 2011).

CHAPTER II

LITERATURE REVIEW

2.1 Background on Lebanon's Waste Management System

In the past 20 years, the public, private, and third sector have been perceived to devote effort, time and money to alter the way wastes are thought about and managed. In 1994 the Council for Development and Reconstruction (CDR), in conjunction with the Ministry of Environment (MoE) contracted Averda Group - mother company of Sukleen and Sukomi – to be responsible for the Solid Waste Management (SWM) plan in Beirut and Mount Lebanon with the exception of Byblos district. Their responsibilities included sweeping, collecting, treating and landfilling solid wastes. Batco was contracted by CDR in 1999 to enhance waste disposal habits and procedures and managing the dump located in Tripoli by retrofitting it with gas extraction wells and flaring units. Lebanon encountered a sequence of SWM plans, including a plan for transforming waste to energy (WTE) in 2010. Then again most of the suggested strategies and policies, along with the WTE, linger inapplicable although they were approved. (BlomInvest Bank, 2015)

As determined by Sweep-Net, approximately 2.55M tons of wastes are annually generated in Lebanon; in which each individual generates between 0.8-1.2 kg per day. A projection of the Municipal Solid Waste (MSW) indicates an increase by an annual rate of 1.65%. Figure 6 below displays the distribution of the types of wastes produced in Lebanon, where more than half (52.5%) of the wastes are organic, while 16% and 11.5% are paper and plastics respectively. (Sweep Net, 2014)

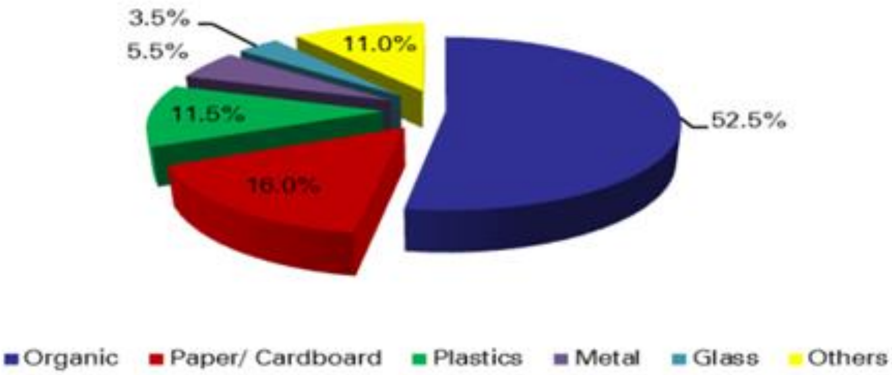


Figure 5: Types of Wastes Produced (Sweep Net, 2014)

Approximately 48% of the generated wastes are landfilled, 28% are dumped in open areas, 15% is composted, and only 8% is recycled. 52.5% of the municipal waste is organic, basically because the Lebanese people are recognized with their hospitality and because the Lebanese cuisine includes many organic products. (BlomInvest Bank, 2015)

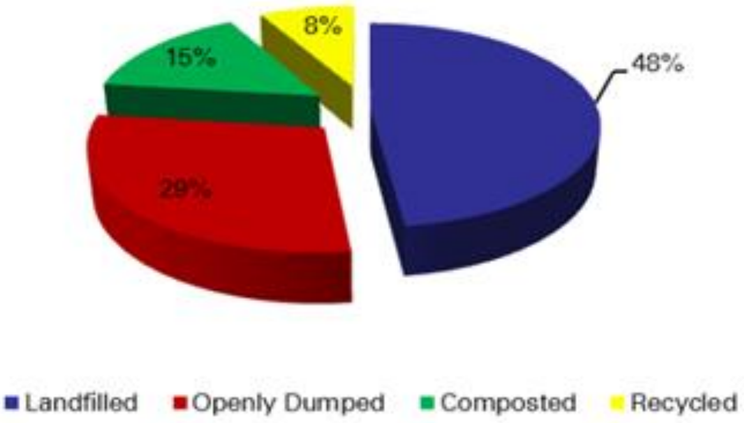
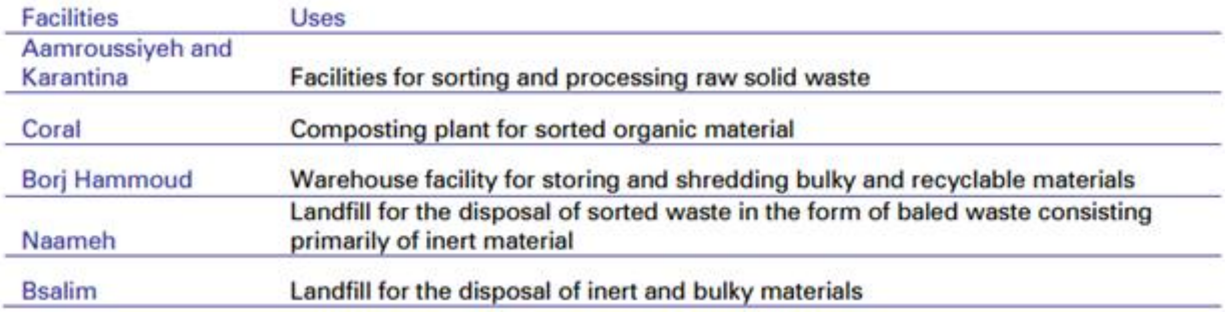


Figure 6: Treatment of Wastes Produced (Green MED Initiative)

As per the World Bank, it costs around $100/ton in upper middle income countries to collect wastes and dispose them in sanitary landfills, however $147/ton are being charged by Sukleen for collected and landfilled waste.

Prior to the MSW emergency plan in 1997, there were two dumpsites located in Burj Hammoud and Normandy. These dumpsites were shutdown by the Lebanese government after inaugurating a waste management system. The facilities involved in the MSW plan are summarized in Table 6 below. (BlomInvest Bank, 2015)

Table 6: Facilities of the MSW Emergency Plan (UNEP)



Facilities	Uses
Aamroussiyeh and Karantina	Facilities for sorting and processing raw solid waste
Coral	Composting plant for sorted organic material
Borj Hammoud	Warehouse facility for storing and shredding bulky and recyclable materials
Naameh	Landfill for the disposal of sorted waste in the form of baled waste consisting primarily of inert material
Bsalim	Landfill for the disposal of inert and bulky materials

The commencement of the Naameh landfill was in 1997, and it was expected to receive up to 3M tons of wastes generated from Beirut and Mount Lebanon for a time period of 10 years. Nonetheless, due to receiving an average quantity of 600,000 tons/year as it was put into operation, the landfill was loaded since April 2001. The Naameh landfill was receiving 2,850 tons/day in 2012, although it was planned to dispose only 1,803 tons/day. This is attributable to the following reasons: (BlomInvest Bank, 2015)

1. Another sanitary landfill was supposed to be constructed in Bsalim, but upon performing an environmental impact assessment, high risk of ground water contamination was revealed.

2. The compost wasn't expanded as planned in order to cope with the increasing capacity of organic materials, thus additional quantities of organic wastes were being disposed at the Naameh landfill.

3. Recovery of recyclables at the Karantina and Aamrousieh sorting plants didn't meet their intended target, thus more recyclables were disposed at the Naameh landfill.

The closure date of the Naameh landfill was rescheduled until the 17th of January 2015, and further extended for a 3 month period twice, to be forced to suspend its work on the 17th of July 2015 after the escalation of the civil movement. (BlomInvest Bank, 2015)

All these factors combined led to random and arbitrary dumping and inadequate handling of the wastes. These activities threaten the environment on many levels, by triggering water contamination, attraction of insects and rodents, amplifying the possibility of floods due to the blockage of the drainage canals. Not to mention the expected safety hazards from fires, and the contribution of poor waste management to the climate change through the increase of GHG emissions. (BlomInvest Bank, 2015)

2.2 Waste Management Options

2.2.1 Sanitary Landfilling

As defined by the UNEP, sanitary landfilling aims to dispose wastes on land in a manner that assures minimal contact between wastes and the environment in which wastes are assembled in a defined region. Void spaces are created in the form of cells which are filled with bales of wastes that are covered progressively, to be later closed with a permanent cap. To be identified as a sanitary landfill UNEP perceives three fundamental conditions: (Annepu, 2012)

1) Bales of wastes should be compact
2) Wastes should be covered up on a daily basis with soil or even other suitable material
3) The presence of a clear strategy for the control and prevention of undesirable impacts whether on the environment or the public health.

Sanitary landfills fall under three categories, and are defined below in descending order on the hierarchy of waste management: (Annepu, 2012)

1) Landfills recovering and using methane (CH4)
2) Landfills recovering and flaring CH4
3) Landfills without any CH4 recovery

The CH4 released from landfills into the atmosphere instead of being captured, has 21 times more global potential compared to CO2. This being said, every single molecule of

CH4 could potentially warm Earth 21 times more than CO2. Note that CH4 is responsible for 16% of the total anthropogenic GHG emissions. (Harajli, 2015)

2.2.2 Material Recovery

2.2.2.1 Aerobic composting

Organic wastes are composted, and the compost generated from this process could be exploited to fertilize agricultural spaces. The obtained organic compost contains macro nutrients (such as nitrogen, phosphorous, and potassium) in abundance, in addition to other important micro nutrients. (Annepu, 2012)

As defined by the United Nation Environment Program (UNEP), composting is "the biological decomposition of biodegradable solid waste under predominantly aerobic conditions to a state that is sufficiently stable for nuisance-free storage and handling and is satisfactorily matured for safe use in agriculture." (Annepu, 2012) The aerobic composting process includes the oxidation of carbon found in the organic wastes; this energy released is the reason behind the increase in the temperature in the windrows throughout the process. This loss of energy is sufficed to make aerobic composting fall behind anaerobic composting on the hierarchy of waste management. (Annepu, 2012)

2.2.3 Energy Recovery

Energy recovery can help meet the community's energy requirements, in addition to being a better substitute to landfilling. The stored chemical energy in the different resources is a portion of the input energy used for the production of these resources.

2.2.3.1 Incineration

Incineration typically entails the combustion of residual MSW resulting in a significant reduction in the wastes' volume. Excess oxygen is needed in order to completely oxidize the wastes which act as a fuel in this case. Ordinarily, the combustion temperature of an incineration plant exceeds 850°C, and results in the conversion of wastes into carbon dioxide and water. Bottom ash (solid), containing slight quantities of residual carbon, is formed from non-combustible materials including metals and glass. (Defra, 2013)

2.2.3.2 Pyrolysis

Pyrolysis is defined as the "thermal degradation of a substance in the absence of oxygen." (Defra, 2013) For the purpose of temperature maintenance an external heat source is needed; where usually the temperature ranges between 300°C and 850°C. The feedstock in the pyrolysis process doesn't accept raw MSW and thus requires the separation of metals and glass besides other inert material. Pyrolysis results in the production of solid residue (char) –mixture of non-combustible material and carbon – and syngas which is a "mixture of gases (combustible constituents include carbon monoxide, hydrogen, methane and a broad range of other volatile organic compounds)." (Defra, 2013) A fraction of these could be condensed for the production of oils, waxes and tars. (Defra, 2013)

2.2.3.3 Gasification

Gasification on the other hand engages partial oxidation of wastes. In other words, oxygen is made available but not to an extent that would allow complete oxidation and combustion to take place, where the temperatures utilized are usually above 650°C. This process is exothermic, however in order to initiate and ensure the sustainability of the process, some heat would be necessary. Similar to pyrolysis, raw MSW are not suitable to provide into the feedstock and thus require separation of metals and glass besides other inert material. Syngas is the main product resulting from the gasification process, containing carbon monoxide, hydrogen and methane. Also solid residue (ash) is produced due to the presence on non-combustible material. These contain low carbon levels. (Defra, 2013)

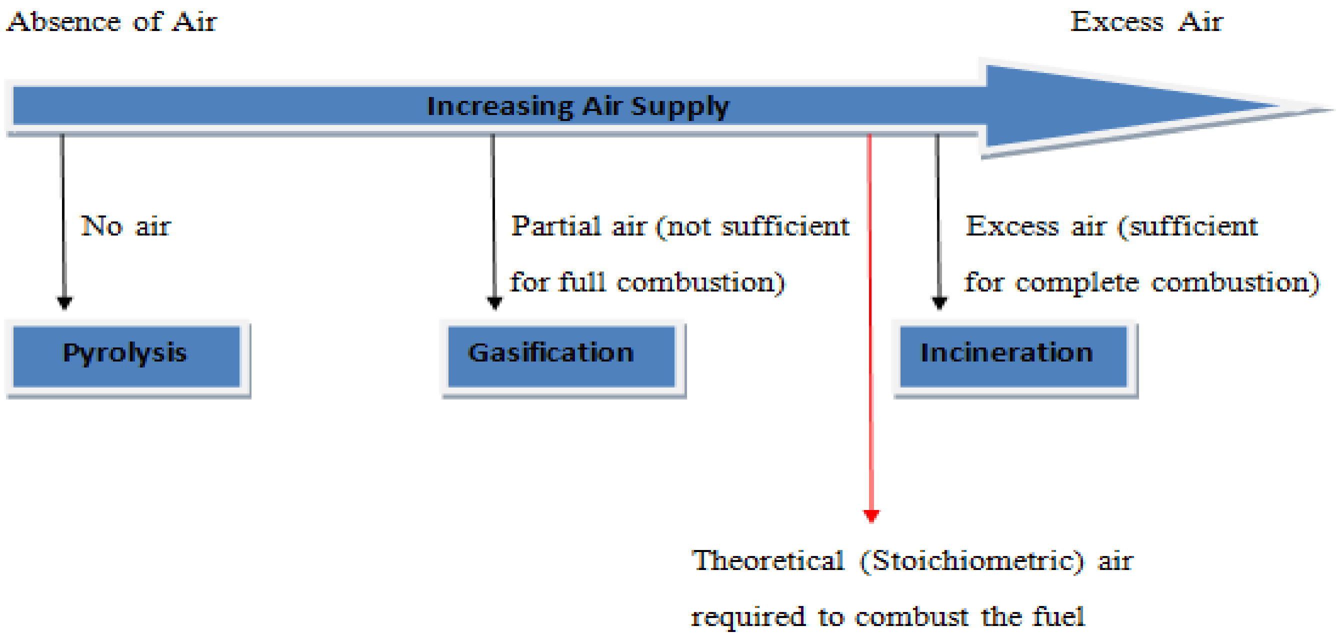


Figure 7: Levels of Air (Oxygen) Present During Pyrolysis, Gasification and Combustion Processes for MSW

2.2.3.4 Anaerobic Digestion

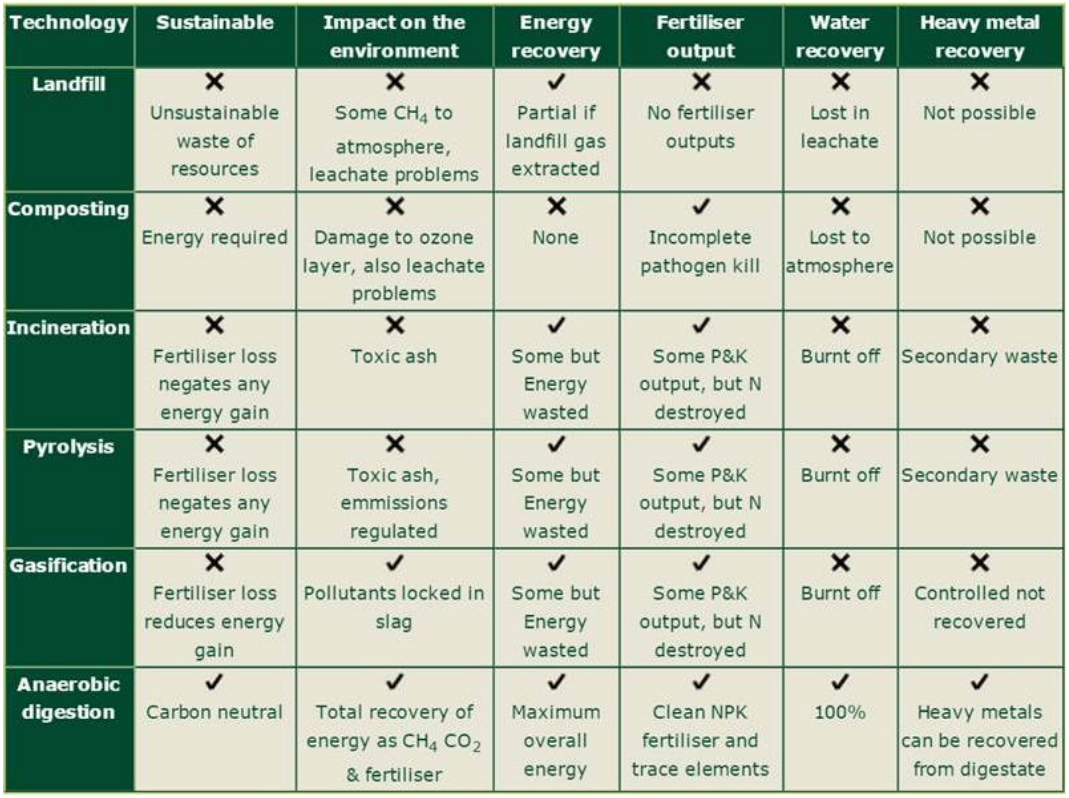
In Anaerobic Digestion (AD), organic wastes are broken down by microorganisms in an oxygen absent environment. Biogas is the end product of the organic wastes which is a form of recovered energy, while another end product is liquid residual which is a form of compost. Methane and carbon dioxide found in the biogas can be utilized as fuel, or can be combusted to generate heat and electricity. Moreover, organic fertilizers can be yielded from the liquid slurry. AD ranks higher than aerobic composting on the hierarchy of waste management noting its capability to recover energy and obtain compost from organic materials. (American Biogas Council)

For a successful and feasible large scale AD process, high level of public awareness is essential in order to achieve source separated organic wastes stream; since a mixed stream would agitate the process. Nevertheless, a small-scale AD (also known as small scale biogas) proved to be a competent process for renewable energy generation. Aside from that, it plays a role in reducing greenhouse gas emissions through exploiting the emitted methane as a source of energy. Nonetheless, the quality and condition of the obtained compost is influenced by the quality of the input waste stream. Treating mixed wastes results in mediocre or even low quality manure; this in turn could possibly result in the introduction of heavy metals into the food chain, thus causing health and environmental problems. (Annepu, 2012)

Based upon the literature on the different available waste management options, Table 7 below summarizes the aspects of each technology. Building on the preliminarily data discussed so far, anaerobic digestion (AD) seems to be the most promising technology.

However, a Multi Criteria Decision Analysis (MCDA) will be conducted in later stages in order to identify the best treatment method to invest in.

Table 7: Comparison of SWM Treatment Technologies (Bachir, 2016)



Technology	Sustainable	Impact on the environment	Energy recovery	Fertiliser output	Water recovery	Heavy metal recovery
Landfill	✗ Unsustainable waste of resources	✗ Some CH_4 to atmosphere, leachate problems	✓ Partial if landfill gas extracted	✗ No fertiliser outputs	✗ Lost in leachate	✗ Not possible
Composting	✗ Energy required	✗ Damage to ozone layer, also leachate problems	✗ None	✓ Incomplete pathogen kill	✗ Lost to atmosphere	✗ Not possible
Incineration	✗ Fertiliser loss negates any energy gain	✗ Toxic ash	✓ Some but Energy wasted	✓ Some P&K output, but N destroyed	✗ Burnt off	✗ Secondary waste
Pyrolysis	✗ Fertiliser loss negates any energy gain	✗ Toxic ash, emmissions regulated	✓ Some but Energy wasted	✓ Some P&K output, but N destroyed	✗ Burnt off	✗ Secondary waste
Gasification	✗ Fertiliser loss reduces energy gain	✓ Pollutants locked in slag	✓ Some but Energy wasted	✓ Some P&K output, but N destroyed	✗ Burnt off	✗ Controlled not recovered
Anaerobic digestion	✓ Carbon neutral	✓ Total recovery of energy as CH_4 CO_2 & fertiliser	✓ Maximum overall energy	✓ Clean NPK fertiliser and trace elements	✓ 100%	✓ Heavy metals can be recovered from digestate

CHAPTER III

WASTE MANAGEMENT STRATEGIES IN DEVELOPED COUNTRIES

Owing to economic and industrial development, and growing population, problems associated with over consumption and resources depletion, and increased production of extensive types of wastes became more severe and attentive. Below are three case studies on some MSW management technologies employed in developed countries.

3.1 Case Study 1: Japan

Referring to the Japanese word “Mottainai”, which conveys the practice of cherishing and making use of things as much as possible, this spirit is found to be the axiom of the Japanese waste management strategy which helped controlling the production of wastes and developing technologies for reusing, recycling, and efficient usage as a result of heat recovery. (Ministry of the Environment Government of Japan, 2012)

Japan lacks ample landscape for building landfill sites, therefore a waste management system was developed by mostly the reliance on incineration, and further disposal into sanitary landfills. Japan embarked on disposing municipal wastes by incineration as of 1960. Today Japan owns the world’s leading facilities of garbage incinerators. 1243 incineration facilities were operating in 2009, using different treatment methods: stoker furnaces, fluidized bed furnaces, and gasification fusion resource furnaces with the objective of ash recycling. Stoker furnaces comprise 70% of all installed furnaces, and worth mentioning is the rapid development of this particular type of furnaces. (Ministry of the Environment Government of Japan, 2012)

The latest stoker furnace innovation under construction is low air incineration targeting high-efficiency power generation. Figure 9 below demonstrates an illustration of the mentioned technology displaying prevention of high pollution and a capacity for generating high-efficiency power. (Ministry of the Environment Government of Japan, 2012)

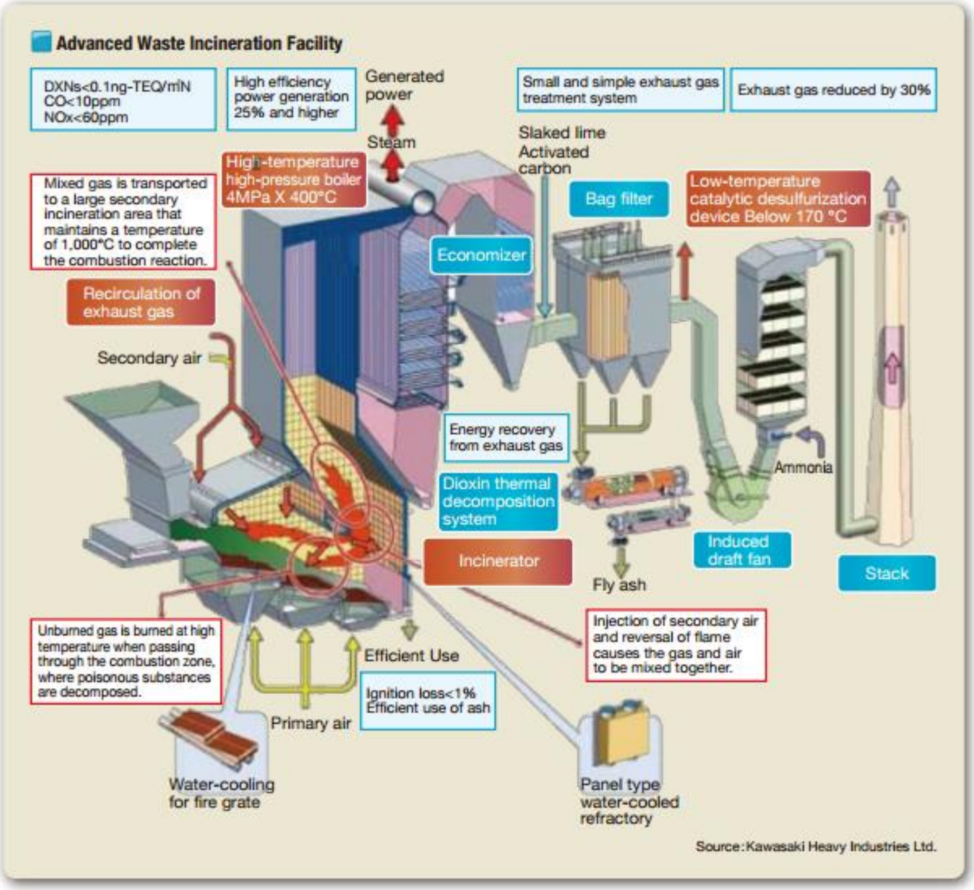
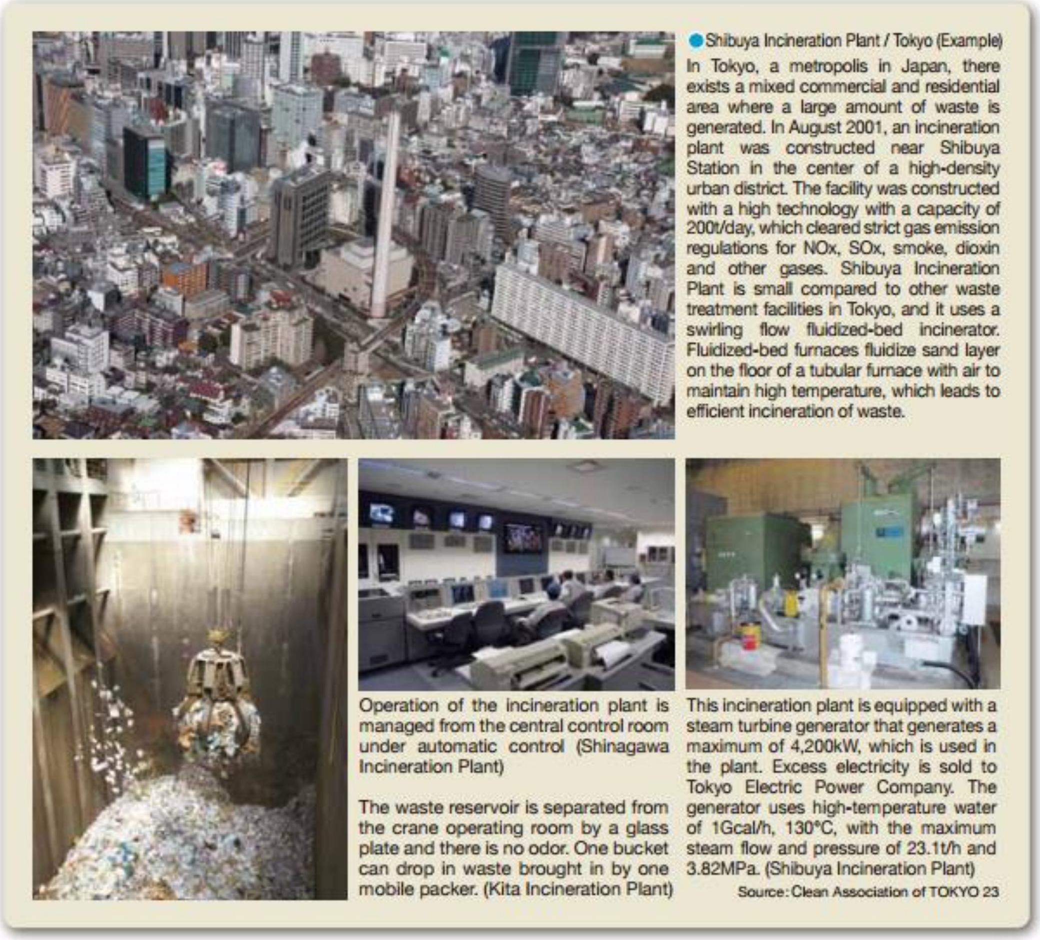


Figure 8: Advanced Waste Incineration Facility (Ministry of the Environment Government of Japan, 2012)

With the high-tech facilities provided by Japan, waste incineration was capable of gaining acceptance as a safe and reliable technology. The construction of incineration facilities in residential and commercial areas proceeds promptly, since the trust and confidence in this technology allows communication with nearby residents to run smoothly. The beneath figure shows pictures of incineration plants located in residential and commercial areas. (Ministry of the Environment Government of Japan, 2012)



● Shibuya Incineration Plant / Tokyo (Example)

In Tokyo, a metropolis in Japan, there exists a mixed commercial and residential area where a large amount of waste is generated. In August 2001, an incineration plant was constructed near Shibuya Station in the center of a high-density urban district. The facility was constructed with a high technology with a capacity of 200t/day, which cleared strict gas emission regulations for NOx, SOx, smoke, dioxin and other gases. Shibuya Incineration Plant is small compared to other waste treatment facilities in Tokyo, and it uses a swirling flow fluidized-bed incinerator. Fluidized-bed furnaces fluidize sand layer on the floor of a tubular furnace with air to maintain high temperature, which leads to efficient incineration of waste.

Operation of the incineration plant is managed from the central control room under automatic control (Shinagawa Incineration Plant)

The waste reservoir is separated from the crane operating room by a glass plate and there is no odor. One bucket can drop in waste brought in by one mobile packer. (Kita Incineration Plant)

This incineration plant is equipped with a steam turbine generator that generates a maximum of 4,200kW, which is used in the plant. Excess electricity is sold to Tokyo Electric Power Company. The generator uses high-temperature water of 1Gcal/h, 130°C, with the maximum steam flow and pressure of 23.1t/h and 3.82MPa. (Shibuya Incineration Plant)

Source: Clean Association of TOKYO 23

Figure 9: Images of Incineration Plants in Residential and Commercial Areas in Japan (Ministry of the Environment Government of Japan, 2012)

3.2 Case Study 2: University of Wisconsin Oshkosh:

In 2011, the University of Wisconsin, Oshkosh constructed on its campus the first full scale dry fermentation anaerobic digester (BD1) in USA, as an initiative towards energy independence and less reliance on fossil fuels. This facility is producing more or less 8% of the university's campus electricity needs. The anaerobic digester was designed to treat 10,000 tons of food and yard wastes annually, producing approximately 3300 MWh of renewable electricity per year. (American Biogas Council; European Biogas Association, 2013)

This plant occupies 19,000 square feet, of which 6,900 square feet are dedicated for biogas production. The biogas collected is incinerated in a 370 kW combined heat and power (CHP) unit designed to operate 24/7 for the purpose of generating electricity and heat. (American Biogas Council)

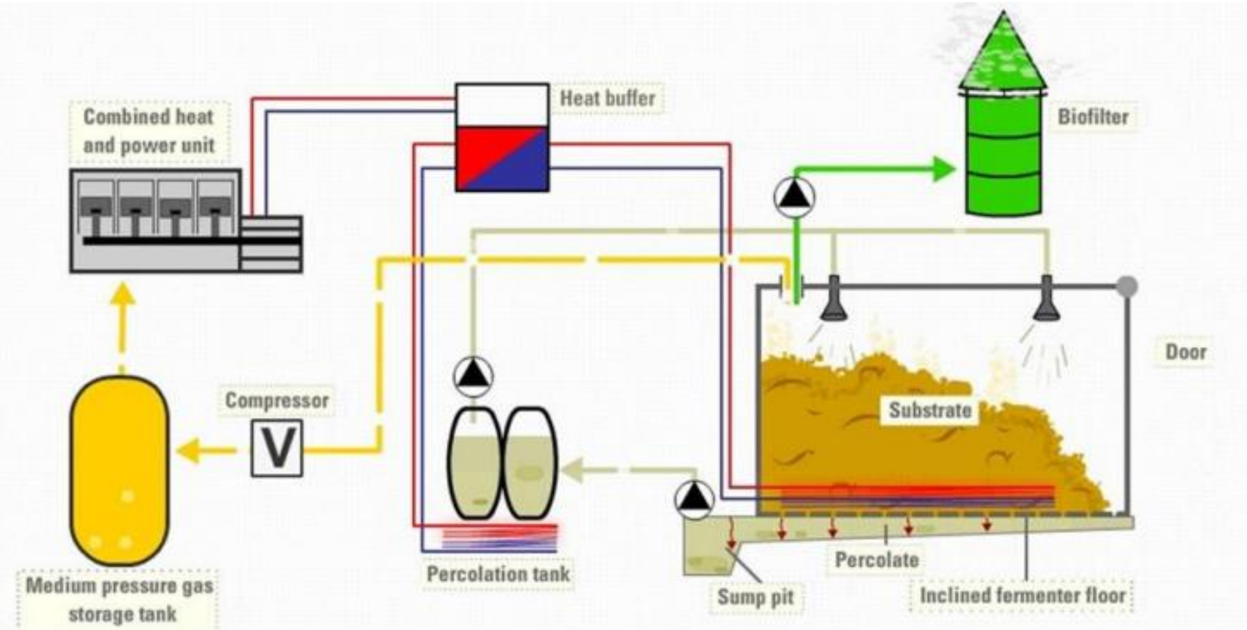


Figure 10: Dry Fermentation Process Layout (BIOFerm, 2012)

3.3 Case Study 3: University of California Davis:

As a step further towards its carbon neutrality initiative, University of California, Davis designed and installed an anaerobic digester that was put into operation in January 2014. This facility treats approximately 20,000 tons of mixed organic wastes annually (50 tons per day), and produces 925 kW (~1 MW) of renewable electricity per day upon mixing the biogas obtained from the anaerobic digester with the gas obtained from the campus landfill. This leads to a reduction of up to 13,500 tons per year of GHG emissions. (American Biogas Council; Zhang, 2015)

Figure 11: Renewable Energy Anaerobic Digestion Facility – UC Davis Biodigester (Zhang, 2015)

CHAPTER IV

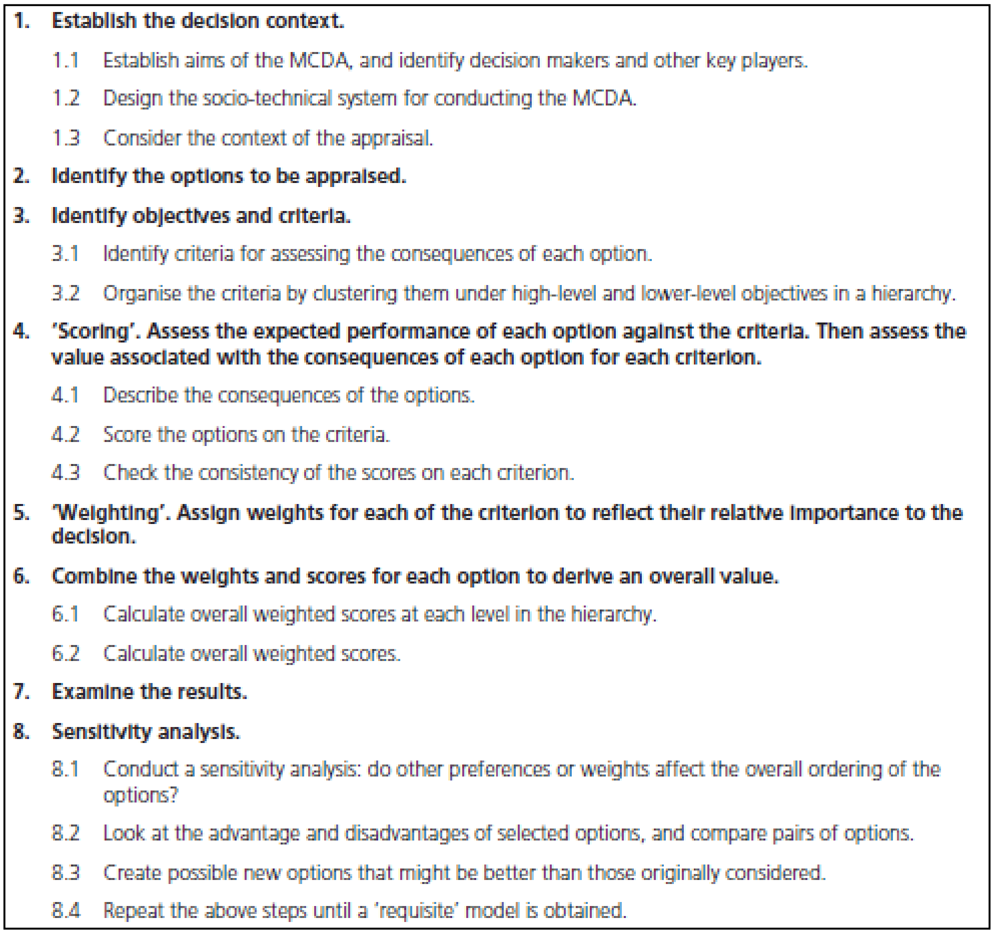
METHODOLOGY

This thesis presents an Analytical Hierarchy Process (AHP) as a decision-making tool that utilizes a combination of quantitative and qualitative approach. The AHP will allow the ranking of the waste treatment alternatives based on comparisons carried out by the decision makers. Five decision makers were selected to complete this exercise due to their interest and vast experience in the waste management sector, and those were chosen from different prospects and mindsets to avoid any biased decision. Detailed data about the four technologies under study was collected from literature reviews and made available to the stakeholders in order to support their comprehension and knowledge of the technologies. Further analysis was done through performing a sensitivity analysis to determine the robustness of the results, and whether the ranking order of the alternatives would be prone to change. The results obtained from this analysis were compared with results obtained from similar studies that aim to assess the different MSW management options with a different approach. All the collected data was analyzed to get our hands on the optimal and most feasible solution.

CHAPTER V

MULTI-CRITERIA DECISION ANALYSIS APPLICATION IN WASTE MANAGEMENT

Multi-Criteria Decision Analysis, or MCDA is an approach and a tool that aims to provide an overall ordering of options, in order to arrange the alternatives from the most preferable to the least preferable. Rather than decision taking, MCDA is only a tool that aids in thinking and making decisions. This is mainly since no one alternative would rank best in achieving all the objectives, and thus there would be a trade-off amongst the objectives. MCDA helps understand complex problems that indulge monetary and non-monetary objectives, by branching out the problem into simpler pieces thus allowing clear judgments, before eventually bringing together the pieces to portray a comprehensible overall image to decision makers. (Department for Communities and Local Government, 2009) Figure 12 below explains the detailed steps of applying MCDA.



1. **Establish the decision context.**
    - 1.1 Establish aims of the MCDA, and identify decision makers and other key players.
    - 1.2 Design the socio-technical system for conducting the MCDA.
    - 1.3 Consider the context of the appraisal.
2. **Identify the options to be appraised.**
3. **Identify objectives and criteria.**
    - 3.1 Identify criteria for assessing the consequences of each option.
    - 3.2 Organise the criteria by clustering them under high-level and lower-level objectives in a hierarchy.
4. **'Scoring'. Assess the expected performance of each option against the criteria. Then assess the value associated with the consequences of each option for each criterion.**
    - 4.1 Describe the consequences of the options.
    - 4.2 Score the options on the criteria.
    - 4.3 Check the consistency of the scores on each criterion.
5. **'Weighting'. Assign weights for each of the criterion to reflect their relative importance to the decision.**
6. **Combine the weights and scores for each option to derive an overall value.**
    - 6.1 Calculate overall weighted scores at each level in the hierarchy.
    - 6.2 Calculate overall weighted scores.
7. **Examine the results.**
8. **Sensitivity analysis.**
    - 8.1 Conduct a sensitivity analysis: do other preferences or weights affect the overall ordering of the options?
    - 8.2 Look at the advantage and disadvantages of selected options, and compare pairs of options.
    - 8.3 Create possible new options that might be better than those originally considered.
    - 8.4 Repeat the above steps until a 'requisite' model is obtained.

Figure 12: Detailed Steps of Applying MCDA

5.1 Analytical Hierarchy Process

For this purpose, Analytical Hierarchy Process (AHP) will be applied. AHP is a "method for converting subjective assessments of relative importance to a set of overall scores or weights." (Department for Communities and Local Government, 2009) AHP is a significant and flexible process that aids decision makers in appointing their priorities to construct the best possible decision, especially when qualitative and quantitative factors should be taken into consideration. Using AHP, complex decisions are reduced "to a series of one-on-one comparisons" (expert choice, 2014), then results are synthesized, thus helping decision makers choose the most appropriate and rationale decision.

AHP allows decision makers to structure decisions into smaller portions, "proceeding from the goal to objectives to sub-objectives down to the alternative courses of action," (expert choice, 2014) as shown in figure 13. "Decision makers then make simple pairwise comparison judgements throughout the hierarchy to arrive at overall priorities for alternatives. The decision problem may involve social, political, technical, and economic factors." (expert choice, 2014)

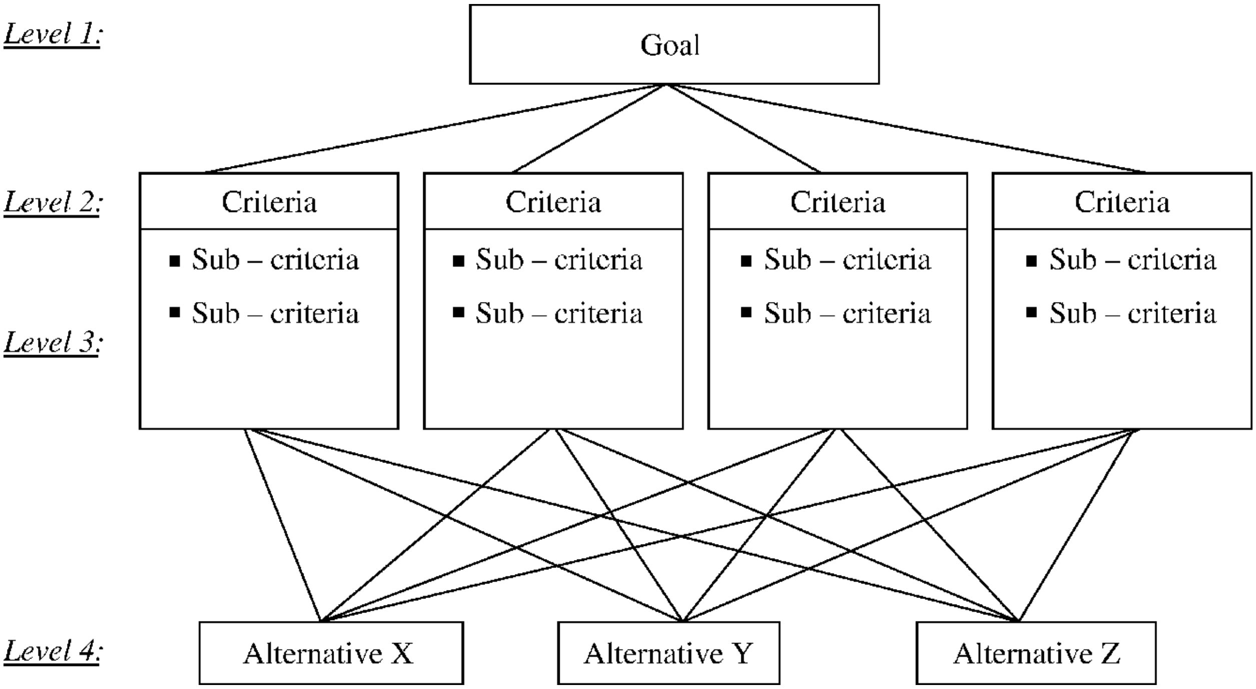


Figure 13: AHP Hierarchy

Decision makers would have to answer questions of the form:" How important is criterion A relative to criterion B". (Department for Communities and Local Government, 2009) In other words, they would be performing pairwise comparison which serves as the basic input to the AHP.

Table 8: AHP Weighing System

How Important is A Relative to B	Preference Index Assigned
Extremely less important	1/9
	1/8
Very strongly less important	1/7
	1/6
Strongly less important	1/5
	1/4
Moderately less important	1/3
	1/2
Equal Importance	1
	2
Moderately more important	3
	4
Strongly more important	5
	6
Very strongly more important	7
	8
Extremely more important	9

*1/2,1/4,1/6,1/8,2,4,6,8 are intermediate values

"The AHP procedure is as follows:

1. Problem Definition and Goal Determination
2. Identification and Hierarchy Structure of Criteria

3. Calculating Relative Weights
    a. Construction of Pairwise Comparison
    b. Relative Weights Computation
    c. Consistency Assessment of Pairwise Judgment
4. Preference Order of Options/Alternative Comparisons" (Babalola, 2015)

5.1.1 Problem Definition

The AHP analysis is set forth to assess the different suggested waste management options, and evaluate their suitability to handle the treatment of the solid wastes, while preserving the environment and enhancing public health by restricting the discharge of wastes, and ensuring proper waste sorting, recycling, handling, and disposal.

Selecting the adequate disposal treatment method will assist in diminishing the environmental impacts by reducing the anticipated risks on the water, air, and soil resources; thus protecting human health, plant life and animals. Nonetheless, the disposal method should avoid causing nuisance upon emitting noise and odors, or disturbing sites of specific significance.

5.1.2 Identification of Criteria

In our proposition to adopt a SSWM plant, our search has been reduced to the following alternatives: incineration, pyrolysis, gasification, and anaerobic digestion. The goal of this study is to determine the best waste treatment technology for AUB campus and its neighborhood. The main goal is broken down into a number of criteria categorized into four groups (environmental, sociocultural, economical, and technical).

- Environmental Criteria: concerned with any change, whether positive or negative, that might occur to "land, ecosystems, and human health" (Babalola, 2015) due to waste management. Waste disposal has environmental impacts that can root serious public health complications. (Babalola, 2015)

Hereby, a list of sub-criteria was developed underneath to further evaluate the alternatives available, based on the environmental impacts and based on the potential for diminishing those environmental impacts (Babalola, 2015):

1. Air and water pollution
2. Land requirement and contamination
3. Waste coverage and elimination

- Sociocultural Criteria: social and economic characteristics determine the aspect of waste generation due to its correlation to the society's attitude. "Campaigns, educational measures, and public awareness" (Babalola, 2015) have proven their positive impact on individuals' behavior and mindset. (Babalola, 2015)

For further evaluation of the suggested alternatives, a list of sub-criteria was suggested taking into consideration the ambition to enhance "working conditions, earnings, and access to social services." (Babalola, 2015):

1. Public acceptance
2. Employment and job creation

- Technical Criteria: is significant for deciding on the waste treatment option. These criteria judge the options against the possibility of proliferations in waste production, and the capability of the facility to manage those additional daily tonnages. Besides, technical criteria reflect on the required equipment and training for the operation of the waste management facility. Hence the following list of sub-criteria was considered (Babalola, 2015):

1. Compatibility with existing systems / recycling programs
2. Retention time

- Economic Criteria: "tactical planning and investment programming" (Babalola, 2015) is required for the development of any waste treatment facility. (Babalola, 2015)

Hereby the following list of sub-criteria is considered to evaluate the proposed alternatives (Babalola, 2015):

1. Capital and construction cost
2. Operation and maintenance cost (O&M)
3. Resource recovery; i.e. nutrient reuse & energy recovery

5.1.3 Methodological Process

The AHP approach is utilized to detect the best suitable alternative for the disposal of wastes, through breaking down the complex and multidimensional problem into smaller parts. Initially, the problem is built into a structural hierarchy as shown in figure 14. The first level of the hierarchy denotes the goal, the next two levels denote the criteria and sub-criteria, and the last level represents the alternatives. Upon doing pairwise comparison, the analyst could focus on each component separately by comparing the importance of one criterion relative to another with respect to the goal. These comparisons form a matrix, allowing the analyst to calculate the priorities, if the matrix is consistent, using the formula:

$$AW = \lambda_{max}W \tag{1}$$

where A represents the comparison matrix, λ_{max} represents the principal eigenvalue, and W the priority vector. Through measuring the consistency ratio (CR), the analyst gets feedback on the consistency of the inputted judgments. CR is calculated using the formula:

$$\mathrm{CR} = \frac{CI}{RI} \tag{2}$$

$$\mathrm{CI} = \frac{\lambda\mathrm{max}-\mathrm{n}}{n-1} \tag{3}$$

where CI denotes the consistency index, n denotes the dimension of the comparison matrix, and RI denotes the ratio index. The ratio index (RI), displayed in Table 9, was computed by calculating the average consistency index of 500 randomly generated matrices. The matrix is considered to be consistent if CR is lower than 0.1, i.e. 10%, else the matrix is regarded as inconsistent and the comparisons require modification to decrease the inconsistency. Once all the priorities and sub-priorities are computed, an aggregated weighted sum is calculated so that the overall priorities of the alternatives under study could be attained in order to base the final judgement based upon the rankings.

Table 9: Random Ratio Index (RI)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

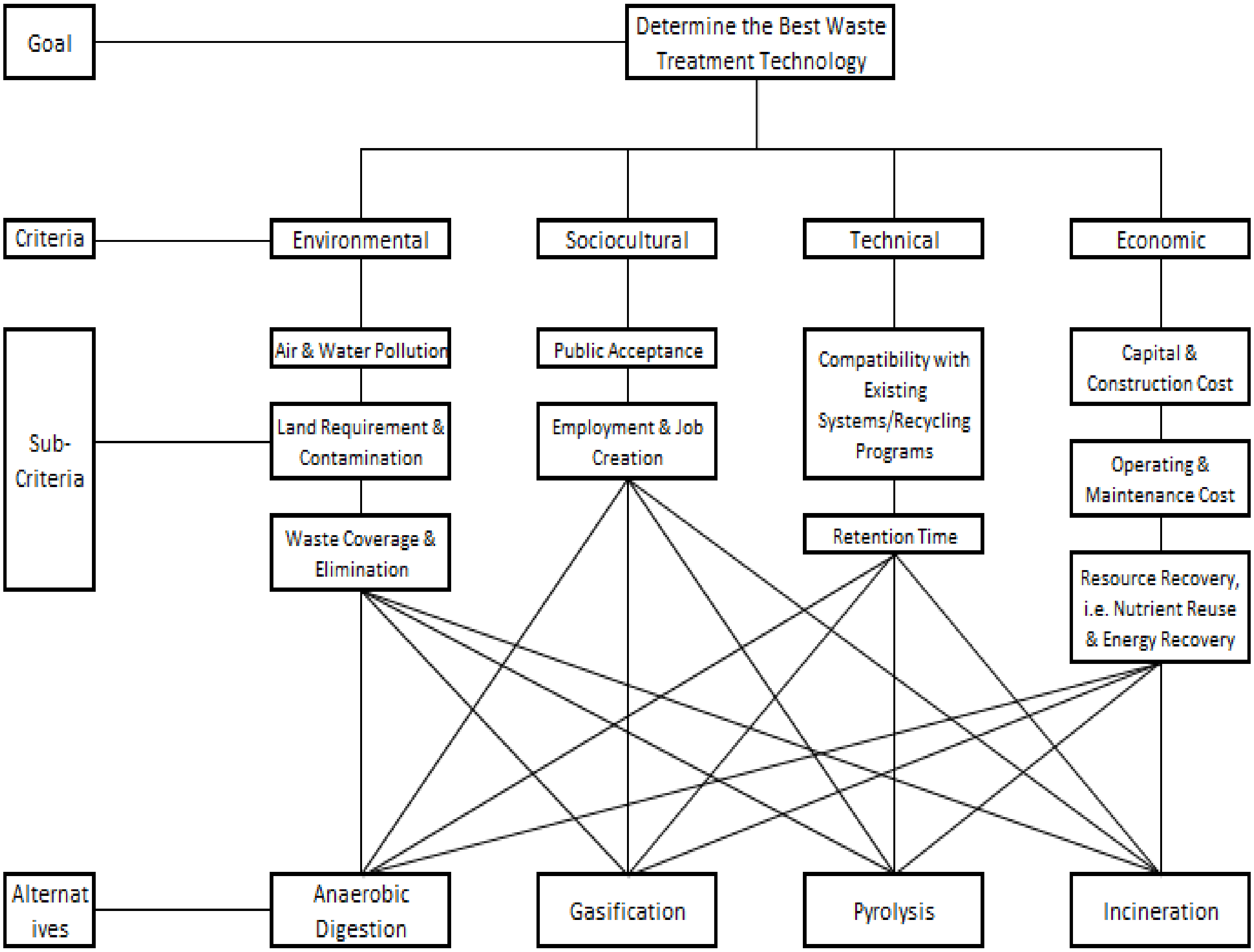


Figure 14: Structural Hierarchy Model - AHP Tree

CHAPTER VI

RESULTS

6.1 Relative Weights

After constructing the hierarchy structure shown in figure 14, the initial step is to develop a pairwise comparison matrix. For the purpose of determining the relative weights, two approaches can be employed; either a single judgement (i.e. one decision maker's judgement) or a group judgement (stakeholders of experts and academic researchers). Afterwards, the quality and reasonability of the outcome is assessed based on the consistency ratio of the input. This study used a group judgement approach, consisting of Dr. Hassan Harajli (PhD, Sustainable Energy Economics), the Project Manager at the UNDP-CEDRO project and Lecturer at AUB, Dr. Najat Saliba (PhD, Surface Science), Professor in the Chemistry Department at AUB and Director of the Nature Conservation Center at AUB, Dr. Arlette Lteif (PhD, Soil Sciences), Research and Development Manager at Averda and Lecturer at AUB, Mr. Farouk Merhebi, Director of the Environment, Health, Safety and Risk Management (EHSRM) department at AUB, and Rawan Hakawati (Chemical Engineering PhD candidate at Queen's University Belfast).

Table 10 demonstrates the pairwise comparison matrix of the main criteria with respect to the goal. The entry in row *i* and column *j* (a_{ij}) designates the importance of criteria *i* relative to criteria *j*. All entries a_{ii} = 1(i=j), since any criteria compared against itself should be equally important. Finally, to ensure the consistency of the matrix, entry a_{ij} must equal $1/a_{ji.}$

The weights assigned in Table 10 indicate that the pairwise comparison of environmental and sociocultural impacts was designated an intermediate value of 6, meaning that the environmental impacts are midway between strongly more important and very strongly more important than the sociocultural impacts. Similarly, the pairwise comparison of environmental and technical impacts was assigned a value of 4, indicating that the environmental impacts are midway between moderately and strongly more important that the technical impacts; while the environmental and technical impact are equally important denoted with a value of 1. Tables 10-26 correspond to the comparison employed by one stakeholder. Appendix B present the judgements of the other four stakeholders.

Table 10: Pairwise Comparison Matrix of Main Criteria

Criteria	Environmental	Sociocultural	Technical	Economic
Environmental	1	6	4	1
Sociocultural	1/6	1	1/2	1/3
Technical	1/4	2	1	1
Economic	1	3	1	1
Sum	**29/12**	**12**	**13/2**	**10/3**

6.2 Priorities Computation and Consistency Ratio Measurement

The priorities of the criteria, sub-criteria, and alternatives are calculated using the normalized eigen vectors of the comparison matrices. In this study an AHP excel template was used to automatically compute the priorities and consistency ratios by applying four iterations, however a trivial mathematical procedure will be presented to demonstrate how to calculate estimates of the priorities and CR without the assistance of any computer software.

Two steps are compulsory to compute the priorities (Chelst & Canbolat, 2012):

1. Normalize the pairwise comparison matrix (column by column): Sum up the weights assigned by the decision maker of each column ($a_{1j} + a_{2j} + a_{3j} + \ldots$), then divide each value in the column by the column sum to obtain the normalized weight ($a_{1j} / a_{1j} + a_{2j} + a_{3j} + \ldots ; a_{2j} / a_{1j} + a_{2j} + a_{3j} + \ldots ; a_{3j} / a_{1j} + a_{2j} + a_{3j} + \ldots ; \ldots$). After normalization, each column will sum up to 1.
2. Average the values (row by row): Determine the average value for each row of the normalized matrix created upon doing step 1 ($\sum a_{i1} / n ; \sum a_{i2} / n ; \sum a_{i3} / n ; \ldots$) . This average value represents the priority of the attribute under consideration.

Table 11 represent the normalized pairwise comparison matrix of the main criteria using hand calculations which gives a good estimate to the values obtained from the AHP excel template shown in Table 12.

Table 11: Normalized Pairwise Comparison Matrix of the Main Criteria using Hand Calculation

Criteria	***Environmental***	***Sociocultural***	***Technical***	***Economic***	***Priority***
Environmental	12/29=1/(29/12)=0.414	0.5	0.615	0.3	0.457
Sociocultural	2/29= (1/6)/(29/12)=0.069	0.083	0.077	0.1	0.082
Technical	3/29= (1/4)/(29/12)=0.103	0.167	0.154	0.3	0.181
Economic	12/29=1/(29/12)=0.414	0.25	0.154	0.3	0.280
Sum	**1**	**1**	**1**	**1**	**1**

Table 12: Pairwise Comparison Matrix of the Main Criteria using AHP Excel Template

	Environmental	**Sociocultural**	**Technical**	**Economic**	Priorities	CR
Environmental	1	6	4	1	0.421	8%
Sociocultural	1/6	1	1/2	1/3	0.081	
Technical	1/4	2	1	1	0.180	
Economic	1	3	1	1	0.318	

As explained earlier in section 5.1.3, decisions shouldn't be justified on judgements with low consistency ratios. Hence, beneath is a four-step procedure to measure the consistency of the stakeholder's comparisons.

Step 1: Compute AW;

$$\text{AW} = \begin{pmatrix} 1 & 6 & 4 & 1 \\ 1/6 & 1 & 1/2 & 1/3 \\ 1/4 & 2 & 1 & 1 \\ 1 & 3 & 1 & 1 \end{pmatrix} \begin{pmatrix} 0.421 \\ 0.081 \\ 0.180 \\ 0.318 \end{pmatrix} = \begin{pmatrix} 1.945 \\ 0.347 \\ 0.765 \\ 1.162 \end{pmatrix}$$

Step 2: Compute λ_{max};

$$\lambda\text{max} = \frac{1}{n}\sum_{i=1}^{i=n} \frac{ith\ entry\ in\ AW}{ith\ entry\ in\ W}$$

$$= \frac{1}{4}\left(\frac{1.945}{0.421} + \frac{0.347}{0.081} + \frac{0.765}{0.180} + \frac{1.162}{0.318}\right) = \frac{1}{4}\,(4.620 + 4.284 + 4.25 + 3.654)$$

$$\lambda\,\text{max} = 4.202$$

Step 3: Compute CI;

$$\mathrm{CI} = \frac{\lambda\mathrm{max} - \mathrm{n}}{n - 1} = \frac{4.202 - 4}{4 - 1}$$

CI = 0.067

Step 4: Calculate CR;

$$\mathrm{CR} = \frac{0.067}{0.90} = 0.074 = 7.4\% < 10\%$$

RI is selected from Table 9 for the appropriate value of n

Again, the estimate of the CR obtained from the hand calculation (7.4%) is close enough to the value obtained from the AHP excel template (8%) as shown in Table 12.

Table 12 shows that the environmental criteria scored the highest, 0.421, followed by the economic criteria with a score of 0.318. Technical and sociocultural criteria ranked third and fourth with a score of 0.180 and 0.081 respectively.

On the level of the sub-criteria, a total of four tables represent the pairwise comparison matrices of the sub-criteria corresponding to the main criteria. The weights are illustrated in Tables 13-17 below.

Table 13: Pairwise Comparison Matrix of Sub-Criteria of Environmental Impact

	Air & Water Pollution	**Land Requirement & Contamination**	**Waste Coverage & Elimination**	Priorities	CR
Air & Water Pollution	1	1	1/3	0.201	1%
Land Requirement & Contamination	1	1	1/4	0.168	
Waste Coverage & Elimination	3	4	1	0.631	

Table 14: Pairwise Comparison Matrix of Sub-Criteria of Sociocultural Impact

	Public Acceptance	**Employment & Job Creation**	Priorities	CR
Public Acceptance	1	1/4	0.200	0%
Employment & Job Creation	4	1	0.800	

Table 15: Pairwise Comparison Matrix of Sub-Criteria of Technical Impact

	Compatibility with Existing Systems/Recycling Programs	**Retention Time**	Priorities	CR
Compatibility with Existing Systems/Recycling Programs	1	4	0.800	0%
Retention Time	1/4	1	0.200	

Table 16: Pairwise Comparison Matrix of Sub-Criteria of Economic Impact

	Capital & Construction Cost	**Operating & Maintenance Cost**	**Resource Recovery, i.e. Nutrient Reuse & Energy Recovery**	Priorities	CR
Capital & Construction Cost	1	1/6	1/3	0.105	6%
Operating & Maintenance Cost	6	1	4	0.703	
Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	3	1/4	1	0.192	

The final level of pairwise comparison is represented in Tables 17-26, showing the weights for the alternatives – Anaerobic Digestion, Gasification, Pyrolysis, and Incineration – with respect to the sub-criteria. To assess the decision makers in their judgements at this level, detailed comparisons between the technologies with respect to the sub-criteria were provided and are available in Appendix A.

Environmental Impact Sub-Criteria

Table 17: Pairwise Comparison Matrix for Alternatives wrt Air and Water Pollution

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	4	4	9	0.616	7%
Gasification	1/4	1	1/2	5	0.146	
Pyrolysis	1/4	2	1	5	0.182	
Incineration	1/9	1/5	1/5	1	0.056	

Table 18: Pairwise Comparison Matrix for Alternatives wrt Land Requirement and Contamination

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	5	5	8	0.653	6%
Gasification	1/5	1	1	4	0.140	
Pyrolysis	1/5	1	1	4	0.140	
Incineration	1/8	1/4	1/4	1	0.067	

Table 19: Pairwise Comparison Matrix for Alternatives wrt Waste Coverage and Elimination

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	8	8	3	0.629	5%
Gasification	1/8	1	1/2	1/5	0.067	
Pyrolysis	1/8	2	1	1/5	0.074	
Incineration	1/3	5	5	1	0.231	

Sociocultural Impact Sub-Criteria

Table 20: Pairwise Comparison Matrix for Alternatives wrt Public Acceptance

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	4	4	8	0.611	9%
Gasification	1/4	1	1/2	5	0.146	
Pyrolysis	1/4	2	1	5	0.183	
Incineration	1/8	1/5	1/5	1	0.061	

Table 21: Pairwise Comparison Matrix for Alternatives wrt Employment and Job Creation

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	8	8	5	0.689	0%
Gasification	1/8	1	1	1/2	0.084	
Pyrolysis	1/8	1	1	1/2	0.084	
Incineration	1/5	2	2	1	0.143	

Technical Impact Sub-Criteria

Table 22: Pairwise Comparison Matrix for Alternatives wrt Compatibility with Existing Systems/Recycling Programs

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	7	8	9	0.720	7%
Gasification	1/7	1	2	3	0.117	
Pyrolysis	1/8	1/2	1	3	0.093	
Incineration	1/9	1/3	1/3	1	0.070	

Table 23: Pairwise Comparison Matrix for Alternatives wrt Retention Time

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/5	1/5	1/8	0.061	9%
Gasification	5	1	1/2	1/4	0.146	
Pyrolysis	5	2	1	1/4	0.183	
Incineration	8	4	4	1	0.611	

Economic Impact Sub-Criteria

Table 24: Pairwise Comparison Matrix for Alternatives wrt Capital and Construction Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	6	1/2	3	0.286	5%
Gasification	1/6	1	1/6	1/3	0.070	
Pyrolysis	2	6	1	5	0.535	
Incineration	1/3	3	1/5	1	0.109	

Table 25: Pairwise Comparison Matrix for Alternatives wrt Operating and Maintenance Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/3	1/4	1/2	0.100	2%
Gasification	3	1	1/2	2	0.267	
Pyrolysis	4	2	1	2	0.445	
Incineration	2	1/2	1/2	1	0.188	

Table 26: Pairwise Comparison Matrix for Alternatives wrt Resource Recovery, i.e. Nutrient Reuse and Energy Recovery

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	7	7	9	0.713	5%
Gasification	1/7	1	1	3	0.109	
Pyrolysis	1/7	1	1	3	0.109	
Incineration	1/9	1/3	1/3	1	0.069	

6.3 Overall Priority of Alternatives

The overall priority of each alternative is computed by multiplying the alternative's priority with regard to each sub-criteria by the sub-criteria's weight and again by the criteria's weight that corresponds to that sub-criteria. Appendix C gives a detailed overview of the overall priority synthesis. Table 27 below summarizes the scores of the alternatives under study of the 5 stakeholders.

Table 27: Average Overall Priorities of the Waste Treatment Alternatives

Decision Maker	**Alternative/Technology**			
	Anaerobic Digestion	Gasification	Pyrolysis	Incineration
Rawan Hakawati	0.5013	0.1386	0.1973	0.1631
Dr Hassan Harajli	0.3551	0.1848	0.2774	0.1835
Dr Najat Saliba	0.6455	0.1453	0.1045	0.1057
Dr Arlette Lteif	0.4233	0.1882	0.1963	0.1930
Farouk Merhebi	0.1990	0.2837	0.3070	0.2111
Average Overall Priority	0.4248	0.1881	0.2165	0.1713

Table 28: Final Results Illustrated as Normalized and Idealized Priorities

Alternative/Technology	**Normalized Priority**	**Idealized Priority**
Anaerobic Digestion	0.4248	1.000
Pyrolysis	0.2165	0.510
Gasification	0.1881	0.443
Incineration	0.1713	0.403

Based on the results summarized in Table 27, Anaerobic Digestion ranked first with an overall priority of 0.4248, followed by pyrolysis with an overall priority of 0.2165. Gasification and incineration raked third and fourth with an overall priority of 0.1881 and 0.1713 respectively. Table 28 shows the results in their idealized form, i.e. making the alternative with the highest score the ideal option, which is anaerobic digestion in this case. Accordingly, this allows the interpretation that pyrolysis has an attractiveness rate of 51% compared to anaerobic digestion, whereas gasification and incineration almost have the same attractiveness rate, 44.3% and 40.3% respectively, as compared to anaerobic digestion.

The analysis using AHP, suggests that anaerobic digestion is the most suitable option to finance, and figure 15 shows that anaerobic digestion is the most appealing on all levels of the main criteria, with the exception of the economic criteria, in which pyrolysis ranked first and anaerobic digestion has a slight advantage on gasification.

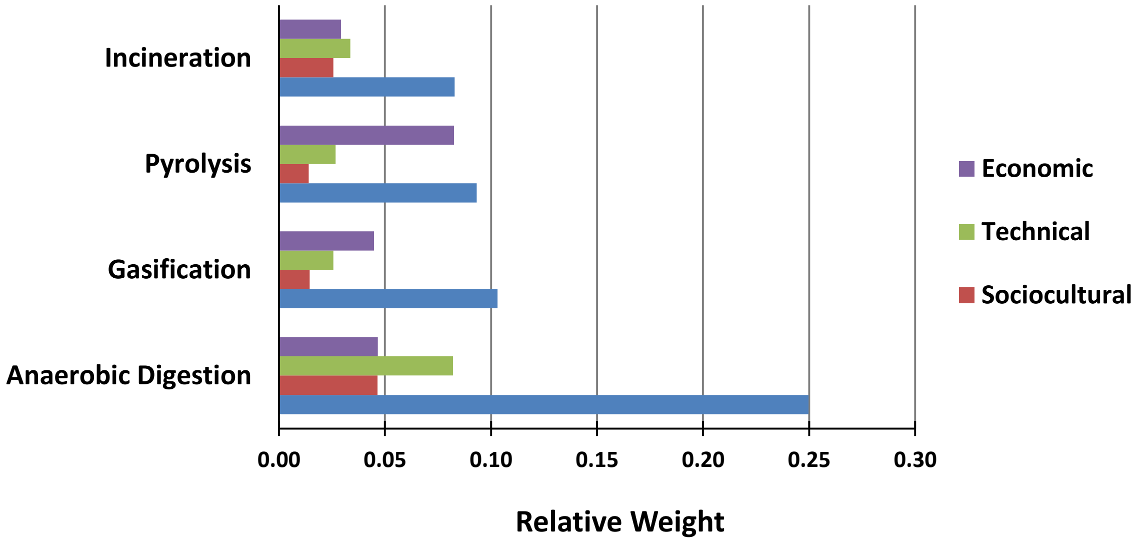


Figure 15: Overall Ranking of Alternatives

CHAPTER VII

SENSITIVITY ANALYSIS

To explore the robustness of the results and to determine the impact of altering the relative weights on the final choice, sensitivity analysis is employed. This was performed by manipulating the relative weights of the different criteria and perceiving the changes in the ranking of the alternatives. This is carried out by applying five situations:

a) One criterion is given a weight of one, while the remaining three criteria are assigned a weight of zero. This situation has four possibilities, where in each single possibility one criterion is given the whole relative weight. Figures 16a, b, and c show that anaerobic digestion ranked first, and only anaerobic digestion was outranked by pyrolysis when the whole relative weight was assigned to the economic criteria.

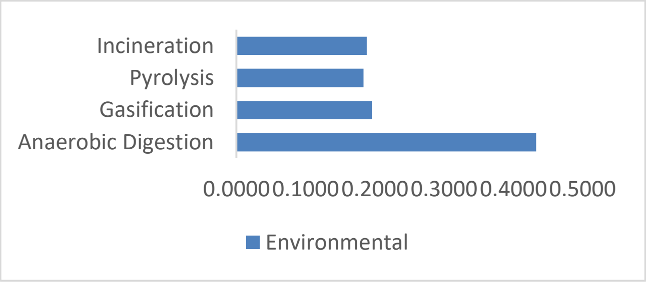


Figure 16a: Sensitivity Analysis- Environmental Criteria Assigned a Relative Weight of 1

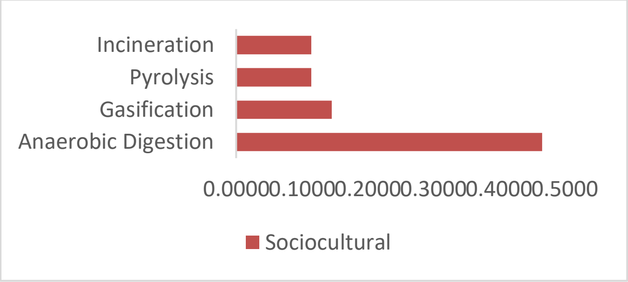


Figure 16b: Sensitivity Analysis- Sociocultural Criteria Assigned a Relative Weight of 1

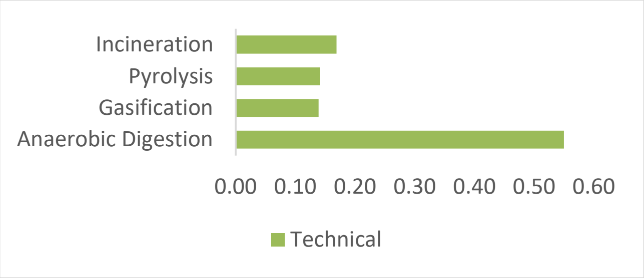


Figure 16c: Sensitivity Analysis- Technical Criteria Assigned a Relative Weight of 1

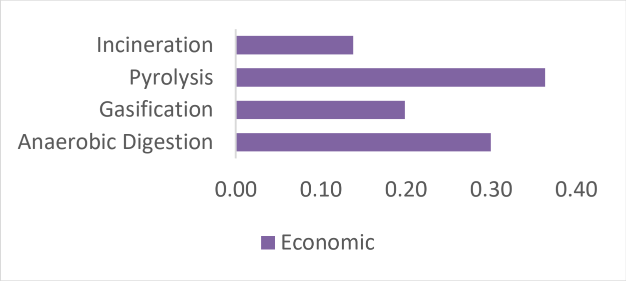


Figure 16d: Sensitivity Analysis- Economic Criteria Assigned a Relative Weight of 1

b) Two criteria are assigned a relative weight of 0.5, and the other two criteria are assigned zero. This situation comprises six different possibilities, but all conclude that anaerobic digestion is the best performing option. However, pyrolysis is more appealing on the level of the economic criteria.

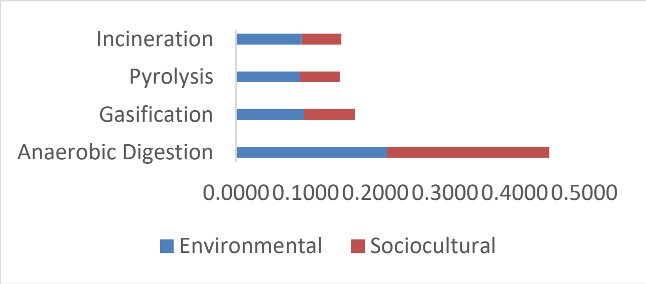


Figure 17a: Sensitivity Analysis- Environmental and Sociocultural Criteria Assigned a Relative Weight of 0.5

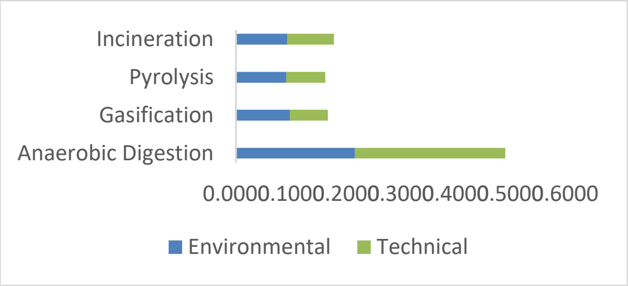


Figure 17b: Sensitivity Analysis- Environmental and Technical Criteria Assigned a Relative Weight of 0.5

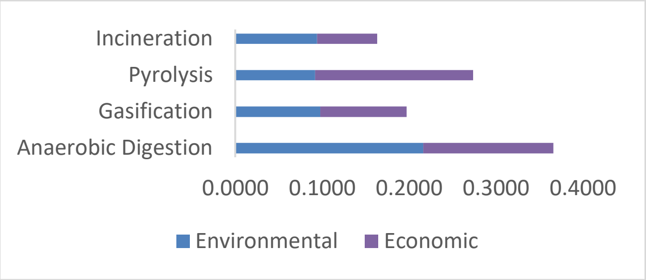


Figure 17c: Sensitivity Analysis- Environmental and Economic Criteria Assigned a Relative Weight of 0.5

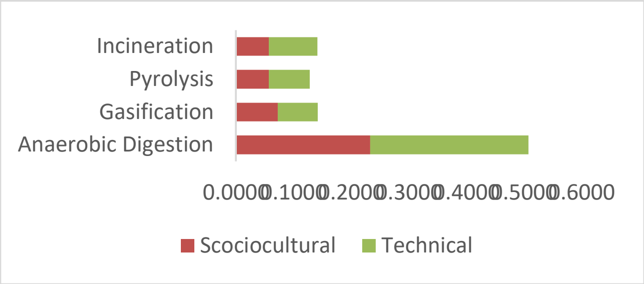


Figure 17d: Sensitivity Analysis- Sociocultural and Technical Criteria Assigned a Relative Weight of 0.5

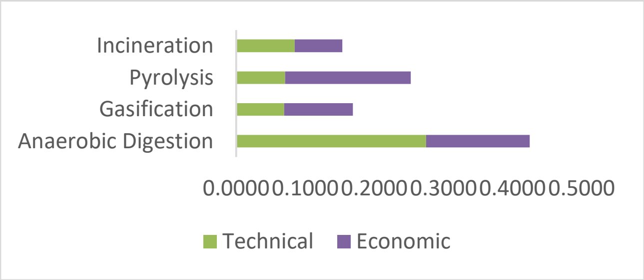


Figure 17e: Sensitivity Analysis- Technical and Economic Criteria Assigned a Relative Weight of 0.5

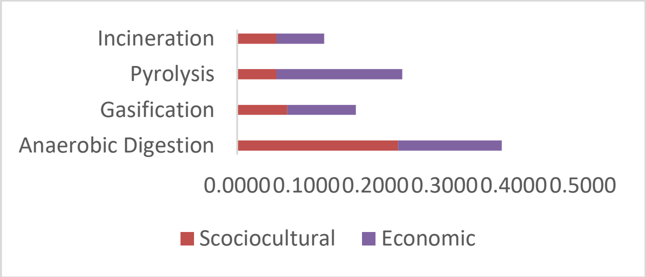


Figure 17f: Sensitivity Analysis- Sociocultural and Economic Criteria Assigned a Relative Weight of 0.5

c) Three criteria are assigned a relative weight of 0.33, and the remaining one is assigned zero. This situation comprises four possibilities, that all suppose that anaerobic digestion is the best suitable option.

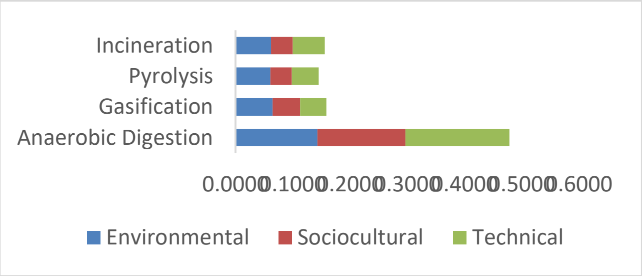


Figure 18a: Sensitivity Analysis- Environmental, Sociocultural, and Technical Criteria Assigned a Relative Weight of 0.33

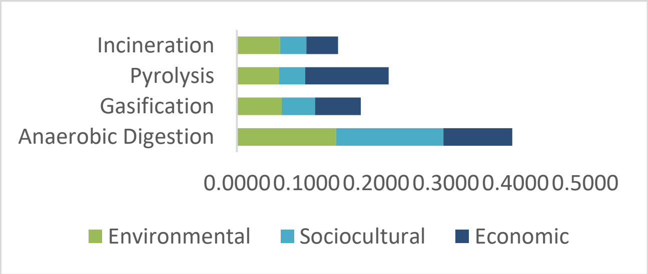


Figure 18b: Sensitivity Analysis- Environmental, Sociocultural, and Economic Criteria Assigned a Relative Weight of 0.33

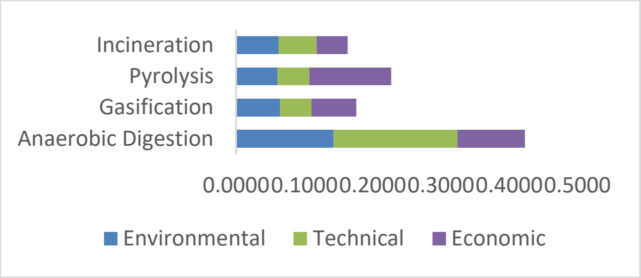


Figure 18c: Sensitivity Analysis- Environmental, Technical, and Economic Criteria Assigned a Relative Weight of 0.33

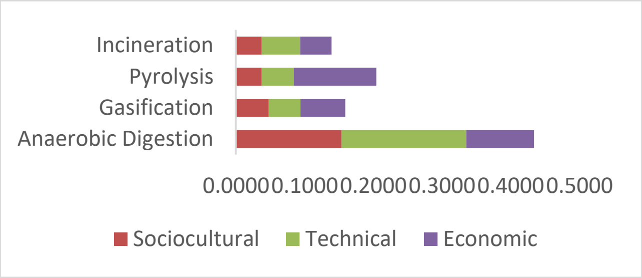


Figure 18d: Sensitivity Analysis- Sociocultural, Technical, and Economic Criteria Assigned a Relative Weight of 0.33

d) All four main criteria are assigned an equal relative weight of 0.25. Once again anaerobic digestion ranked first, whereas pyrolysis and gasification ranked second and third respectively, and incineration gives the impression of being the worst option.

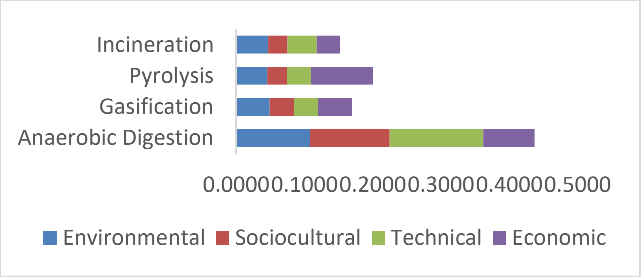


Figure 19: Sensitivity Analysis- All Main Criteria Assigned an Equal Relative Weight of 0.25

e) Last situation assumes all criteria and sub-criteria are equally important and thus the relative weights are fragmented equally among the criteria/sub-criteria. Also, this situation shows that anaerobic digestion has the best performance, whereas, pyrolysis and incineration ranked second and third respectively, while gasification fell behind and ranked last.

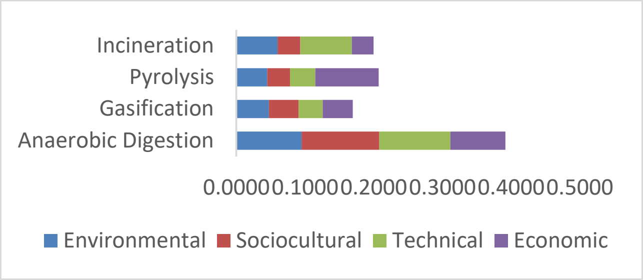


Figure 20: Sensitivity Analysis- Equity Among Main Criteria and Sub-criteria

The 16 different scenarios show a wide variation in the ranking of the proposed alternatives. However, the major findings are that seven situations show the following pattern: Anaerobic Digestion > Pyrolysis > Gasification > Incineration; and four situations show this pattern: Anaerobic Digestion > Gasification > Incineration > Pyrolysis. Five other patterns are displayed; however, those weren’t reiterative. Furthermore, Table 29 shows that anaerobic digestion ranked first 15 times, while pyrolysis ranked second 8 times, gasification ranked third 9 times, and incineration ranked last 8 times.

Therefore, although this analysis points to the robustness of the results, it can be deduced that the sensitivity analysis approves the ranking obtained by the AHP analysis conducted by the five stakeholders.

Table 29: Ranking Count of the Waste Treatment Technologies

Alternatives/Options	Rank 1	Rank 2	Rank 3	Rank 4
Anaerobic Digestion	15	1	NA	NA
Gasification	NA	5	9	2
Pyrolysis	1	8	2	5
Incineration	NA	2	6	8

CHAPTER VIII

DISCUSSION

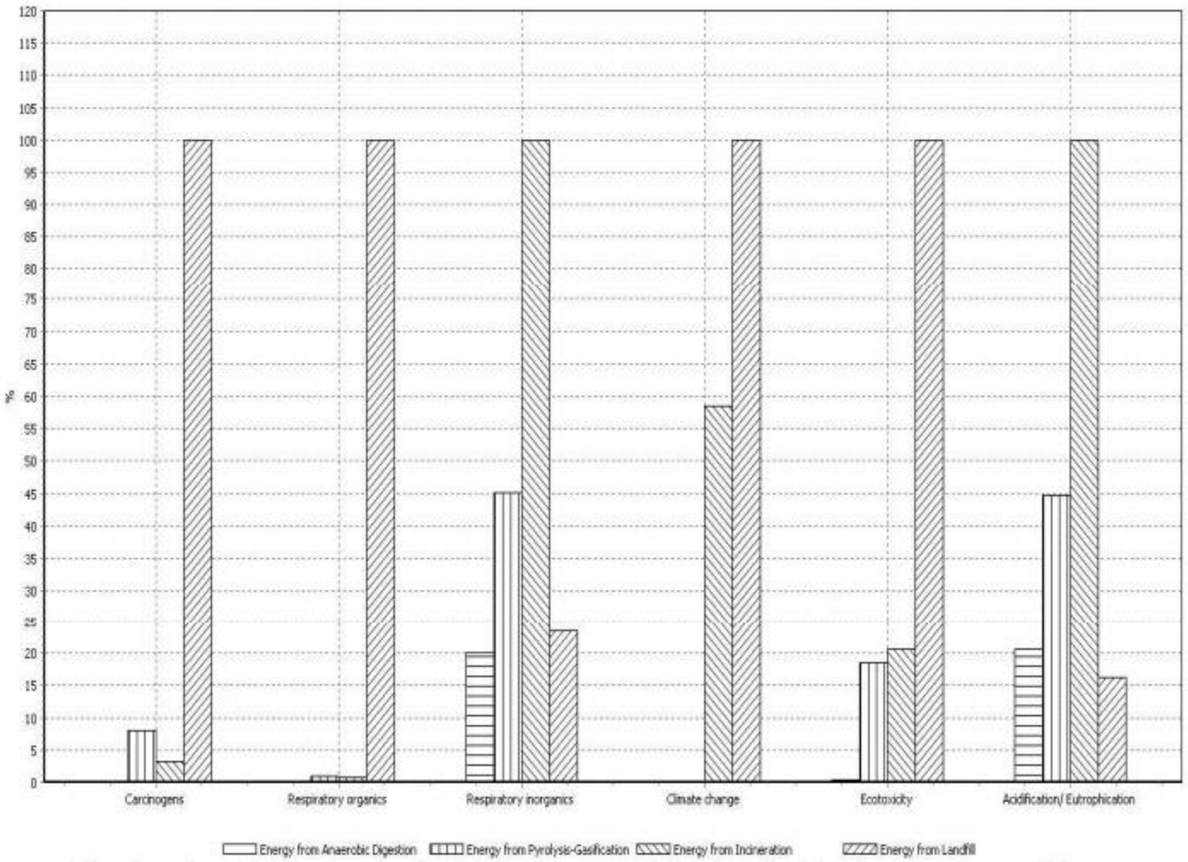
This dissertation presents an evaluation of the available MSW treatment systems. The investigation in this analysis takes into consideration environmental, sociocultural, technical and economic criteria, and therefore the proposed solution presents a balanced assessment. However, it is prominent to touch on the importance of incorporating the 3Rs in any proposed solution, and on reducing landfill's space requirement and capacity.

Tables 12 to 26 illustrate how pairwise comparisons allow the computation of the priorities of the criteria, sub-criteria, and waste treatment alternatives. Tables 27 and 28 show the overall priorities of the alternatives, and thus clarify the overall ordering of the options, i.e. the display of the alternatives from the most preferable to the least preferable. Anaerobic digestion was perceived to have the best performance on the level of environmental, sociocultural, and technical criteria; however, with regard to the economic criteria, pyrolysis outranked anaerobic digestion. Nonetheless, anaerobic digestion ranked first, while pyrolysis occupied the second rank with the interpretation that it has 51% of the appeal of AD for stakeholders. Gasification and incineration followed the guide, with incineration being the least favorable option, although it scored more than gasification with regard to the sociocultural and technical criteria. This can be justified due to the greater job creation potential of incineration (19-37 jobs per 100,000 tpa) compared to gasification (12-36 jobs per 100,000 tpa), and due to the shorter retention time of incineration, 2 seconds at a temperature above 850^{o}C, compared to 49 seconds at 750^{o}C at best for gasification.

Consistency ratios were calculated for each pairwise comparison matrix, and were all observed to be less than 0.1, which assures the consistency of the judgement. However, for further analysis and as previously drawn attention to, sensitivity analysis was conducted to determine the robustness of the results. Hence, a what-if-analysis was carried out to pinpoint any variation in the ranking of the alternatives upon changing the weights of the criteria. The results match the findings of the study, given that anaerobic digestion claimed the first rank in 15 out of 16 situations.

Noteworthy, is that the evaluation utilized in this study was based on the judgement of a group of experts and academic researchers (group judgement) who are concerned with the waste management and environmental sector. The AHP model put forward in this thesis, can be perceived as a guiding framework to aid stakeholders in their decision-making process for deciding on the most suitable SWM treatment method.

The findings of this study agree with several studies that aim to assess the different MSW management options even with a different approach. One of which was conducted by Atiq Uz Zaman through a Life Cycle Assessment (LCA) model. The WTE technologies under study were landfill, incineration, pyrolysis-gasification – an advanced hybrid thermal waste treatment technology – and anaerobic digestion. The major findings of this assessment where that, “landfill has the highest efficient and environmentally sound MSW disposal, impact on environmental and mainly in climate change, Incineration has also climate change and respiratory inorganic impacts. Pyrolysis-Gasification is comparatively favorable due to lower environmental impact, and AD has the lowest potential impact among the four WTE options.” (Zaman, 2009) Figure 21 below summarizes the contribution of the four technologies in several impact categories included in the LCA model. Another study that considered the following five MSW treatment technologies: incineration, gasification, anaerobic digestion, bio-landfills, and composting; based its assessment on the energy recovery potential and on a LCA approach. “From an energy recovery viewpoint, it was found that it is best to recycle paper, wood and plastics; to anaerobically digest food and yard wastes; and to incinerate textile waste.” (Arafat, et al., 2015) These results are clearly shown in Figure 22 below. “On the other hand, the level of environmental impact for each process depends on the considered impact category. Generally, anaerobic digestion and gasification were found to perform better environmentally than the other processes, while composting had the least environmental benefit.” (Arafat, et al., 2015)



Comparing 1 kWh 'Energy from Anaerobic Digestion', 1 kWh 'Energy from Pyrolysis-Gasification', 1 kWh 'Energy from Incineration' and 1 kWh 'Energy from Landfill'; Method: Eco-indicator 99 (E) V2.06 / Europe EI 99 E/A / characterization

Figure 21: Comparative LCA Characterization Results of the WTE Facilities (Zaman, 2009)

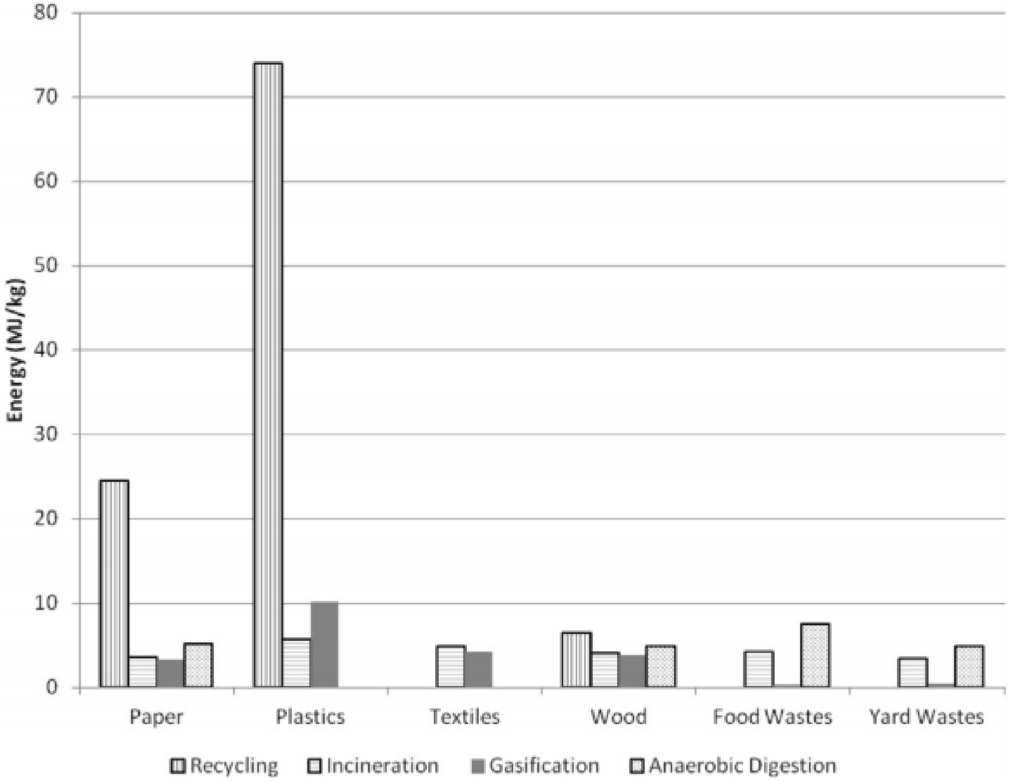


Figure 22: Electrical Efficiency-Adjusted Energy Obtained from Applying Waste to Energy Technologies or Recycling to the Different MSW Streams (Arafat, et al., 2015)

The implementation of any solid waste management facility could be met with more than a few challenges. These challenges, may have to do with existing policies and authorities, and views held by citizens of the Beirut area (especially in the proximity of the AUB), and the student body. The AHP approach allows the involvement of all the above mentioned parties due to its capability of breaking down complex problems that involve monetary and non-monetary objectives, into simpler pieces thus allowing clear judgments.

Noting that AUB is part of the Lebanese community, and thus any proposed solid waste management plan must compliment the plan adopted by the government to ensure best performance. However, until this moment the Lebanese government hasn’t laid all its cards on the table, and thus the waste management strategy is still vague. Rumors say Beirut municipality has the intention to build an incineration plant to treat wastes generated in the Mohafaza of Beirut, yet this is met with public rejection, especially that an economic feasibility and environmental impact assessment hasn’t been performed.

CHAPTER IX

LIMITATIONS

This section outlines the limitations of this study. A prominent limitation in the conducted analysis is that data on the various MSW options were collected from different countries due to the difficulty of finding generalized data, let alone data for Lebanon. Moreover, although AHP is a significant tool that allows the assessment of different options based on many aspects and criteria, it still has some limitations. To start with, AHP is prone to the subjectivity and arbitrariness of the decision makers involved in the analytical process, which might lead to biased judgements. However, upon conducting a sensitivity analysis that allows creating different situations by manipulating the weights assigned to the criteria, this imperfection can be diminished to some extent. Moreover, the number of sub-criteria included in the analytical hierarchy had to be limited in order to avoid further complexity of the procedure. Besides that, at least 15 experts in the waste management sector were contacted, having in mind a target of 10 participants, but only 5 were responsive. This low responsiveness rate is associated with the fact that the pairwise comparison procedure is time consuming and tedious, especially that it usually requires the revision of the matrices more than once in order to ensure the consistency of the comparisons. Other experts refused to participate either due to their opposition to WTE technologies, or to avoid having their names linked to the recommendations presented in the study. It is recommended to expand this exercise to a larger group of participants, yet due to time and budget constraints, the number of participants was limited. Having a larger group of stakeholders and additional or different set of sub-criteria might have affected the final judgement, and consequently result in different recommendations. Keep in mind that AHP is a decision aiding tool rather than a decision making tool, and any investment cannot be solely based on the results of such analyses.

CHAPTER X

CONCLUSION

The increasing generation of MSW can be influenced by policies and regulations that encourage and promote the 3 Rs, in order to start off on the right foot towards achieving an integrated sustainable solid waste management system for AUB campus and its neighborhood. Policies and effective practices can make waste a valuable resource rather than disposable one. The 3 Rs continue to be the cornerstone for any successful waste management system, in addition to sorting at source since the performance of any waste treatment facility greatly relies on the input stream.

In this thesis, the focus was on the waste recovery technologies – anaerobic digestion, gasification, pyrolysis, and incineration – while scrutinizing the environmental, sociocultural, technical, and economic impacts and benefits of these technologies. An AHP approach was presented with the intention of identifying the most suitable waste treatment alternative while providing reliable data for the decision makers to base their judgement on. To ensure the suitability of the proposed waste treatment technology with regard to environmental, sociocultural, technical, and economic criteria, it is fundamental to have a consistent judgmental process. Therefore, the consistency ratio was computed for each pairwise comparison matrix, and in case of obtaining a value greater than 0.1, the decision maker was asked to revise his comparison. In total, five stakeholders participated in this study, and those were chosen due to their strong background in the waste management sector and their interest in the topic.

The results revealed that anaerobic digestion is the most adequate alternative to go forth with. Moreover, the sensitivity analysis employed was evident that anaerobic digestion would still be the first option, even when manipulating the weights assigned to the criteria. The investment in an anaerobic digestion waste treatment facility would somehow reduce the burden of the waste crisis on the government, and could also allow AUB to lead by example through demonstrating a successful waste management strategy, and eventually reduce wastes that end up at landfills. Furthermore, the successful performance of an anaerobic digestion plant, could raise the trust and confidence of the citizens in the worth of energy recovery in the MSW management. Finally, this dissertation serves as a guide for future research, in which further investigations and improvement of input data are recommended. The implementation of a wider analysis which focuses on different areas not covered in this study could pose greater confidence in the results obtained and intensify the worth of adopting waste management technologies.

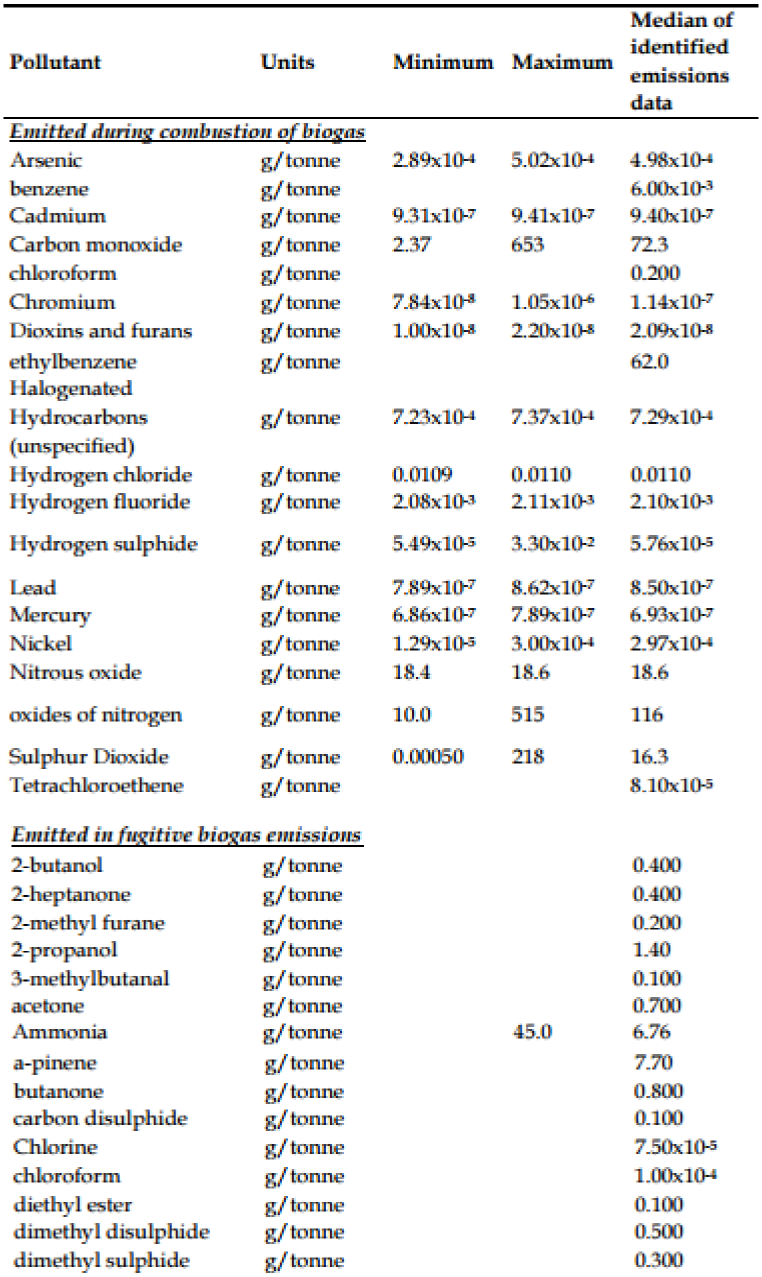
Appendix A:

Characteristics of the Waste Treatment Technologies

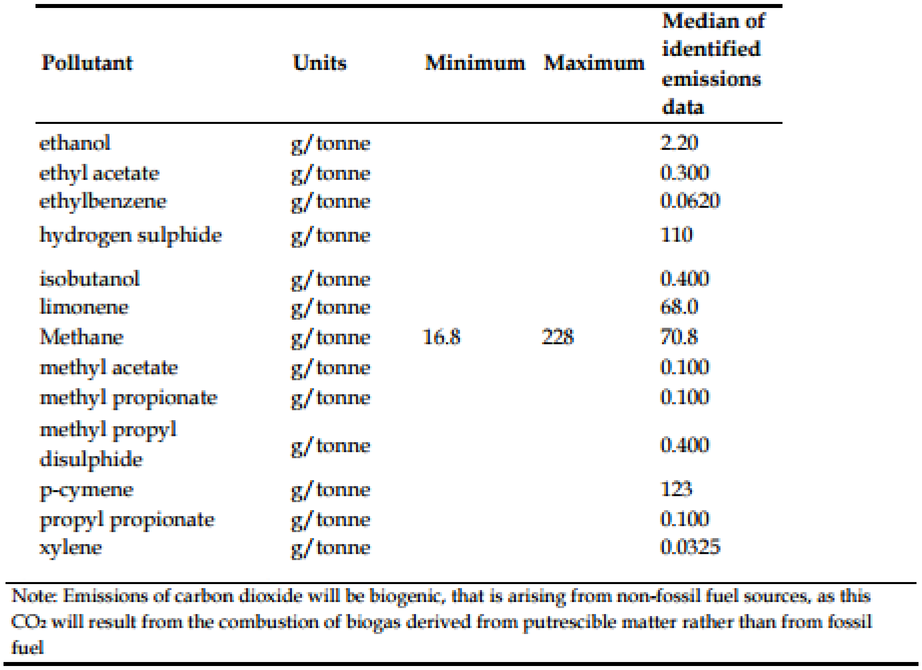
Environmental

- **Air and water pollution:**
    1. Anaerobic Digestion:

Table 30: Pollutant Emissions to Air from Anaerobic Digestion Plants



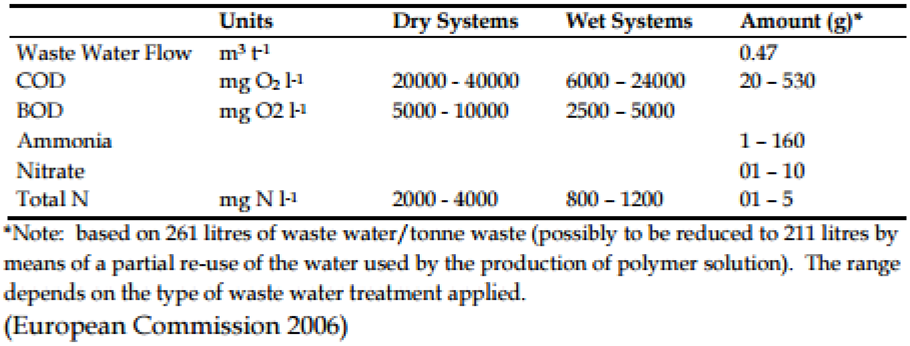
Pollutant	Units	Minimum	Maximum	Median of identified emissions data
Emitted during combustion of biogas				
Arsenic	g/tonne	2.89×10^{-4}	5.02×10^{-4}	4.98×10^{-4}
benzene	g/tonne			6.00×10^{-3}
Cadmium	g/tonne	9.31×10^{-7}	9.41×10^{-7}	9.40×10^{-7}
Carbon monoxide	g/tonne	2.37	653	72.3
chloroform	g/tonne			0.200
Chromium	g/tonne	7.84×10^{-8}	1.05×10^{-6}	1.14×10^{-7}
Dioxins and furans	g/tonne	1.00×10^{-8}	2.20×10^{-8}	2.09×10^{-8}
ethylbenzene	g/tonne			62.0
Halogenated Hydrocarbons (unspecified)	g/tonne	7.23×10^{-4}	7.37×10^{-4}	7.29×10^{-4}
Hydrogen chloride	g/tonne	0.0109	0.0110	0.0110
Hydrogen fluoride	g/tonne	2.08×10^{-3}	2.11×10^{-3}	2.10×10^{-3}
Hydrogen sulphide	g/tonne	5.49×10^{-5}	3.30×10^{-2}	5.76×10^{-5}
Lead	g/tonne	7.89×10^{-7}	8.62×10^{-7}	8.50×10^{-7}
Mercury	g/tonne	6.86×10^{-7}	7.89×10^{-7}	6.93×10^{-7}
Nickel	g/tonne	1.29×10^{-5}	3.00×10^{-4}	2.97×10^{-4}
Nitrous oxide	g/tonne	18.4	18.6	18.6
oxides of nitrogen	g/tonne	10.0	515	116
Sulphur Dioxide	g/tonne	0.00050	218	16.3
Tetrachloroethene	g/tonne			8.10×10^{-5}
Emitted in fugitive biogas emissions				
2-butanol	g/tonne			0.400
2-heptanone	g/tonne			0.400
2-methyl furane	g/tonne			0.200
2-propanol	g/tonne			1.40
3-methylbutanal	g/tonne			0.100
acetone	g/tonne			0.700
Ammonia	g/tonne		45.0	6.76
a-pinene	g/tonne			7.70
butanone	g/tonne			0.800
carbon disulphide	g/tonne			0.100
Chlorine	g/tonne			7.50×10^{-5}
chloroform	g/tonne			1.00×10^{-4}
diethyl ester	g/tonne			0.100
dimethyl disulphide	g/tonne			0.500
dimethyl sulphide	g/tonne			0.300



Pollutant	Units	Minimum	Maximum	Median of identified emissions data
ethanol	g/tonne			2.20
ethyl acetate	g/tonne			0.300
ethylbenzene	g/tonne			0.0620
hydrogen sulphide	g/tonne			110
isobutanol	g/tonne			0.400
limonene	g/tonne			68.0
Methane	g/tonne	16.8	228	70.8
methyl acetate	g/tonne			0.100
methyl propionate	g/tonne			0.100
methyl propyl disulphide	g/tonne			0.400
p-cymene	g/tonne			123
propyl propionate	g/tonne			0.100
xylene	g/tonne			0.0325

Note: Emissions of carbon dioxide will be biogenic, that is arising from non-fossil fuel sources, as this CO_2 will result from the combustion of biogas derived from putrescible matter rather than from fossil fuel

Table 31: Typical Waste Water Characteristics from Anaerobic Digestion Plants



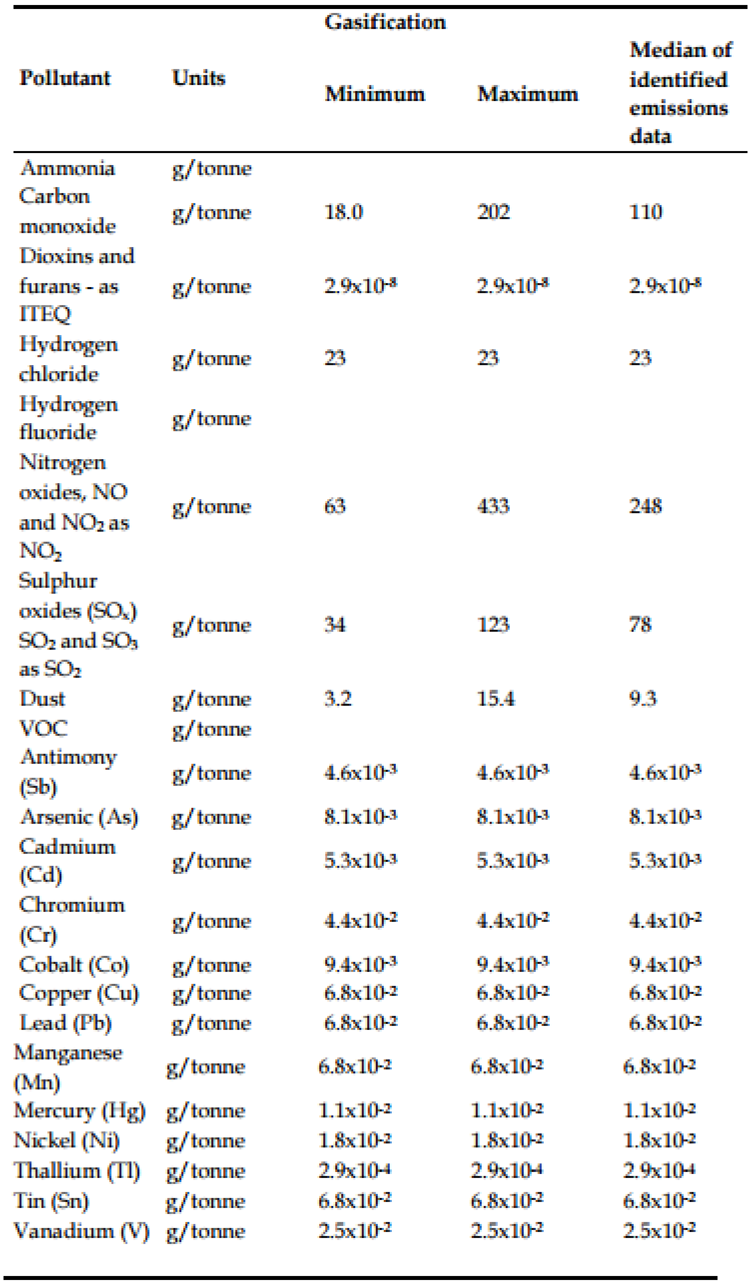
	Units	Dry Systems	Wet Systems	Amount (g)*
Waste Water Flow	$m^3 t^{-1}$			0.47
COD	mg O_2 l^{-1}	20000 - 40000	6000 – 24000	20 – 530
BOD	mg O2 l^{-1}	5000 - 10000	2500 – 5000	
Ammonia				1 – 160
Nitrate				01 – 10
Total N	mg N l^{-1}	2000 - 4000	800 – 1200	01 – 5

*Note: based on 261 litres of waste water/tonne waste (possibly to be reduced to 211 litres by means of a partial re-use of the water used by the production of polymer solution). The range depends on the type of waste water treatment applied.

(European Commission 2006)

2. Gasification:

Table 32: Pollutant Emissions to Air from Gasification Plants



Pollutant	**Units**	**Gasification**		
		Minimum	**Maximum**	**Median of identified emissions data**
Ammonia	g/tonne			
Carbon monoxide	g/tonne	18.0	202	110
Dioxins and furans - as ITEQ	g/tonne	$2.9\text{x}10^{-8}$	$2.9\text{x}10^{-8}$	$2.9\text{x}10^{-8}$
Hydrogen chloride	g/tonne	23	23	23
Hydrogen fluoride	g/tonne			
Nitrogen oxides, NO and NO_2 as NO_2	g/tonne	63	433	248
Sulphur oxides (SO_x) SO_2 and SO_3 as SO_2	g/tonne	34	123	78
Dust	g/tonne	3.2	15.4	9.3
VOC	g/tonne			
Antimony (Sb)	g/tonne	$4.6\text{x}10^{-3}$	$4.6\text{x}10^{-3}$	$4.6\text{x}10^{-3}$
Arsenic (As)	g/tonne	$8.1\text{x}10^{-3}$	$8.1\text{x}10^{-3}$	$8.1\text{x}10^{-3}$
Cadmium (Cd)	g/tonne	$5.3\text{x}10^{-3}$	$5.3\text{x}10^{-3}$	$5.3\text{x}10^{-3}$
Chromium (Cr)	g/tonne	$4.4\text{x}10^{-2}$	$4.4\text{x}10^{-2}$	$4.4\text{x}10^{-2}$
Cobalt (Co)	g/tonne	$9.4\text{x}10^{-3}$	$9.4\text{x}10^{-3}$	$9.4\text{x}10^{-3}$
Copper (Cu)	g/tonne	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$
Lead (Pb)	g/tonne	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$
Manganese (Mn)	g/tonne	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$
Mercury (Hg)	g/tonne	$1.1\text{x}10^{-2}$	$1.1\text{x}10^{-2}$	$1.1\text{x}10^{-2}$
Nickel (Ni)	g/tonne	$1.8\text{x}10^{-2}$	$1.8\text{x}10^{-2}$	$1.8\text{x}10^{-2}$
Thallium (Tl)	g/tonne	$2.9\text{x}10^{-4}$	$2.9\text{x}10^{-4}$	$2.9\text{x}10^{-4}$
Tin (Sn)	g/tonne	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$	$6.8\text{x}10^{-2}$
Vanadium (V)	g/tonne	$2.5\text{x}10^{-2}$	$2.5\text{x}10^{-2}$	$2.5\text{x}10^{-2}$

Pollutant Emissions to Water:

- Many of the systems under the category of gasification and pyrolysis do not produce effluent, since it is reused as part of the process. However, due to the lack of experience of operating MSW gasification and pyrolysis plants, such data are not available. Moreover, "gasification and pyrolysis have significant wastewater impacts: quenching water and water used in cleaning steps is contaminated and generally cannot be released into sewer systems and wastewater treatment plants without additional treatment." (Tellus Institute, 2008).

3. Pyrolysis:

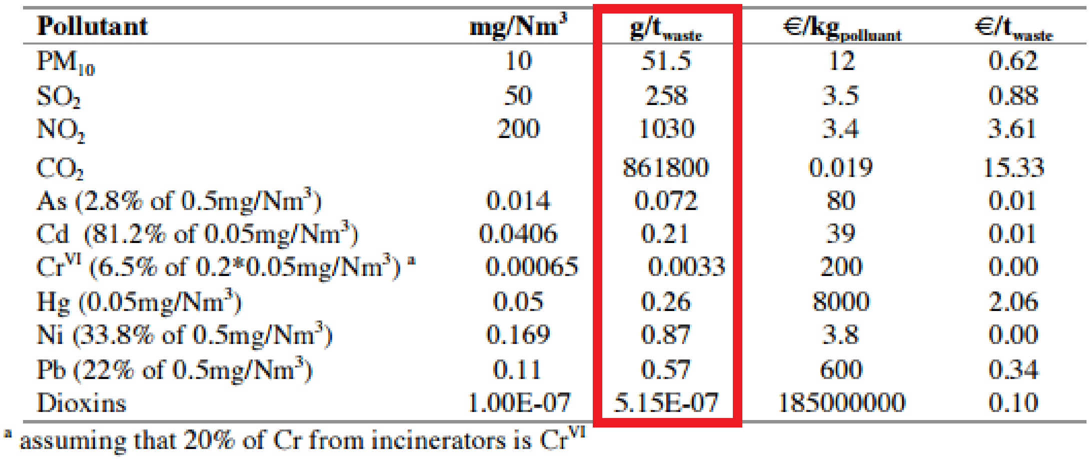
Table 33: Pollutant Emissions to Air from Pyrolysis Plants

Pollutant	Units	Pyrolysis		
		Minimum	Maximum	Median of identified emissions data
Ammonia	g/tonne	1.77	1.82	1.8
Carbon monoxide	g/tonne	3.1	19.1	6.3
Dioxins and furans - as ITEQ	g/tonne	$1.7x10^{-9}$	$3.0x10^{-8}$	$5.8x10^{-9}$
Hydrogen chloride	g/tonne	5.7	29	23
Hydrogen fluoride	g/tonne	0.12	0.68	0.34
Nitrogen oxides, NO and NO_2 as NO_2	g/tonne	19	939	348
Sulphur oxides (SO_x) SO_2 and SO_3 as SO_2	g/tonne	1.5	126	82
Dust	g/tonne	1.2	7.9	2.4
VOC	g/tonne	2.1	2.1	2.1
Antimony (Sb)	g/tonne	$4.7x10^{-3}$	$6.0x10^{-3}$	$5.3x10^{-3}$
Arsenic (As)	g/tonne	$8.3x10^{-3}$	$6.0x10^{-2}$	$4.5x10^{-2}$
Cadmium (Cd)	g/tonne	$5.5x10^{-3}$	$1.7x10^{-2}$	$6.9x10^{-3}$
Chromium (Cr)	g/tonne	$4.5x10^{-2}$	$6.4x10^{-2}$	$6.2x10^{-2}$
Cobalt (Co)	g/tonne	$5.6x10^{-3}$	$9.7x10^{-3}$	$7.7x10^{-3}$
Copper (Cu)	g/tonne	$1.1x10^{-2}$	$1.3x10^{-1}$	$1.2x10^{-2}$
Lead (Pb)	g/tonne	$1.4x10^{-1}$	$2.6x10^{-1}$	$1.4x10^{-1}$
Manganese (Mn)	g/tonne	$1.7x10^{-2}$	$1.5x10^{-1}$	$1.7x10^{-2}$
Mercury (Hg)	g/tonne	$1.2x10^{-2}$	$6.9x10^{-2}$	$4.1x10^{-2}$
Nickel (Ni)	g/tonne	$1.1x10^{-2}$	$4.0x10^{-2}$	$1.8x10^{-2}$
Thallium (Tl)	g/tonne	$3.2x10^{-4}$	$1.7x10^{-2}$	$8.7x10^{-3}$
Tin (Sn)	g/tonne	$8.1x10^{-2}$	$8.1x10^{-2}$	$8.1x10^{-2}$
Vanadium (V)	g/tonne	$1.7x10^{-2}$	$2.6x10^{-2}$	$1.7x10^{-2}$

Pollutant Emissions to Water: (see gasification section)

4. Incineration:

Table 34: Pollutant Emissions to Air from Incineration Plants (Rabl, et al., 2008)



Pollutant	**mg/Nm^3**	**g/t$_{waste}$**	**€/kg$_{pollutant}$**	**€/t$_{waste}$**
PM$_{10}$	10	51.5	12	0.62
SO$_2$	50	258	3.5	0.88
NO$_2$	200	1030	3.4	3.61
CO$_2$		861800	0.019	15.33
As (2.8% of 0.5mg/Nm^3)	0.014	0.072	80	0.01
Cd (81.2% of 0.05mg/Nm^3)	0.0406	0.21	39	0.01
Cr^{VI} (6.5% of 0.2*0.05mg/Nm^3) [a]	0.00065	0.0033	200	0.00
Hg (0.05mg/Nm^3)	0.05	0.26	8000	2.06
Ni (33.8% of 0.5mg/Nm^3)	0.169	0.87	3.8	0.00
Pb (22% of 0.5mg/Nm^3)	0.11	0.57	600	0.34
Dioxins	1.00E-07	5.15E-07	185000000	0.10

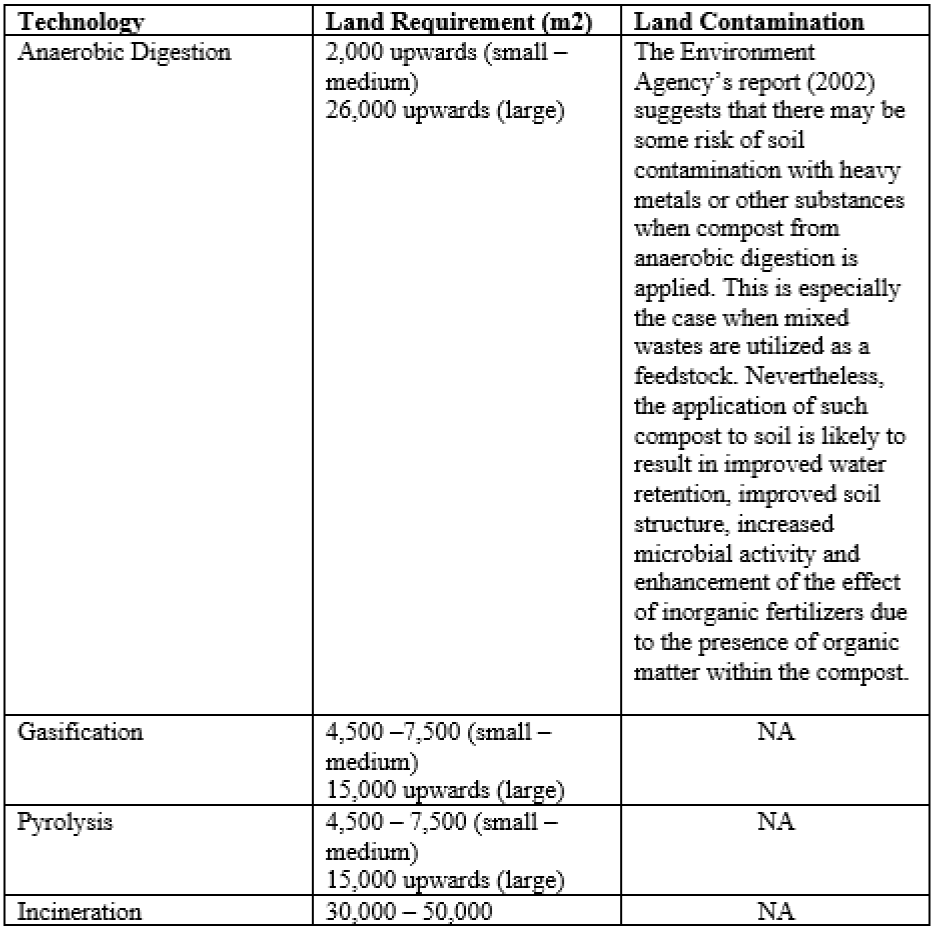
[a] assuming that 20% of Cr from incinerators is Cr^{VI}

Pollutant Emissions to Water:

No direct emissions from incinerators to water.

- **Land requirement and contamination:**

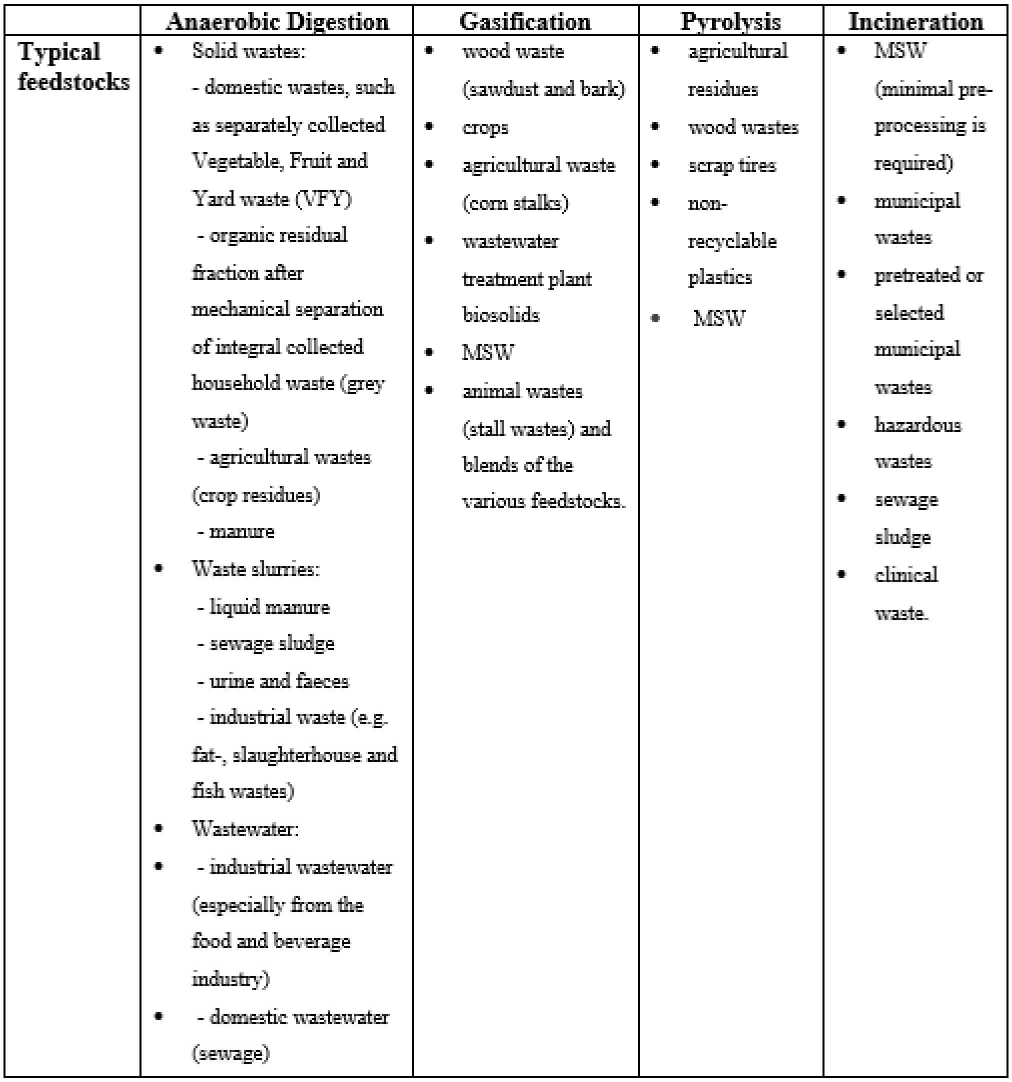
Table 35: Land Requirement and Contamination of the Different Waste Treatment Technologies (SLR, 2004; Monnet, 2003)



Technology	Land Requirement (m2)	Land Contamination
Anaerobic Digestion	2,000 upwards (small – medium) 26,000 upwards (large)	The Environment Agency's report (2002) suggests that there may be some risk of soil contamination with heavy metals or other substances when compost from anaerobic digestion is applied. This is especially the case when mixed wastes are utilized as a feedstock. Nevertheless, the application of such compost to soil is likely to result in improved water retention, improved soil structure, increased microbial activity and enhancement of the effect of inorganic fertilizers due to the presence of organic matter within the compost.
Gasification	4,500 –7,500 (small – medium) 15,000 upwards (large)	NA
Pyrolysis	4,500 – 7,500 (small – medium) 15,000 upwards (large)	NA
Incineration	30,000 – 50,000	NA

- **Waste Coverage and Elimination:**

Table 36: Waste Coverage and Elimination of the Different Waste Treatment Technologies (Mes, et al., 2003; Gasification Technologies Council, 2014; Zafar, 2015; Stantec, 2010; European Commission, 2006)

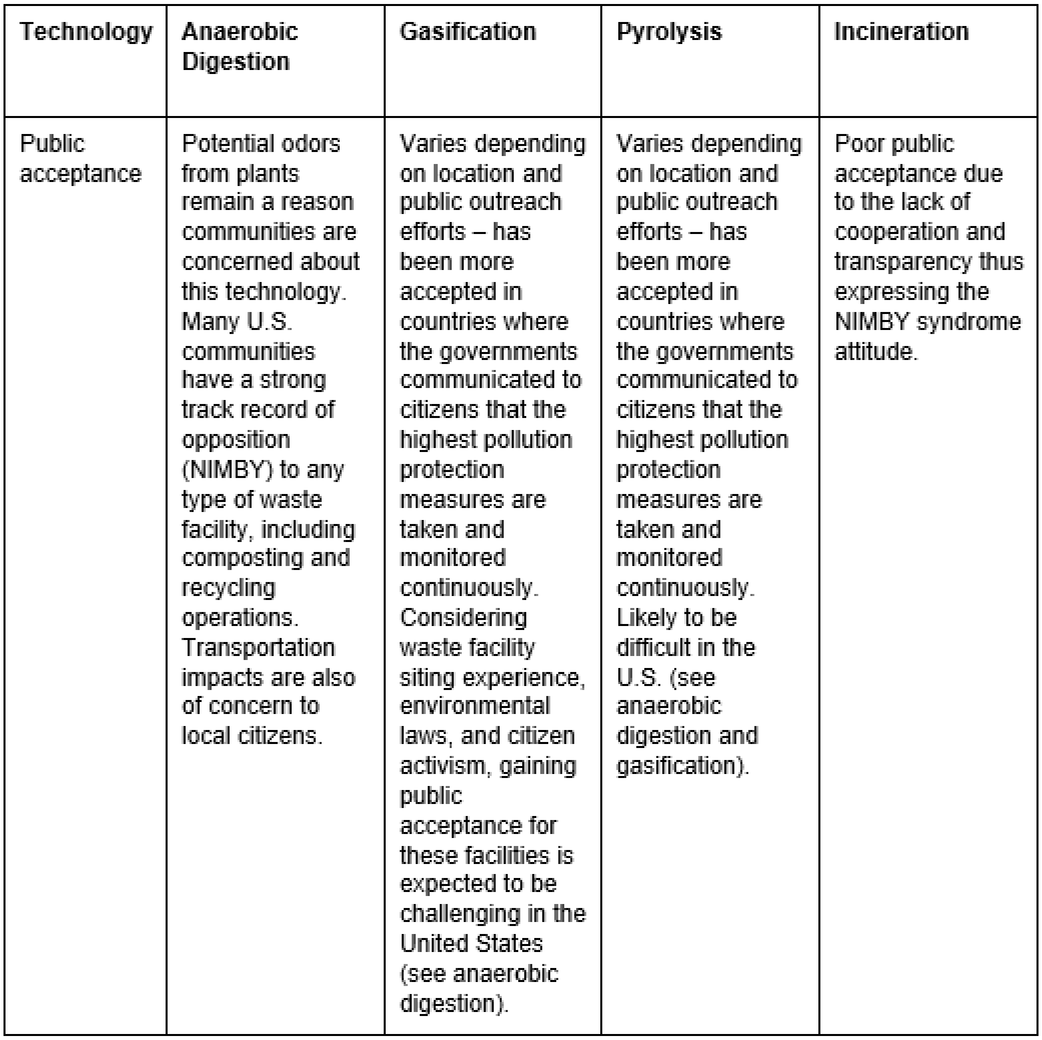


	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**
Typical feedstocks	• Solid wastes: - domestic wastes, such as separately collected Vegetable, Fruit and Yard waste (VFY) - organic residual fraction after mechanical separation of integral collected household waste (grey waste) - agricultural wastes (crop residues) - manure • Waste slurries: - liquid manure - sewage sludge - urine and faeces - industrial waste (e.g. fat-, slaughterhouse and fish wastes) • Wastewater: • - industrial wastewater (especially from the food and beverage industry) • - domestic wastewater (sewage)	• wood waste (sawdust and bark) • crops • agricultural waste (corn stalks) • wastewater treatment plant biosolids • MSW • animal wastes (stall wastes) and blends of the various feedstocks.	• agricultural residues • wood wastes • scrap tires • non-recyclable plastics • MSW	• MSW (minimal pre-processing is required) • municipal wastes • pretreated or selected municipal wastes • hazardous wastes • sewage sludge • clinical waste.

Socio-Cultural

- **Public Acceptance:**

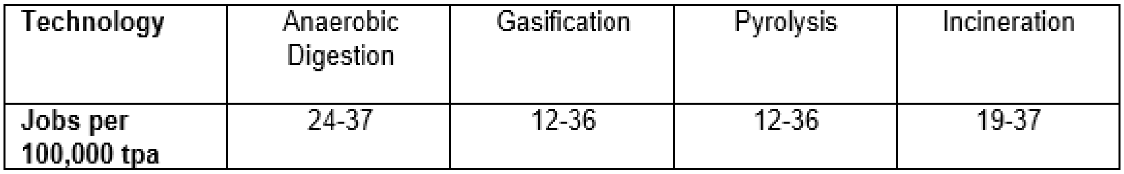
Table 37: Public Acceptance of the Different Waste Treatment Technologies (Tellus Institute, 2008; Coolsweep, 2015; Ministry of Ecology and Sustaiable Development, 2004)



Technology	Anaerobic Digestion	Gasification	Pyrolysis	Incineration
Public acceptance	Potential odors from plants remain a reason communities are concerned about this technology. Many U.S. communities have a strong track record of opposition (NIMBY) to any type of waste facility, including composting and recycling operations. Transportation impacts are also of concern to local citizens.	Varies depending on location and public outreach efforts – has been more accepted in countries where the governments communicated to citizens that the highest pollution protection measures are taken and monitored continuously. Considering waste facility siting experience, environmental laws, and citizen activism, gaining public acceptance for these facilities is expected to be challenging in the United States (see anaerobic digestion).	Varies depending on location and public outreach efforts – has been more accepted in countries where the governments communicated to citizens that the highest pollution protection measures are taken and monitored continuously. Likely to be difficult in the U.S. (see anaerobic digestion and gasification).	Poor public acceptance due to the lack of cooperation and transparency thus expressing the NIMBY syndrome attitude.

- **Employment and Job Creation:**

Table 38: Job Creation Potential per 100,000 tpa of the Different Waste Treatment Technologies (Cant, 2006; Defra, 2005; Vernon & George, 2001)



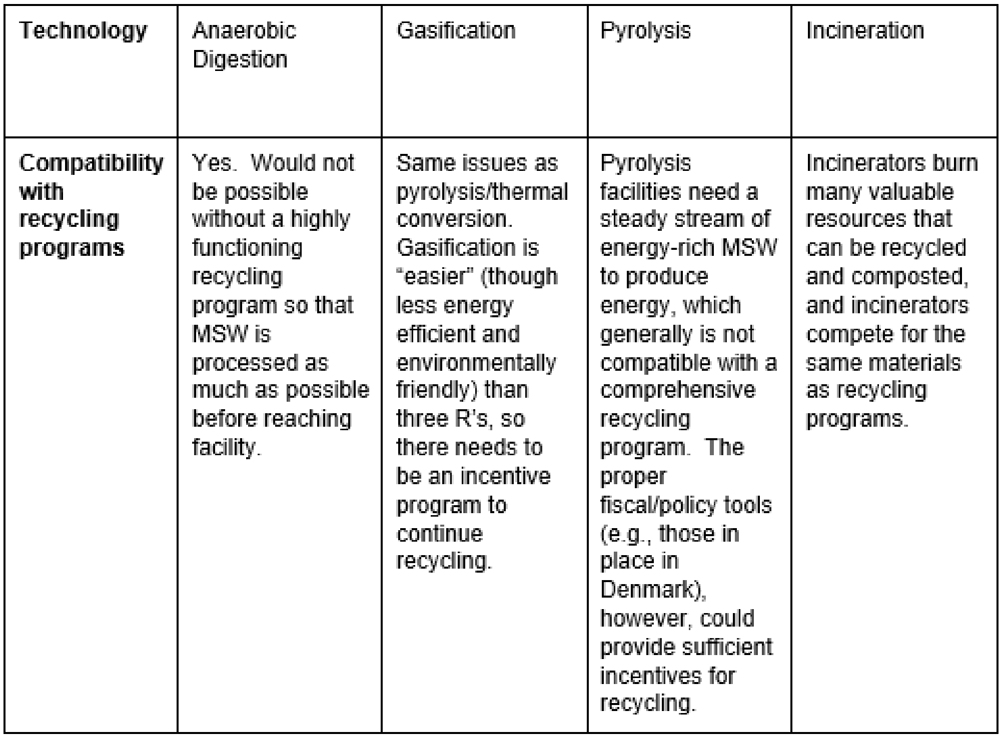
Technology	Anaerobic Digestion	Gasification	Pyrolysis	Incineration
Jobs per 100,000 tpa	24-37	12-36	12-36	19-37

*Jobs created for the operation of the plant only. Jobs created from plant construction and waste collection are not taken into account.

Technical

- **Compatibility with Existing Systems/Recycling Programs:**

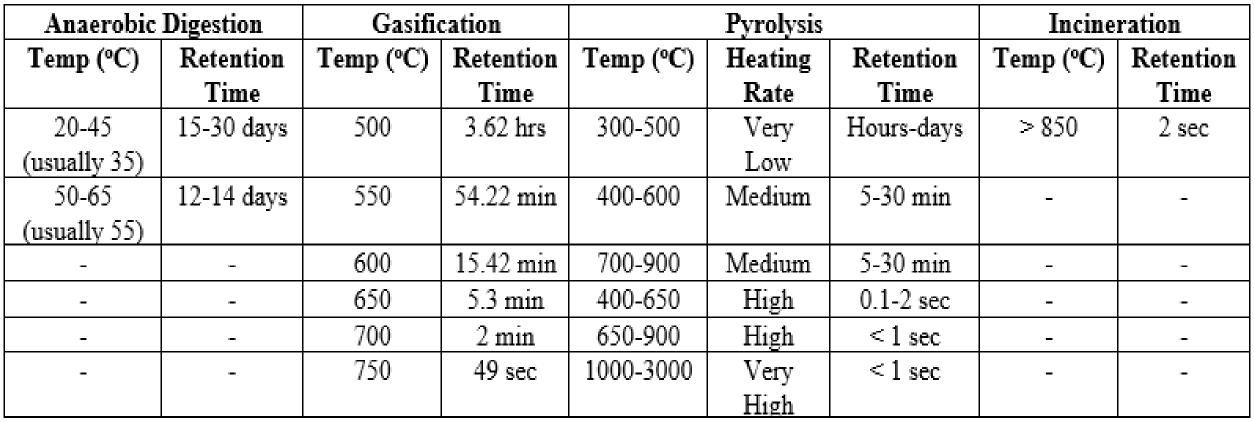
Table 39: Compatibility of the Different Waste Treatment Technologies with Recycling Programs (Tellus Institute, 2008; GAIA, 2012)



Technology	Anaerobic Digestion	Gasification	Pyrolysis	Incineration
Compatibility with recycling programs	Yes. Would not be possible without a highly functioning recycling program so that MSW is processed as much as possible before reaching facility.	Same issues as pyrolysis/thermal conversion. Gasification is "easier" (though less energy efficient and environmentally friendly) than three R's, so there needs to be an incentive program to continue recycling.	Pyrolysis facilities need a steady stream of energy-rich MSW to produce energy, which generally is not compatible with a comprehensive recycling program. The proper fiscal/policy tools (e.g., those in place in Denmark), however, could provide sufficient incentives for recycling.	Incinerators burn many valuable resources that can be recycled and composted, and incinerators compete for the same materials as recycling programs.

- **Retention Time:**

Table 40: Retention Time of the Different Waste Treatment Technologies (Monnet, 2003; Williams, 2012; Sahraei & Akhlaghi, 2011; Defra, 2013)

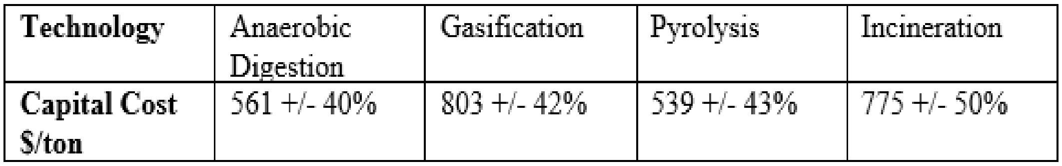


Anaerobic Digestion		**Gasification**		**Pyrolysis**			**Incineration**	
Temp (°C)	**Retention Time**	**Temp (°C)**	**Retention Time**	**Temp (°C)**	**Heating Rate**	**Retention Time**	**Temp (°C)**	**Retention Time**
20-45 (usually 35)	15-30 days	500	3.62 hrs	300-500	Very Low	Hours-days	> 850	2 sec
50-65 (usually 55)	12-14 days	550	54.22 min	400-600	Medium	5-30 min	-	-
-	-	600	15.42 min	700-900	Medium	5-30 min	-	-
-	-	650	5.3 min	400-650	High	0.1-2 sec	-	-
-	-	700	2 min	650-900	High	< 1 sec	-	-
-	-	750	49 sec	1000-3000	Very High	< 1 sec	-	-

Economic

- **Capital Cost:**

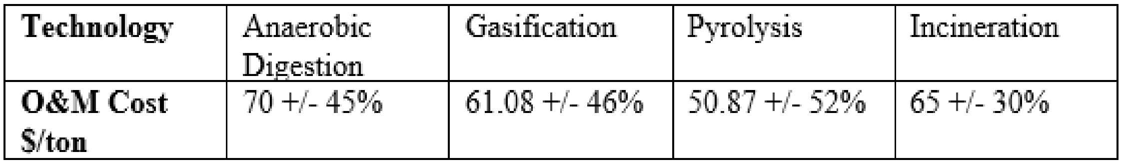
Table 41: Capital Cost of the Different Waste Treatment Technologies (Moriarty, 2013; Santec, 2010)



Technology	Anaerobic Digestion	Gasification	Pyrolysis	Incineration
Capital Cost $/ton	561 +/- 40%	803 +/- 42%	539 +/- 43%	775 +/- 50%

- **O&M Cost:**

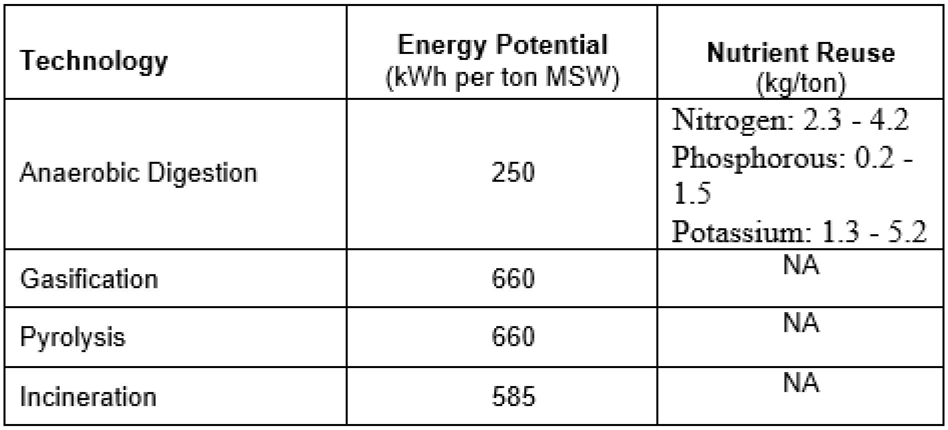
Table 42: O&M Cost of the Different Waste Treatment Technologies (Moriarty, 2013; Santec, 2010)



Technology	Anaerobic Digestion	Gasification	Pyrolysis	Incineration
O&M Cost $/ton	70 +/- 45%	61.08 +/- 46%	50.87 +/- 52%	65 +/- 30%

- **Resource Recovery; i.e. Nutrient Reuse & Energy Recovery:**

Table 43: Energy Recovery and Nutrient Reuse of the Different Waste Treatment Technologies (Tellus Institute, 2008; Pell Frischmann, 2012)



Technology	**Energy Potential** (kWh per ton MSW)	**Nutrient Reuse** (kg/ton)
Anaerobic Digestion	250	Nitrogen: 2.3 - 4.2 Phosphorous: 0.2 - 1.5 Potassium: 1.3 - 5.2
Gasification	660	NA
Pyrolysis	660	NA
Incineration	585	NA

Appendix B:
Pairwise Comparisons of Decision Makers

<u>Decision maker: Dr. Arlette Lteif</u>

Table 44: Pairwise Comparison Matrix of the Main Criteria

	Environmental	Sociocultural	Technical	Economic	Priorities	CR
Environmental	1	4	7	3	0.575	8%
Sociocultural	1/4	1	4	2	0.187	
Technical	1/7	1/4	1	1/4	0.067	
Economic	1/3	1/2	4	1	0.171	

Table 45: Pairwise Comparison Matrix of Sub-Criteria of Environmental Impact

	Air & Water Pollution	Land Requirement & Contamination	Waste Coverage & Elimination	Priorities	CR
Air & Water Pollution	1	1	8	0.471	0%
Land Requirement & Contamination	1	1	8	0.471	
Waste Coverage &Elimination	1/8	1/8	1	0.059	

Table 46: Pairwise Comparison Matrix of Sub-Criteria of Sociocultural Impact

	Public Acceptance	Employment & Job Creation	Priorities	CR
Public Acceptance	1	1/4	0.200	0%
Employment & Job Creation	4	1	0.800	

Table 47: Pairwise Comparison Matrix of Sub-Criteria of Technical Impact

	Compatibility with Existing Systems/Recycling Programs	Retention Time	Priorities	CR
Compatibility with Existing Systems/Recycling Programs	1	4	0.800	0%
Retention Time	1/4	1	0.200	

Table 48: Pairwise Comparison Matrix of Sub-Criteria of Economic Impact

	Capital & Construction Cost	Operating & Maintenance Cost	Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	Priorities	CR
Capital & Construction Cost	1	1/4	1/6	0.093	3%
Operating & Maintenance Cost	4	1	1	0.445	
Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	6	1	1	0.462	

Environmental Impact Sub-Criteria

Table 49: Pairwise Comparison Matrix for Alternatives wrt Air and Water Pollution

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	4	5	4	0.581	6%
Gasification	1/4	1	2	1	0.157	
Pyrolysis	1/5	1/2	1	2	0.129	
Incineration	1/4	1	1/2	1	0.134	

Table 50: Pairwise Comparison Matrix for Alternatives wrt Land Requirement and Contamination

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	3	3	4	0.521	5%
Gasification	1/3	1	1	3	0.189	
Pyrolysis	1/3	1	1	3	0.189	
Incineration	1/4	1/3	1/3	1	0.101	

Table 51: Pairwise Comparison Matrix for Alternatives wrt Waste Coverage and Elimination

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1	3	1/4	0.158	4%
Gasification	1	1	4	1/4	0.163	
Pyrolysis	1/3	1/4	1	1/7	0.072	
Incineration	4	4	7	1	0.607	

Sociocultural Impact Sub-Criteria

Table 52: Pairwise Comparison Matrix for Alternatives wrt Public Acceptance

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/4	1/5	4	0.103	6%
Gasification	4	1	1	5	0.407	
Pyrolysis	5	1	1	7	0.425	
Incineration	1/4	1/5	1/7	1	0.065	

Table 53: Pairwise Comparison Matrix for Alternatives wrt Employment and Job Creation

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	4	4	1	0.400	0%
Gasification	1/4	1	1	1/4	0.100	
Pyrolysis	1/4	1	1	1/4	0.100	
Incineration	1	4	4	1	0.400	

Technical Impact Sub-Criteria

Table 54: Pairwise Comparison Matrix for Alternatives wrt Compatibility with Existing Systems/Recycling Programs

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	8	7	8	0.713	8%
Gasification	1/8	1	1	3	0.101	
Pyrolysis	1/7	1	1	3	0.110	
Incineration	1/8	1/3	1/3	1	0.076	

Table 55: Pairwise Comparison Matrix for Alternatives wrt Retention Time

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/7	1/7	1/9	0.050	8%
Gasification	7	1	1	1/3	0.195	
Pyrolysis	7	1	1	1/4	0.166	
Incineration	9	3	4	1	0.588	

Economic Impact Sub-Criteria

Table 56: Pairwise Comparison Matrix for Alternatives wrt Capital and Construction Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	8	1/2	7	0.309	7%
Gasification	1/8	1	1/7	1/2	0.063	
Pyrolysis	2	7	1	9	0.568	
Incineration	1/7	2	1/9	1	0.060	

Table 57: Pairwise Comparison Matrix for Alternatives wrt Operating and Maintenance Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/3	1/4	1/2	0.104	4%
Gasification	3	1	1/2	1	0.236	
Pyrolysis	4	2	1	1	0.368	
Incineration	2	1	1	1	0.293	

Table 58: Pairwise Comparison Matrix for Alternatives wrt Resource Recovery, i.e. Nutrient Reuse and Energy Recovery

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	1/7	1/7	1/6	0.052	4%
Gasification	7	1	1	3	0.402	
Pyrolysis	7	1	1	3	0.402	
Incineration	6	1/3	1/3	1	0.143	

Decision maker: Dr. Hassan Harajli

Table 59: Pairwise Comparison Matrix of the Main Criteria

	Environmental	**Sociocultural**	**Technical**	**Economic**	Priorities	CR
Environmental	1	3	1	2	0.359	6%
Sociocultural	1/3	1	1/3	1/5	0.092	
Technical	1	3	1	1	0.299	
Economic	1/2	5	1	1	0.251	

Table 60: Pairwise Comparison Matrix of Sub-Criteria of Environmental Impact

	Air & Water Pollution	**Land Requirement & Contamination**	**Waste Coverage & Elimination**	Priorities	CR
Air & Water Pollution	1	3	2	0.545	2%
Land Requirement & Contamination	1/3	1	1	0.203	
Waste Coverage &Elimination	1/2	1	1	0.252	

Table 61: Pairwise Comparison Matrix of Sub-Criteria of Sociocultural Impact

	Public Acceptance	**Employment & Job Creation**	Priorities	CR
Public Acceptance	1	2	0.667	0%
Employment & Job Creation	1/2	1	0.333	

Table 62: Pairwise Comparison Matrix of Sub-Criteria of Technical Impact

	Compatibility with Existing Systems/Recycling Programs	**Retention Time**	Priorities	CR
Compatibility with Existing Systems/Recycling Programs	1	3	0.750	0%
Retention Time	1/3	1	0.250	

Table 63: Pairwise Comparison Matrix of Sub-Criteria of Economic Impact

	Capital & Construction Cost	Operating & Maintenance Cost	Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	Priorities	CR
Capital & Construction Cost	1	2	2	0.500	0%
Operating & Maintenance Cost	1/2	1	1	0.250	
Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	1/2	1	1	0.250	

Environmental Impact Sub-Criteria

Table 64: Pairwise Comparison Matrix for Alternatives wrt Air and Water Pollution

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	5	6	9	0.674	6%
Gasification	1/5	1	1	4	0.139	
Pyrolysis	1/6	1	1	4	0.124	
Incineration	1/9	1/4	1/4	1	0.063	

Table 65: Pairwise Comparison Matrix for Alternatives wrt Land Requirement and Contamination

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/5	1/5	5	0.095	7%
Gasification	5	1	1	7	0.424	
Pyrolysis	5	1	1	7	0.424	
Incineration	1/5	1/7	1/7	1	0.056	

Table 66: Pairwise Comparison Matrix for Alternatives wrt Waste Coverage and Elimination

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/2	1/3	1/6	0.085	8%
Gasification	2	1	1/2	1/3	0.166	
Pyrolysis	3	2	1	1/5	0.165	
Incineration	6	3	5	1	0.583	

Sociocultural Impact Sub-Criteria

Table 67: Pairwise Comparison Matrix for Alternatives wrt Public Acceptance

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	3	3	5	0.534	2%
Gasification	1/3	1	1	2	0.182	
Pyrolysis	1/3	1	1	1	0.169	
Incineration	1/5	1/2	1	1	0.115	

Table 68: Pairwise Comparison Matrix for Alternatives wrt Employment and Job Creation

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	4	4	2	0.500	1%
Gasification	1/4	1	1	1/3	0.113	
Pyrolysis	1/4	1	1	1/3	0.113	
Incineration	1/2	3	3	1	0.275	

Technical Impact Sub-Criteria

Table 69: Pairwise Comparison Matrix for Alternatives wrt Compatibility with Existing Systems/Recycling Programs

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	2	3	4	0.476	7%
Gasification	1/2	1	1/2	3	0.205	
Pyrolysis	1/3	2	1	2	0.217	
Incineration	1/4	1/3	1/2	1	0.102	

Table 70: Pairwise Comparison Matrix for Alternatives wrt Retention Time

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/5	1/4	1/9	0.060	9%
Gasification	5	1	1/2	1/5	0.130	
Pyrolysis	4	2	1	1/5	0.154	
Incineration	9	5	5	1	0.656	

Economic Impact Sub-Criteria

Table 71: Pairwise Comparison Matrix for Alternatives wrt Capital and Construction Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	7	1/2	6	0.304	4%
Gasification	1/7	1	1/8	1/2	0.059	
Pyrolysis	2	8	1	7	0.564	
Incineration	1/6	2	1/7	1	0.072	

Table 72: Pairwise Comparison Matrix for Alternatives wrt Operating and Maintenance Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/5	1/8	1/3	0.066	8%
Gasification	5	1	1/4	3	0.188	
Pyrolysis	8	4	1	6	0.644	
Incineration	3	1/3	1/6	1	0.102	

Table 73: Pairwise Comparison Matrix for Alternatives wrt Resource Recovery, i.e. Nutrient Reuse and Energy Recovery

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/3	1/3	1/2	0.112	0%
Gasification	3	1	1	2	0.353	
Pyrolysis	3	1	1	2	0.353	
Incineration	2	1/2	1/2	1	0.183	

Decision maker: Dr. Najat Saliba

Table 74: Pairwise Comparison Matrix of the Main Criteria

	Environmental	**Sociocultural**	**Technical**	**Economic**	Priorities	CR
Environmental	1	9	9	9	0.745	8%
Sociocultural	1/9	1	1/3	1/3	0.072	
Technical	1/9	3	1	1	0.092	
Economic	1/9	3	1	1	0.092	

Table 75: Pairwise Comparison Matrix of Sub-Criteria of Environmental Impact

	Air & Water Pollution	**Land Requirement & Contamination**	**Waste Coverage & Elimination**	Priorities	CR
Air & Water Pollution	1	9	9	0.818	0%
Land Requirement & Contamination	1/9	1	1	0.091	
Waste Coverage & Elimination	1/9	1	1	0.091	

Table 76: Pairwise Comparison Matrix of Sub-Criteria of Sociocultural Impact

	Public Acceptance	**Employment & Job Creation**	Priorities	CR
Public Acceptance	1	1/7	0.125	0%
Employment & Job Creation	7	1	0.875	

Table 77: Pairwise Comparison Matrix of Sub-Criteria of Technical Impact

	Compatibility with Existing Systems/Recycling Programs	**Retention Time**	Priorities	CR
Compatibility with Existing Systems/Recycling Programs	1	9	0.900	0%
Retention Time	1/9	1	0.100	

Table 78: Pairwise Comparison Matrix of Sub-Criteria of Economic Impact

	Capital & Construction Cost	**Operating & Maintenance Cost**	**Resource Recovery, i.e. Nutrient Reuse & Energy Recovery**	Priorities	CR
Capital & Construction Cost	1	1/8	1/7	0.066	5%
Operating & Maintenance Cost	8	1	2	0.614	
Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	7	1/2	1	0.320	

Environmental Impact Sub-Criteria

Table 79: Pairwise Comparison Matrix for Alternatives wrt Air and Water Pollution

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	5	7	9	0.682	9%
Gasification	1/5	1	3	5	0.161	
Pyrolysis	1/7	1/3	1	3	0.094	
Incineration	1/9	1/5	1/3	1	0.063	

Table 80: Pairwise Comparison Matrix for Alternatives wrt Land Requirement and Contamination

	Anaerobic Digestion	**Gasification**	**Pyrolysis**	**Incineration**	Priorities	CR
Anaerobic Digestion	1	6	6	9	0.689	7%
Gasification	1/6	1	1	4	0.124	
Pyrolysis	1/6	1	1	4	0.124	
Incineration	1/9	1/4	1/4	1	0.064	

Table 81: Pairwise Comparison Matrix for Alternatives wrt Waste Coverage and Elimination

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/6	1/6	1/7	0.059	7%
Gasification	6	1	1	1/3	0.195	
Pyrolysis	6	1	1	1/3	0.195	
Incineration	7	3	3	1	0.552	

Sociocultural Impact Sub-Criteria

Table 82: Pairwise Comparison Matrix for Alternatives wrt Public Acceptance

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1	1	1	0.250	0%
Gasification	1	1	1	1	0.250	
Pyrolysis	1	1	1	1	0.250	
Incineration	1	1	1	1	0.250	

Table 83: Pairwise Comparison Matrix for Alternatives wrt Employment and Job Creation

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	5	5	5	0.625	0%
Gasification	1/5	1	1	1	0.125	
Pyrolysis	1/5	1	1	1	0.125	
Incineration	1/5	1	1	1	0.125	

Technical Impact Sub-Criteria

Table 84: Pairwise Comparison Matrix for Alternatives wrt Compatibility with Existing Systems/Recycling Programs

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	9	9	9	0.750	0%
Gasification	1/9	1	1	1	0.083	
Pyrolysis	1/9	1	1	1	0.083	
Incineration	1/9	1	1	1	0.083	

Table 85: Pairwise Comparison Matrix for Alternatives wrt Retention Time

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	7	7	7	0.700	0%
Gasification	1/7	1	1	1	0.100	
Pyrolysis	1/7	1	1	1	0.100	
Incineration	1/7	1	1	1	0.100	

Economic Impact Sub-Criteria

Table 86: Pairwise Comparison Matrix for Alternatives wrt Capital and Construction Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	9	9	9	0.750	0%
Gasification	1/9	1	1	1	0.083	
Pyrolysis	1/9	1	1	1	0.083	
Incineration	1/9	1	1	1	0.083	

Table 87: Pairwise Comparison Matrix for Alternatives wrt Operating and Maintenance Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	9	9	9	0.750	0%
Gasification	1/9	1	1	1	0.083	
Pyrolysis	1/9	1	1	1	0.083	
Incineration	1/9	1	1	1	0.083	

Table 88: Pairwise Comparison Matrix for Alternatives wrt Resource Recovery, i.e. Nutrient Reuse and Energy Recovery

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	9	9	9	0.750	0%
Gasification	1/9	1	1	1	0.083	
Pyrolysis	1/9	1	1	1	0.083	
Incineration	1/9	1	1	1	0.083	

Decision maker: Mr. Farouk Merhebi

Table 89: Pairwise Comparison Matrix of the Main Criteria

	Environmental	Sociocultural	Technical	Economic	Priorities	CR
Environmental	1	6	3	3	0.543	8%
Sociocultural	1/6	1	1/7	1/3	0.071	
Technical	1/3	7	1	1	0.202	
Economic	1/3	3	1	1	0.185	

Table 90: Pairwise Comparison Matrix of Sub-Criteria of Environmental Impact

	Air & Water Pollution	Land Requirement &Contamination	Waste Coverage & Elimination	Priorities	CR
Air & Water Pollution	1	3	7	0.677	1%
Land Requirement & Contamination	1/3	1	3	0.231	
Waste Coverage & Elimination	1/7	1/3	1	0.092	

Table 91: Pairwise Comparison Matrix of Sub-Criteria of Sociocultural Impact

	Public Acceptance	Employment & Job Creation	Priorities	CR
Public Acceptance	1	1/2	0.333	0%
Employment & Job Creation	2	1	0.667	

Table 92: Pairwise Comparison Matrix of Sub-Criteria of Technical Impact

	Compatibility with Existing Systems/Recycling Programs	Retention Time	Priorities	CR
Compatibility with Existing Systems/Recycling Programs	1	3	0.750	0%
Retention Time	1/3	1	0.250	

Table 93: Pairwise Comparison Matrix of Sub-Criteria of Economic Impact

	Capital & Construction Cost	Operating & Maintenance Cost	Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	Priorities	CR
Capital & Construction Cost	1	1/3	1/4	0.134	8%
Operating & Maintenance Cost	3	1	1/3	0.237	
Resource Recovery, i.e. Nutrient Reuse & Energy Recovery	4	3	1	0.628	

Environmental Impact Sub-Criteria

Table 94: Pairwise Comparison Matrix for Alternatives wrt Air and Water Pollution

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/3	1/3	5	0.141	3%
Gasification	3	1	1	7	0.403	
Pyrolysis	3	1	1	7	0.403	
Incineration	1/5	1/7	1/7	1	0.053	

Table 95: Pairwise Comparison Matrix for Alternatives wrt Land Requirement and Contamination

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/3	1/3	1/5	0.088	2%
Gasification	3	1	1	1/3	0.188	
Pyrolysis	3	1	1	1/3	0.188	
Incineration	5	3	3	1	0.535	

Table 96: Pairwise Comparison Matrix for Alternatives wrt Waste Coverage and Elimination

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/3	1/3	1/6	0.077	0%
Gasification	3	1	1	1/2	0.231	
Pyrolysis	3	1	1	1/2	0.231	
Incineration	6	2	2	1	0.462	

Sociocultural Impact Sub-Criteria

Table 97: Pairwise Comparison Matrix for Alternatives wrt Public Acceptance

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	3	5	9	0.606	4%
Gasification	1/3	1	3	5	0.224	
Pyrolysis	1/5	1/3	1	3	0.112	
Incineration	1/9	1/5	1/3	1	0.058	

Table 98: Pairwise Comparison Matrix for Alternatives wrt Employment and Job Creation

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	3	3	1/3	0.216	1%
Gasification	1/3	1	1	1/6	0.092	
Pyrolysis	1/3	1	1	1/6	0.092	
Incineration	3	6	6	1	0.599	

Technical Impact Sub-Criteria

Table 99: Pairwise Comparison Matrix for Alternatives wrt Compatibility with Existing Systems/Recycling Programs

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	3	3	6	0.545	1%
Gasification	1/3	1	1	3	0.188	
Pyrolysis	1/3	1	1	3	0.188	
Incineration	1/6	1/3	1/3	1	0.079	

Table 100: Pairwise Comparison Matrix for Alternatives wrt Retention Time

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/5	1/5	1/9	0.058	8%
Gasification	5	1	1/2	1/5	0.127	
Pyrolysis	5	2	1	1/4	0.179	
Incineration	9	5	4	1	0.637	

Economic Impact Sub-Criteria

Table 101: Pairwise Comparison Matrix for Alternatives wrt Capital and Construction Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	5	1	3	0.393	3%
Gasification	1/5	1	1/5	1/3	0.075	
Pyrolysis	1	5	1	4	0.408	
Incineration	1/3	3	1/4	1	0.124	

Table 102: Pairwise Comparison Matrix for Alternatives wrt Operating and Maintenance Cost

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/3	1/5	1/2	0.094	2%
Gasification	3	1	1/3	1	0.190	
Pyrolysis	5	3	1	3	0.535	
Incineration	2	1	1/3	1	0.181	

Table 103: Pairwise Comparison Matrix for Alternatives wrt Resource Recovery, i.e. Nutrient Reuse and Energy Recovery

	Anaerobic Digestion	Gasification	Pyrolysis	Incineration	Priorities	CR
Anaerobic Digestion	1	1/5	1/5	1/4	0.072	4%
Gasification	5	1	1	3	0.393	
Pyrolysis	5	1	1	3	0.393	
Incineration	4	1/3	1/3	1	0.142	

Appendix C:

Sample of the Overall Priority Synthesis

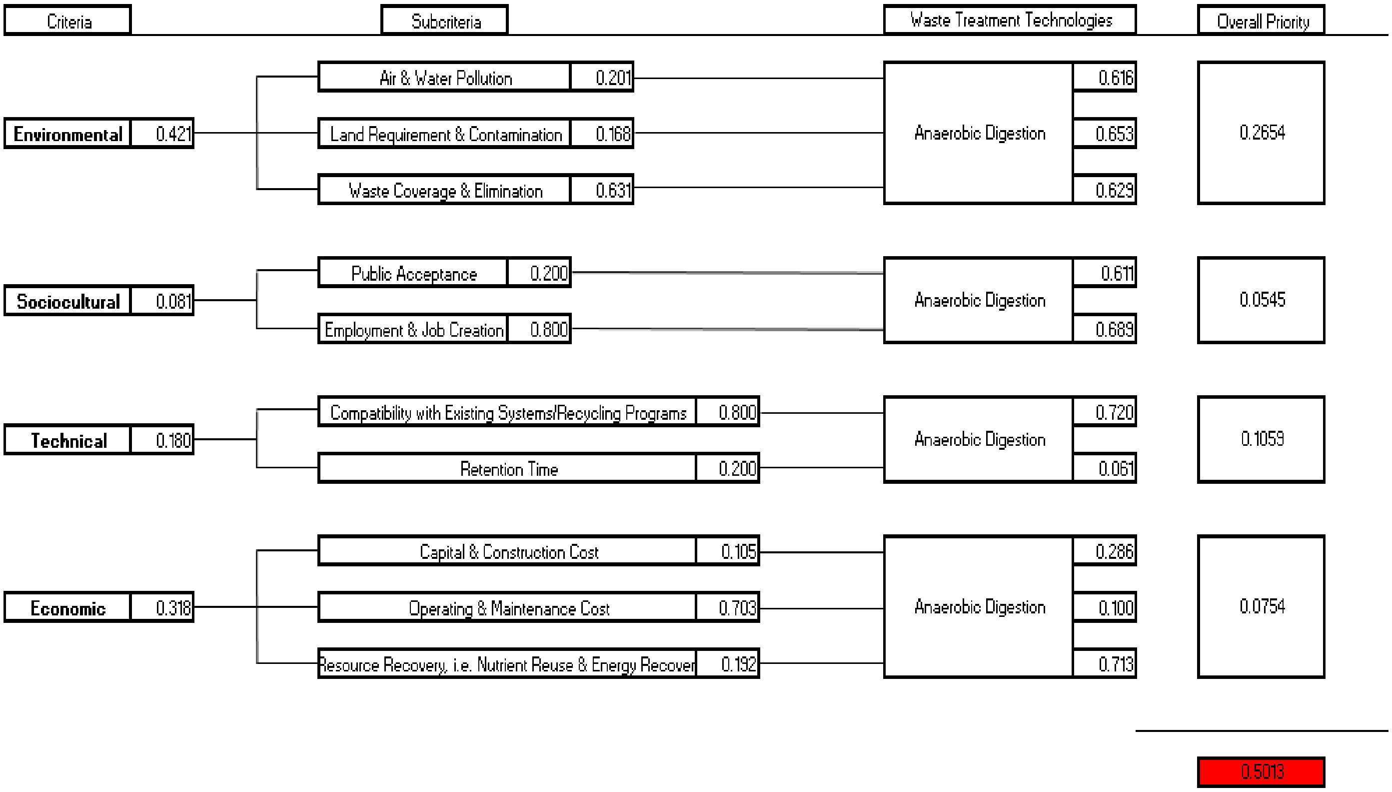


Figure 23: Overall Priority Synthesis of Anaerobic Digestion

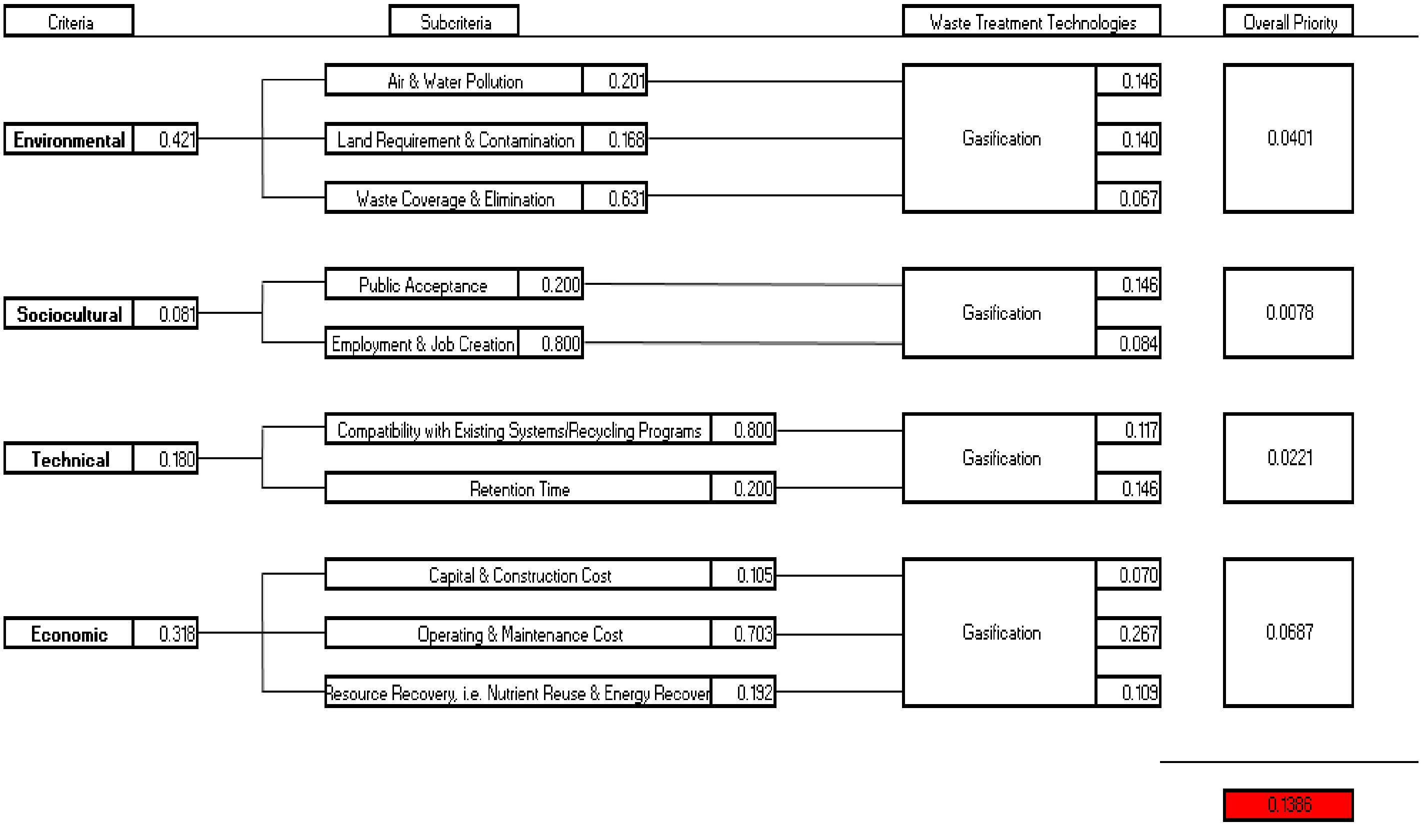


Figure 24: Overall Priority Synthesis of Gasification

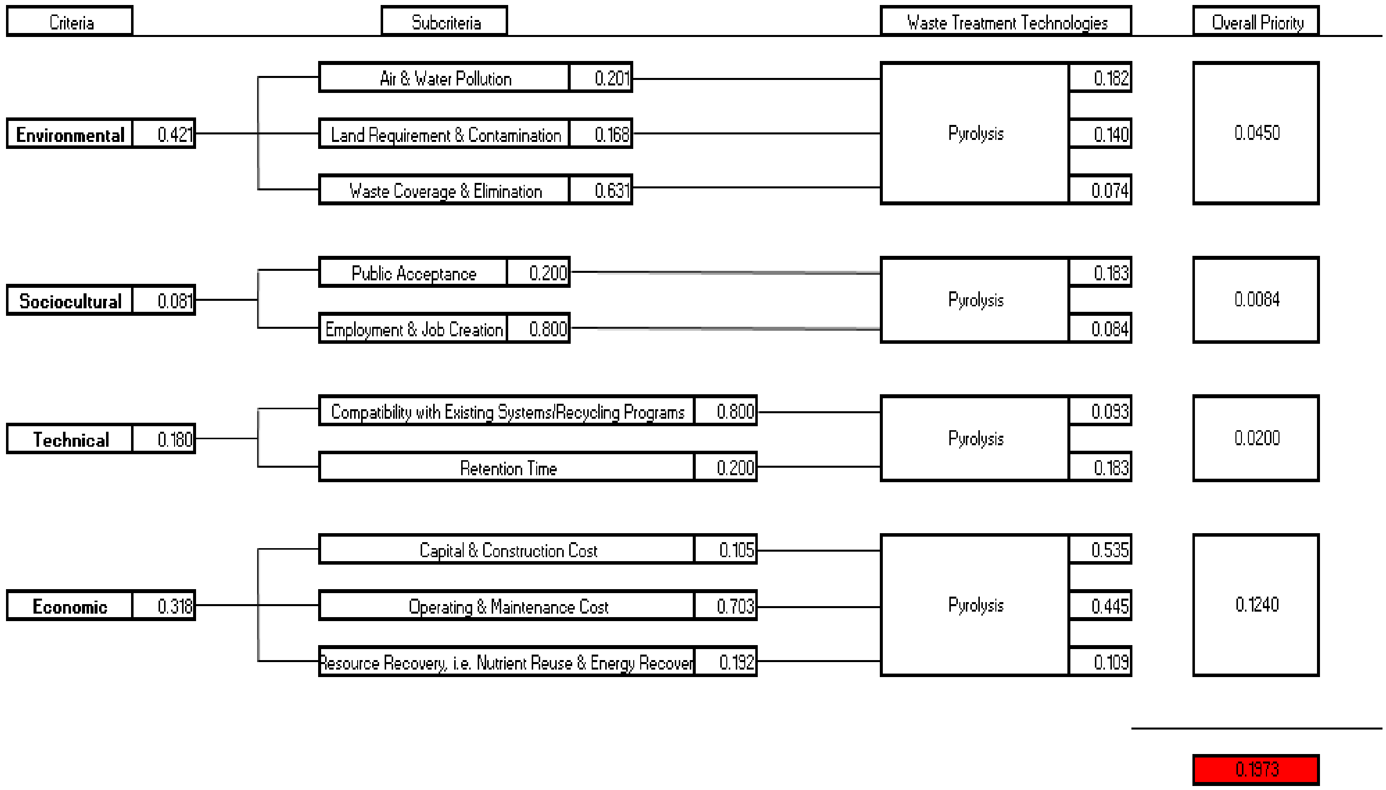


Figure 25: Overall Priority Synthesis of Pyrolysis

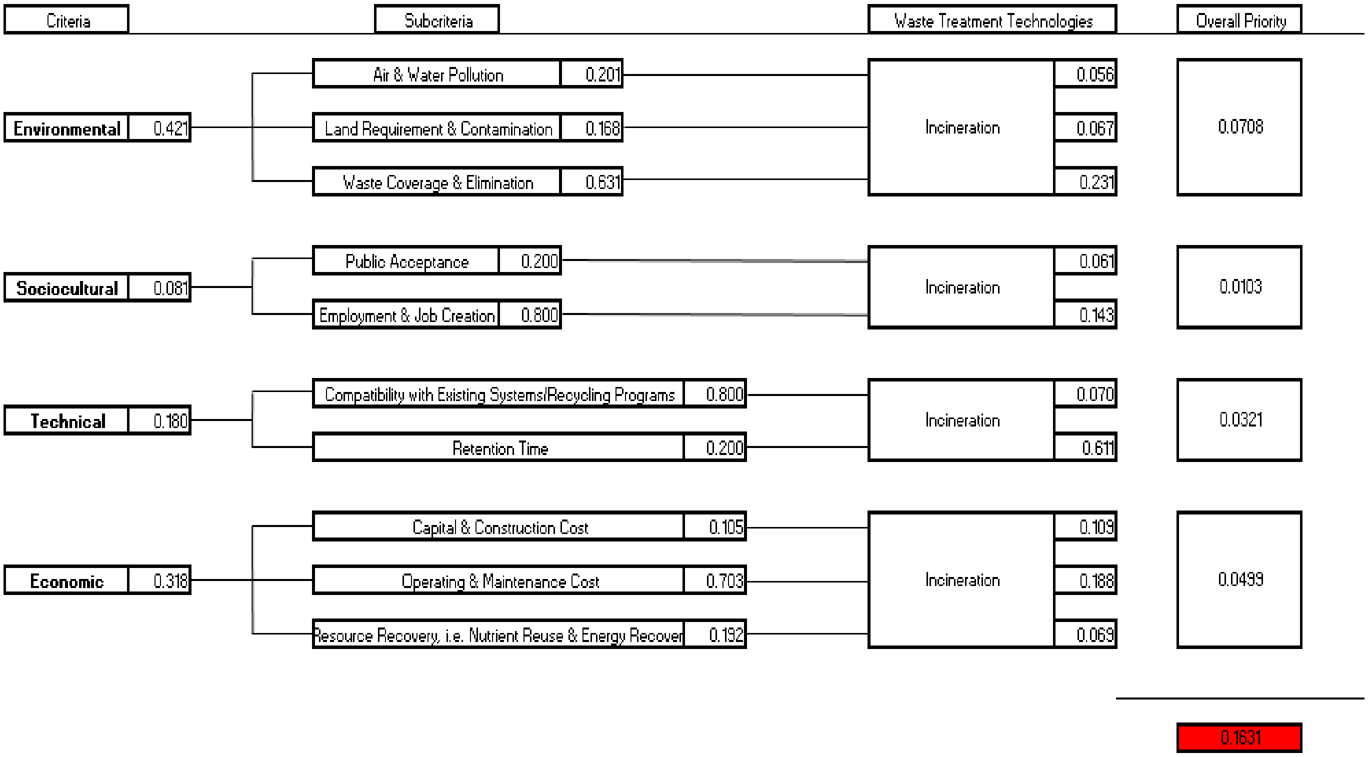


Figure 26: Overall Priority Synthesis of Incineration

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