FEASIBILITY OF ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE BY INCINERATION AND ANAEROBIC DIGESTION PROCESS

WATTANANARONG MARKPHAN

A DISSERTATION APPROVED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY IN
BIOTECHNOLOGY
THAKSIN UNIVERSITY
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DISSERTATION CERTIFICATION

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บทคัดย่อ

ชื่อดุษฎีนิพนธ์ : ศักยภาพการให้พลังงานของขยะเทศบาลโดยเผาไหม้และกระบวนการย่อยแบบ
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ขยะของแข็งจากเทศบาลมีการจัดการโดยการเผาไหม้ ส่งผลให้มีขยะเศษเหลือที่เผาไม่ได้ คือ ขยะของแข็งจากเทศบาลที่มีความชื้นสูง มีการนำขยะของแข็งจากเทศบาลที่มีความชื้นสูงไปผลิตก๊าซชีวภาพด้วยการย่อยสลายแบบไร้อากาศ แต่ระบบมีความเสถียรต่ำ เนื่องจากการผลิตกรดอย่างรวดเร็วจากของเสียประเภทคาร์โบไฮเดรต ส่งผลให้มีอัตราการผลิตก๊าซมีเทนและการย่อยสลายของแข็งต่ำ งานวิจัยนี้มีวัตถุประสงค์เพื่อประเมินการผลิตก๊าซมีเทนจากขยะของแข็งจากเทศบาลที่มีความชื้นสูงในระบบย่อยสลายแบบไร้อากาศขั้นตอนเดี่ยวและสองขั้นตอน โดยศึกษาภาระบรรทุกสารอินทรีย์ การเติมขี้เถ้าเพื่อช่วยควบคุมพีเอชของระบบ การผลิตมีเทนในระบบย่อยสลายแบบไร้อากาศขั้นตอนเดี่ยวและสองขั้นตอน ให้ผลได้มีเทนสูงสุด 218 และ 400 มิลลิลิตรมีเทนต่อกรัมของแข็งระเหย ภาระบรรทุกสารอินทรีย์เริ่มต้นที่เหมาะสมสำหรับการผลิตมีเทนในระบบย่อยสลายแบบไร้อากาศขั้นตอนเดี่ยวและสองขั้นตอน คือ 26 กรัมต่อลิตร มีการเติมขี้เถ้าร้อยละ1 และ 43 กรัมต่อลิตร มีการเติมขี้เถ้าร้อยละ 0.5 และ1 ระบบย่อยสลายแบบไร้อากาศสองขั้นตอนให้ผลผลิตก๊าซไฮโดรเจนและก๊าซมีเทนสูงสุด 7.9 ลูกบาศก์เมตรไฮโดรเจนต่อตันขยะของแข็งจากเทศบาลที่มีความชื้นสูง และ 68.1 ลูกบาศก์เมตรมีเทนต่อตันขยะของแข็งจากเทศบาลที่มีความชื้นสูง ที่ภาระบรรทุกสารอินทรีย์เริ่มต้น 26 กรัมต่อลิตร การผลิตก๊าซชีวภาพจากขยะของแข็งจากเทศบาลที่มีความชื้นสูงด้วยระบบย่อยสลายแบบไร้อากาศสองขั้นตอนสามารถเก็บเกี่ยวพลังงานได้มากกกว่าขั้นตอนเดี่ยวร้อยละ 18.5 การเติมขี้เถ้าร้อยละ 0.5 และ 1 ลงไปในขยะของแข็งจากเทศบาลที่มีความชื้นสูงเป็นวิธีการที่มีประสิทธิภาพในการควบคุมพีเอชและเพิ่มผลผลิตก๊าซชีวภาพ

ได้ถึงร้อยละ 87-92 เมื่อเปรียบเทียบกับการไม่เติมขี้เถ้า การเก็บเกี่ยวไฟฟ้าและพลังงานจากการจัดการของเสียโดยการรวมการเผาไหม้กับการย่อยสลายไร้อากาศสองขั้นตอน คือ 9,874 แมกจูลต่อตันขยะของแข็งจากเทศบาลที่มีความชื้นต่ำ และ 76 ลูกบาศก์เมตรมีเทนต่อตันขยะของแข็งจากเทศบาลที่มีความชื้นสูง

Abstract

Dissertation Title: Feasibility of Energy Recovery from Municipal Solid Waste by Incineration and Anaerobic Digestion Process
Student's Name : Mr. Wattananarong Markphan
Advisory Committee : Asst. Prof. Dr. Sompong O-Thong
Dr. Chonticha Mamimin
Degree and Program : Doctor of Philosophy in Biotechnology
Academic Year : 2019

Municipal solid waste (MSW) managed by the incineration method generating high moisture MSW as residue. Anaerobic digestion of high moisture MSW has low stability, easy to acidified due to carbohydrate content resulting in low methane production rate and low volatile solids (VS) removal efficiency. This work aimed to evaluate the methane production from high moisture MSW in single-stage AD and two-stage AD processes. The effect of the organic loading and fly ash addition as a pH adjustment on biogas production was investigated. Maximum methane yield from high moisture MSW by single-stage process and the two-stage process was 218 and 400 mL $CH_4 \cdot g^{-1}$VS. Suitable initial organic loading of single-stage AD was 26 gVS$\cdot L^{-1}$ with ash addition of 1% while the two-stage process was 43 gVS$\cdot L^{-1}$ with ash addition of 0.5 and 1%. The highest hydrogen and methane production of 7.9 m^3 $H_2 \cdot ton^{-1}$ high moisture MSW and 68.1 m^3 $CH_4 \cdot ton^{-1}$ high moisture MSW was achieved at the initial loading of 26 gVS$\cdot L^{-1}$ by two-stage AD. The biogas production via two-stage AD has 18.5% energy recovery higher than a single-stage AD. The addition of 0.5% and 1% of ash into high moisture MSW were effective for controlling pH for both stages and enhanced biogas production for 87-92% when compared with without ash addition. The electricity recovery and energy recovery from combine incineration with a two-stage biogas production of 1-ton MSW were 9874 MJ and 89 %, respectively.

Acknowledgments

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Last but not least, I would like to thank my family: my wife and my son for supporting me spiritually throughout writing this thesis and my life in general.

Wattananarong Markphan

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CHAPTER 1
Introduction

Rationale and Background

Municipal solid waste (MSW) has become one of the major environmental concerns in many countries as well as in Thailand. At present, the landfill has been practiced as the major treatment method in Thailand. However, this treatment method was extremely constrained to the conditions that the land is very scarce and the population density is very high in Thailand (Pollution Control Department. 2015) Due to the increasing cost and scarcity of landfill sites, thermal treatment technology has been developed as an attractive method of disposing of municipal solid waste. (Jie, Yu, Lushi, Limei, Wenxia and Chuan. 2015)

Greenhouse Gases (GHG) emissions vary significantly among different waste management scenarios (Mahmoudkhani, Valizadeh and Khastoo. 2014; Habib, Schmidt and Christensen. 2013) pointed out that the technology development for incineration as well as the energy and material recovery accounted for significant savings of global warming potential during the past five decades. The life cycle assessment (LCA) has been widely used to evaluate different MSW management scenarios. The previous studies concluded that the critical factors affecting the GHG emissions in different treatment methods were (1) Landfill gas (LFG) collection efficiency, LFG recovery and the biogenic carbon storage (Manfredi, Tonini and Christensen. 2009; Liu, Ni, and Kong. 2017); (2) the content of fossil carbon in the input waste and the energy conversion efficiency (Astrup, Moller and Fruergaard. 2009); (3) composting process and the utilization of the compost product (Boldrin, Andersen and Moller. 2009); (4) energy substitution by biogas recovery, fugitive emission of GHG and the carbon storage donated by digested residue (Moller, Boldrin and Christensen. 2009) as to landfilling, incineration, composting and anaerobic digestion (AD) technologies correspondingly.

Cities have created a centralized waste collection and management system. The rest of the towns and villages are either managing a rudimentary waste management system (run by the councils) or do not have any at all. While attempts have been made to characterize municipal solid waste in Cameroon as mainly biodegradable (Mbeng, Phillips and Fairweather. 2012) and to propose sustainable management solutions with regards to its delivery (Manga, Forton and Read. 2008), there is still hardly any information in the literature that identifies and quantifies GHG emissions from such open dumpsites in the country. Given the usually high tropical temperatures and moisture, waste in open dumps is prone to anaerobic degradation, resulting in potentially large quantities of CH_4 as the main emission (Sankoh, Yan and Tran. 2013). Emission inventory data, combined with waste characterization should be able to help direct policy on improved sustainable management strategies of municipal solid waste. An additional benefit of improved management of waste would be a reduction in GHG emissions from this sector and an improvement in the country's GHG budget.

Thus, municipal solid waste incinerator (MSWI) is inevitably chosen as an effective alternative for MSW treatment. It is selected because MSWI takes the lesser area of operation site and has the advantage of reducing MSW volume in an efficient way. Generally, residues are comprised of bottom ash and fly ash and consist of many minerals and inorganic compounds (Huang. 2005) Thailand government is now building more incinerators to treat continuously growing MSW. Nevertheless, in terms of environmental consideration, MSW incineration faces many serious restrictions. During an incineration process, various solid residues, such as bottom ash, fly ash and particulate are produced. For a typical moving grate incinerator, 250-300 kg bottom ash and 25-50 kg fly ash are produced for 1000 kg municipal solid waste. Bottom ash is mainly used as construction materials, such as for coffering road and making brick, or used as material for landfill (Banks, Lo, H.-M. 2003). Nevertheless, MSW fly ash is generally classified as a hazardous material because it contains higher amount of heavy metals and soluble salts. In order to evaluate possible environmental effects related to the release of contaminants from bottom and fly ashes, the toxicity characteristic leaching procedure (TCLP) was used comprehensively to evaluate the hazardous properties of the ashes (Feng, Wang, Wei, Peng, Yang and Cao. 2007)

Ash addition with refuse substrate taken into the anaerobic reactors has resulted in ash constituents release, including heavy metals, alkali metals, and other probable leaching ions. Heavy metals have been recognized to be the potential ions that might cause detrimental effects on the anaerobic digestion process. (Huang. 2005) The properties of fly ash in a particular incinerator are affected by the compositions of feed waste, the type of incinerator. (Chien-H, Jyh-Cherng, Kui-Hao and Ming-yen. 2015) The main chemical compositions of fly ash are mainly composed of Si, Ca, Al and Mg. In the incinerator, contributing to the high amount of Si and Ca in ash. Si, Ca and Cl account for the majority of elements in fly ash. (Jie, et al. 2015) Further, the potential release of alkali metals from bottom ash with acids titration curve have indicated that they have contributed to the acids neutralizing capacity for the buffer of intermediate acids produced in the anaerobic digestion process leading to a suitable pH 6.5–7.6 for the anaerobic environment, although a higher level of alkali metal concentrations have been demonstrated to be likely detrimental to the anaerobic digestion process. Therefore, it is concluded that leaching ions and heavy metals from bottom ash exerted no detrimental effects on the anaerobic systems. However, the released alkali metals from bottom ash were found to cause beneficial effects on the anaerobic co-digestion of MSWI bottom ash and MSW. (Huang-Mu. 2005)

The organic waste from a household that the treatment of the municipal solid waste by the anaerobic digestion or biogas technology can potentially contribute to the generation of huge amounts of renewable energy as biogas. In addition, the treated organic matters could be used as biochemical and fertilizer in the agriculture land for crop cultivation. (Abdeshahian, Shiun Lim, Shin Ho, Hashim and Tin Lee. 2016) But the recirculation of methanogenic effluent at 30% recirculation rate could compensate for alkalinity required by the reactor. Both reactor effluents were effective in keeping at optimal pH with 2 times increase in biogas production. (O-Thong, Boe and Angelidaki. 2012)

This study examined the biogas production from the organic function and green waste by a single-stage and two-stage fermentation process. The effect of the organic loading and fly ash addition as a pH adjustment on biogas production was investigated.

Research Objectives

1 To study the composition of municipal solid waste from landfills at Nakhon Si Thammarat Municipality.

2 To study biogas production from the organic function and green waste of municipal solid waste by one-stage and two-stage anaerobic digestion process.

3 To study the amount of greenhouse gas emissions from municipal solid waste management.

Hypothesis

1. Municipal waste in Thailand. When considering the composition of garbage thoroughly can be separated into garbage that can burn, including paper, plastic, wood, up to 29 percent, which is currently being eradicated by landfills or piles, making it a source of germs, but this type of waste can be used to generate heat energy for electricity generation by burning.

2. Organic waste up to 48 percent, can be used to produce compost. The production of composting is oxygen-degradable. The energy in organic waste is not harvested. But will be left in the form of heat and is used as a fertilizer to improve soil in agriculture if this type of waste is brought to produce methane in an airless state, solid-state can harvest energy in the form of methane during the fermentation process. Thus, making use of waste that can burn and organic waste is more economically worthwhile than landfill or compost alone.

3. The waste management system of Nakhon Si Thammarat Municipality has carbon dioxide emissions from to design and improve existing systems to reduce emissions.

Expected Benefits

1. Information about the composition of waste is used in the design of solid waste management systems.

2. Potential of methane production from municipal solid waste, organic waste and green waste by anaerobic decomposition process in solid-liquid state and design of semi- continuous reactor systems which will be information for entrepreneurs in commercial applications Revealing cellulases gene of GH5 family and that was showed stable at high temperature

3. Data on carbon dioxide emissions from the waste management system of Nakhon Si Thammarat Municipality in order to design and improve existing systems to reduce emissions.

4. Municipal waste can be the utilization, which reduces the amount of waste, reduce pollution and reduce the sources of infection caused by the dumping, including the cost of removal.

Research Plan

Research plan of this study was divided into 3 parts as shown in figure 1

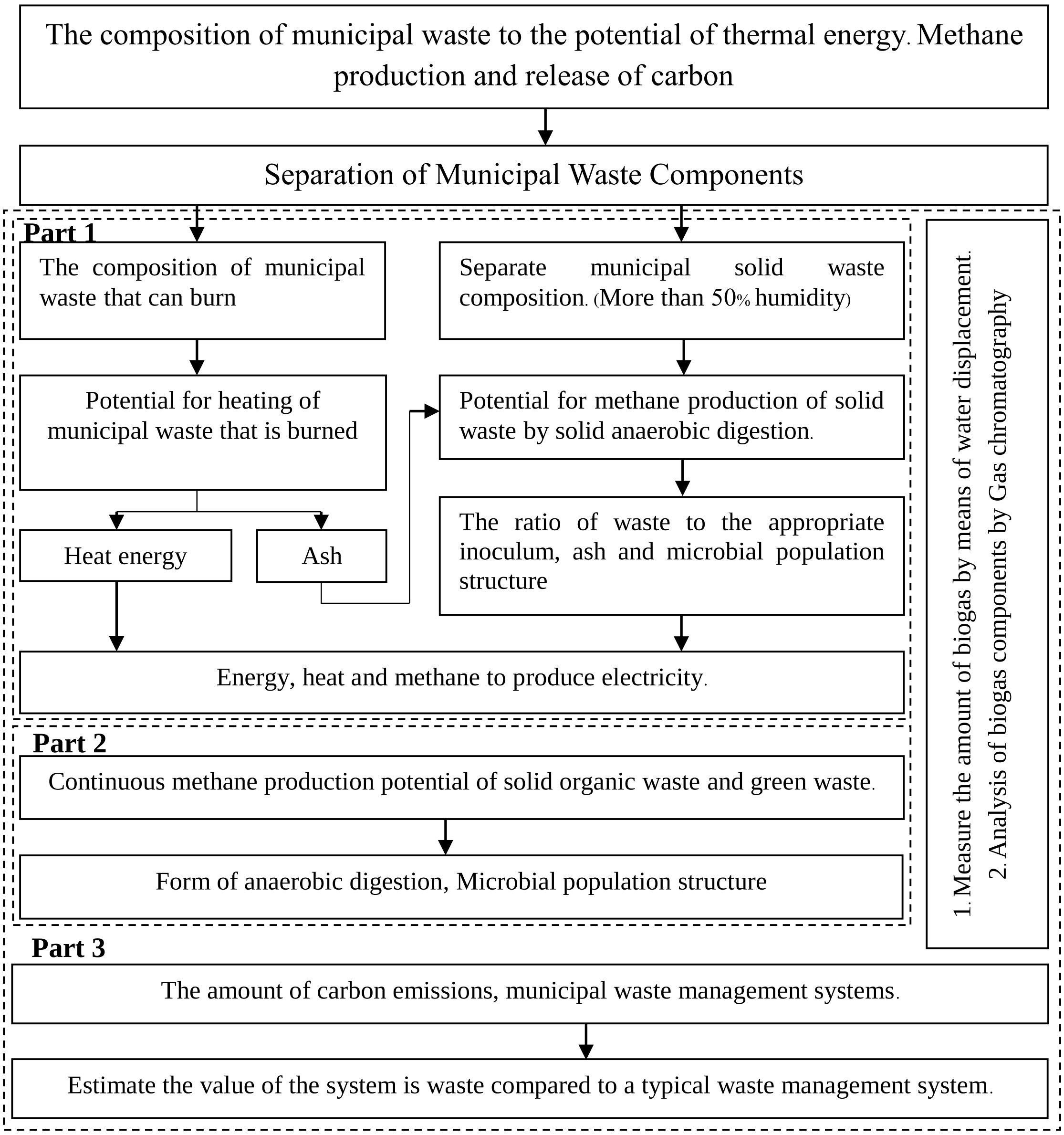


Figure 1 Research Plan of this study

Abbreviation

IFA	Incineration Fly Ash
MSW	Municipal Solid Waste
OFMSW	Organic Fraction Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
GHG	Green House Gas
GW	Green Waste
LCA	Life Cycle Assessment
LFG	Landfill Gas
AD	Anaerobic Digestion
TCLP	Toxicity Characteristic Leaching Procedure
HMC	High Moisture Content
LMC	Low Moisture Content
TS	Total Solid
VS	Volatile Solids
BMP	Biological Methane Potential
BHP	Biological Hydrogen Potential
DGGE	Denaturing Gradient Gel Electrophoresis
PCR	Polymerase Chain Reaction
DNA	Deoxyribonucleic Acid
RDF	Refuse-Derived Fuel
SRF	Solid Recovered Fuel

CHAPTER 2

Literature Review

2.1 Municipal Solid Waste

2.1.1 Waste

"Waste is a left-over, a redundant product or material of no or marginal value for the owner and which the owner wants to discard."

An important characteristic is that being 'waste' is not an intrinsic property of an item but depends on the situation in which the item appears as defined by its owner or in other words, how the owner values the item. The owner sees little value in an item if the effort required converting the excessive item to cash value or preserving the item for future use or consumption exceeds the effort it takes to obtain the same cash value or function of the item by other means. Then the item becomes waste. This means that becoming 'waste' may depend on many factors, for example.

Time: If supplies are scarce, for example, during wartime and embargos, the owner will spend more time and effort repairing an item since the alternative may be costly and hard to find.

Location: Farming communities may easily make use of food waste for animal feeding, while this is less feasible in a Highrise in an urban area.

State: The item may be repairable depending on its state (price, age, type of damage) and thereby avoid being discarded.

Income level: The higher your income, the more food you may discard or the more items you may discard because they no longer are in fashion or up to date.

Personal preferences: Certain types of items may be collector's items or possess veneration for some individuals (Christensen. 2011)

This also suggests that what is waste to one person may not be waste to another person and there may be a potential for trading if the cost for transferring the item does not exceed the value of the item as perceived by the new owner. Hence quantity and purity of the item is a key issue. In addition to the abovementioned factors, what actually becomes waste depends on which items are being purchased and consumed. Or in other words, culture, climate, religious and ethnic background as well as economic abilities affect what becomes waste. Hence, waste quantities and composition vary widely, both geographically (regionally, locally) and overtime. The introduced definition of waste may teach us about the complexity of waste, but the definition may not suffice in a legal context since it has a high degree of subjectivity

2.1.1.1 Solid Waste

The definition of 'solid waste' would be anticipated to be 'waste in a solid-state'. However, solid waste may be solid, or liquid as sludge or as a free chemical phase. This originates from defining solid waste as waste that is not water (wastewater) or airborne (flue gasses). This also suggests that solid waste has no transporting media like water and air that must be cleaned. While obtaining clean water and clean air are the main purposes of treating wastewater and cleaning flue gasses, the purpose of waste management is not to clean the waste bins, but to handle the waste in the bins, as discussed later. Solid waste is mostly in a solid-state, but also sludge from wastewater treatment and liquid chemical waste are included.

2.1.1.2 Hazardous versus Nonhazardous Waste

It is often convenient to distinguish between nonhazardous waste and hazardous waste. This may apply to practical waste management as well as to the regulatory aspects of waste management. Hazardous waste is more dangerous to the environment and to those handling the waste and must be technically managed with more strict controls than nonhazardous waste (Christensen. 2011)

The hazardousness of waste is assessed according to criteria as

- Explosive under the effect of flame, shock, or friction.
- Oxidizing in contact with other materials resulting in highly exothermic reactions.
- Flammable in contact with air having flashpoint less than 55 °C (highly flammable, with a flashpoint less than 21°C).
- Irritant: causing inflammation through contact with skin or mucous membrane.
- Harmful: causing limited health risks through inhalation, ingestion or penetration of the skin.

- Toxic: causing serious, acute or chronic health risks and even death through inhalation, ingestion or penetration of the skin.

- Carcinogenic: inducing cancer or increasing cancer incidence through inhalation, ingestion or penetration of the skin.

- Corrosive by destroying living tissue on contacts.

- Infectious due to viable microorganisms or their toxins are known or reliably believed to cause disease in man or other living organisms.

- 'Toxic for reproduction': substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce nonhereditary congenital malformations or increase their incidence.

- Mutagenic: inducing hereditary genetic defects or increasing their incidence through inhalation, ingestion, or penetration of skin.

- Releasing toxic gases in contact with water, air or an acid.

- 'Sensitizing': substances and preparations which, if they are inhaled or if they penetrate the skin, are capable of eliciting a reaction of hypersensitization such that on further exposure to the substance or preparation, characteristic adverse effects are produced.

- Ecotoxic: presenting any immediate or delayed risks for any sector of the environment.

- Substances were capable by any means after disposal of yielding another substance that possesses any of the characteristics listed above.

These criteria are for practical assessments supplemented with quantitative limits as well as methods for their determination (CEC. 2008 and in particular CEC. 2000)

2.1.2 Material Flow and Waste Generation

Waste generation is linked to economic activities and flow of materials in society. The schematic diagram in figure 2 (Vesilind, Worrell and Reinhart. 2002) illustrates the flow of materials from the environment through society and back to the environment. The diagram pictures the fact that resources are not consumed but merely transformed in the process of extraction from the environment, production, and use before ending up as waste. This waste may be returned back into the production-use cycle in society or disposed of into the environment. The material flow is driven by a significant use of energy and emissions to air, water, and soil are associated with all activities within the flow system. Also, the extraction of resources and the disposal of waste into the environment may have associated environmental burdens. A large extraction of resources may also lead to the depletion of resources. For example certain metals; and disposal activities may damage resources by contamination, for example groundwater resources at a landfill. Modern society is characterized by a very large extraction of resources from the environment and a very large disposal of waste in the environment. As the economy expands, the material flow traditionally also expands, leading to increased environmental burdens and resource consumption. Schematically it may seem possible to link the disposal with the extraction of resources and thereby ‘close the loop,’ but the resources mined and the biomasses grown (inputs) are so different from the waste disposed (outputs) that this is neither technical nor economically feasible. The control of the material flow allowing for continued economic expansion, also for the less developed part of the world, is rather linked to a more efficient use of the resources extracted and increased recycling and utilization of the waste generated. This again reduces the amount - at least relatively - being disposed of into the environment.

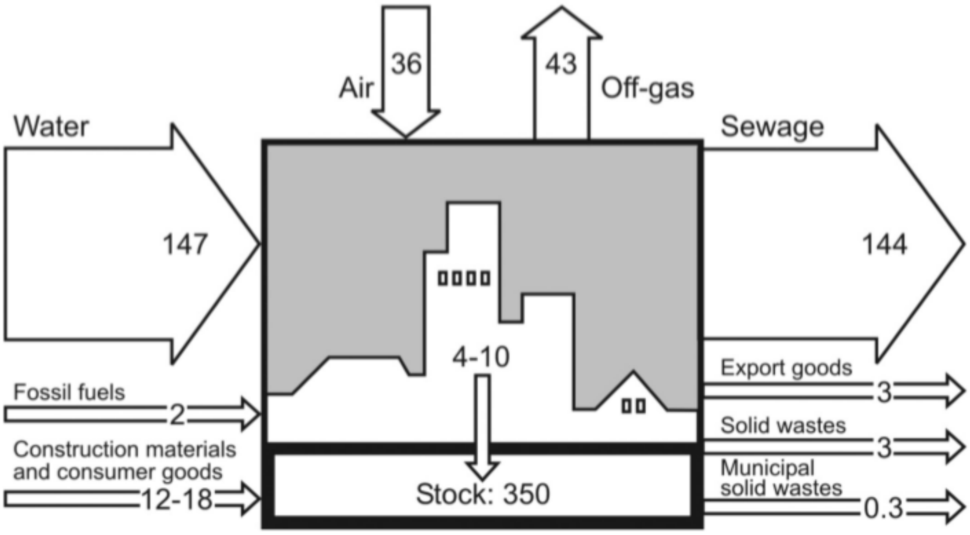


Figure 2 Mass flows (t/year/person, except for stock which is t/person) estimated for Vienna (based on Brunner and Rechberger. 2004). Reproduced with permission from Lewis Publishers, USA. © (2004) Taylor & Francis Group LLC - Books.

Figure 2 neglects the fact that many of the goods produced and consumed have very different retention times in society: Packaging has a very short lifetime (days to weeks), daily consumer products like telephones, clothing, etc. have a moderate lifetime (few years), large consumer products like furniture, vehicles, etc. have a long lifetime (many years to decades), while buildings and civic constructions (e.g., roads) have very long lifetimes (decades to centuries). This implies that waste generation is not directly linked to production and use, since many of the goods produced may accumulate in society and appear as waste at a much later point in time (Brunner and Rechberger. 2004)

2.1.3 Issues Associated with Solid Waste

A range of important issues is associated with solid waste, as discussed below. The listed issues should not constitute a problem if the solid waste is properly managed, but whatever solid waste management system is introduced, its implementation should be made in respect of these issues. The issues are listed in the order as they historically often have emerged and have been addressed, although not all waste management systems around the world are fully addressing all the issues satisfactorily.

- Volume/space: Waste takes up space and does not disappear by itself. Removing waste from premises and public areas is still today the first and main goal of all waste management.

- Nuisances: Where waste accumulates over time because of ineffective waste collection and public cleansing, nuisances such as odors, flies, blowing litter, etc. may develop and become a problem for neighbors and an aesthetic problem for the community.

- Public health issues: Accumulated waste easily accessible by insects, animals, and humans, in particular children, may constitute a health issue. Pathogens in the waste may spread by direct or indirect contact (water, air, insects, small rodents) or the waste may enhance the survival and spread of infected vectors such as rats, seagulls, etc that feed or nest in the waste.

- Economy: In urban areas where large quantities of waste must be managed and no easy ways of disposal are available within a short distance, the cost of solid waste management becomes significant. The annual cost may in metropolitan areas be as high as 100 €/person; this corresponds as an order of magnitude to 0.5% of GDP. The cost issues, therefore, are important in all waste management.

- Contamination of the environment: Waste disposal leads to transfer of substances from the waste to air, water, and soil and may cause contamination of the environment: For example, groundwater pollution at landfills, air quality affected by air emissions from incineration, metals in soil and crops after compost use. This has, in many parts of the world, led to stricter and stricter emission controls at waste management facilities.

- Resource issues: Waste contains resources that should be used in order to save on other resources. In many parts of the world, this is done of economic reasons, for example scavengers and small-scale recyclers that are recovering resources from the waste for a living. But resource recovery can also be viewed in the context of avoiding environmental impacts from production of virgin resources and at the same time avoiding environmental impacts from waste disposal. This suggests that resource recovery should not be viewed only in private economic terms (Swan, Crook and Gilbert. 2002)

2.1.4 Waste Management Systems

Although this primarily focusses on the municipal waste management system, it is important to realize that several systems are dealing with waste or items that could become waste. Municipal solid waste is, however not well defined.

- Inhouse waste handling: ‘Waste’ may be utilized on the premises or in an industrial symbiosis; the latter is when one industry directly uses ‘waste’ from another industry as a resource in its production. For example, low-quality wood chips could be used for inhouse generation of power. In principle this is not a ‘waste’ according to our definition, but inhouse waste handling could be an important initiative in promoting waste minimization or waste prevention, as later discussed.

- Littering/unmanaged waste handling: Common littering in terms of waste thrown away in the countryside, along transportation lines or in public areas, is found everywhere, although on a variable scale. Littering is usually in the form of packaging and newspapers, but also infrequently arising waste (such as waste from building renovation and old white goods) may appear ‘dumped’ in the countryside or in derelict areas. Littering and dumped waste may later demand public cleansing of the affected areas and thereby become a part of the public waste management system.

- Return system: Used products may be returned to the store where bought or to a similar store depending on the business structure. Returnable beverage bottles and cans with a deposit are common. The recovery of the deposit is the economic incentive for the consumer to return the items. Return systems may also exist without deposits as a part of voluntary agreements between environmental authorities and business chains, as an element in the environmental profiling of a branch or as part of legally enforced producer responsibility. Such systems could, for example, involve batteries, medicine, car tires, and electronic equipment.
- Municipal waste management system (public or private): Organized handling of municipal waste is usually a public issue, although many of the elements in the system may be privately owned and operated. Municipal waste is the waste that is generated by citizens and civil work and similar waste from small businesses and industries. The public is the governing authority.
- Industrial waste management system: The term industrial waste is used for the waste of industrial origin that is found in large quantities of special composition or in smaller quantities but hazardous. The latter usually is handled in the hazardous waste management system. Industrial waste is often dealt with case-by-case because the large quantities and special features determine the ways of disposal. Systems for managing the waste at an industry may be an integrated part of the authorities' environmental approval or licensing of the industry.
- Hazardous waste management system: The nature of hazardous waste calls for special ways and rules of collecting, storing and transporting the waste. Also, the treatment and disposal facilities have special features and regulations. This typically leads to a higher cost per tonne than the common cost for municipal solid waste (Strange, 2002; Vesilind, et al. 2002)

2.1.5 Waste Management Criteria

The ideal waste management system does probably not exist, but it may be useful to identify some of the main criteria that waste management as a service and a public obligation should consider and try to balance. The following criteria should be considered in all waste management planning:

- Provide customized and robust handling of all waste with a minimum of effort for the customer and the citizen.
- Ensure the lowest possible load on the environment in terms of noise and contamination of air, water, and soil.
- Provide a maximum of resource recovery from the waste while minimizing the use of resources in waste handling.
- Be a safe and healthy occupation for the workers offering work and achievable challenges.
- Provide only little impact on the city with respect to traffic, vehicle exhaust, noise, traffic accidents and spill of waste
- Include aesthetic and architectural considerations in establishing waste collection and treatment facilities.
- Respect as a minimum current law, regulations, and code of practice. Be economically acceptable and fair.

These ideal criteria are partially in conflict: for example, fulfilling environmental criteria increases the cost. All waste management systems must identify which criteria are the most important and then reach an acceptable compromise. No simple relation can combine these partly contradictory criteria into one single criterion function to be optimized unless all criteria are forced into economic terms (Strange. 2002)

2.1.6 Waste Management Approaches

Waste management decisions take place on many levels but are characterized by a dominance of local decisions. This also suggests that local conditions, criteria, and preferences play an important role in defining the waste management system. However, some main types of approaches have been used extensively or are emerging on the scene, as described below.

2.1.6.1 Common Sense Approach

The common- sense approach accepts that some of the mentioned criteria meet defined minimum standards (occupational health, level of service, compatibility with regulations, etc.), while the balancing of the other issues is a matter of discussion among the political decision- makers. Often costs have been the main criteria, and often, environmental issues have been dealt with in an opinionated way rather than in scientific terms.

2.1.6.2 Waste Hierarchy

The Western world and parts of Asia have since the early 1980s used the waste hierarchy as the main approach to waste management. The wording used and the name may vary (In Japan the approach is called 3R, for reduce, reuse and recover), but the main message is that priorities in waste management should be:

The waste hierarchy is a strong approach and easy to communicate and quantify if the purpose is to avoid landfilling, but two aspects are not well addressed by the waste hierarchy. One aspect is that waste minimization and cleaner technology is a very difficult issue for local and regional bodies because they do not have the mandate and power to address this. Waste minimization is primary a state or interstate issue since globalized industrial manufacturing and marketing of products must be the focus. The second aspect is that, as energy prices go up and the Kyoto protocol forces many countries to reduce their use of fossil fuel, energy recovery from solid waste may be as beneficial as material recovery and thereby question the rigid prioritization of material recovery over energy recovery.

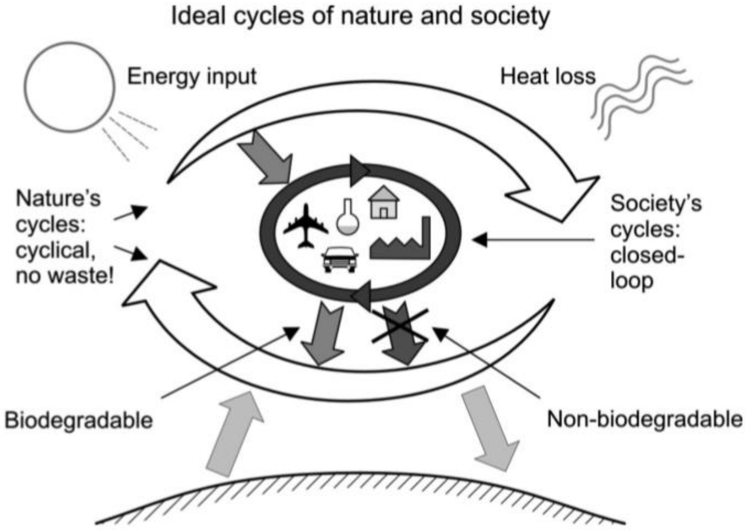


Figure 3 The concept of zero waste does not put an end to waste as defined, but message focusing on waste minimization and recycling of waste. One could say that zero waste for municipal authorities is just another way of expressing the waste hierarchy

(Source : Snow. 2003.).

2.1.6.3 Sustainability

The concept of sustainability was introduced by the World Commission on Environment and Development in 1987. Sustainability is defined as: 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.' Sustainability has an environmental as well as a social and economic dimension. The definition does not provide much guidance as to waste management but has fostered a way of thinking suggesting that long-term issues should receive more attention, that each generation should solve its own problems and that local solutions should be sought. The lack of concrete guidance has inhibited the introduction of the sustainability concept in waste management although the word is often used in the context of waste management (WCED. 1987)

2.1.6.4 Life Cycle Thinking and Life Cycle Assessment

Life cycle assessment (LCA) is a common tool used to evaluate and minimize the environmental impact of industrial products but is still fairly new in waste management. LCA basically accounts for all mass flows and emissions, as well as energy use and production within the waste management system and any upstream (e.g. lime used in flue gas cleaning) and downstream processes (e.g. recovery of recycled glass). All the emissions and resources used are aggregated into commonly agreed impact categories, as for example global warming and acidification. LCA is a comprehensive accounting system that makes it possible to evaluate alternatives according to defined environmental criteria. Life cycle thinking builds around the same concept as LCA but is less data-demanding and rigoristic and hence easier to introduce. The EU waste directive suggests that life cycle thinking should be introduced in all waste management decision-making, and derogation from the waste hierarchy should be based on life cycle thinking (CEC. 2008)

2.1.6.5 Environmental Economics

In environmental economics, prices are estimated for all environmental emissions from a system and added to the traditional economic data for the system. The external cost is said to be internalized, i.e., brought into the system by putting a price on them. Thereby all aspects of importance in principle are ascribed an economic value and alternative systems can be assessed in terms of cost as a single parameter. Environmental economics is just starting to find a role in waste management. In environmental economics, national boundaries are often chosen as system boundaries and costs distributed in time are discounted, suggesting that future costs associated with waste management have less weight than today's cost. It is evident that environmental economics use assumptions and methods which are very different from the concepts of sustainability and LCA. The sustainability concept accepts emissions today in order to avoid future emissions ('each generation should solve own problems') while environmental economics as a consequence of discounting pay less attention to future emissions than to emissions happening today. LCA considers all emissions induced by the waste management system no matter where they appear, while environmental economics often disregard emissions in foreign countries, assuming that the price for trading goods across a border includes all environmental costs.

2.1.7 Current Waste Management Practice

Although the criteria for waste management are developing, as described above, the management of waste varies significantly among countries. This is due to differences in the waste, availability of land, possibilities for using the materials and energy held in the waste, costs, political focus and national preferences. Worldwide, a lot of municipal waste is not managed in an organized way but is still being dumped, and landfill is definitely still the predominant waste management technology (CEC. 2008)

2.2 Residential Waste

Residential waste comes from residential areas with multi-family and single-family housing and includes four types of waste: household waste, garden waste, bulky waste, and household hazardous waste: typical unit generation rates, material composition, chemical composition.

Characterizing residential waste is faced with the problem that many residences already divert some waste away from the official collection systems, for example performing home composting of vegetable waste and garden waste, having their bundled newspaper picked up by the scouts twice a year or bringing their used furniture to the flea markets organized by charity clubs. Thus, much of the data available on residential waste represents collected waste and not necessarily all generated waste. The latter can only be characterized by careful studies directly at the source, but such studies are very expensive if the fair representation of both spatial and temporal variations should be obtained. In addition, onsite studies may affect the waste generation in residence because of the increased focus on the issue.

Residential waste is defined in different ways in different countries, which makes a comparison among countries difficult. In addition, the statistical base may vary among countries (Fischer and Crowe. 2000)

2.2.1 Residential Waste: Definition and Unit Generation Rates

Residential waste is here considered to constitute household waste, bulky waste, garden waste, and household hazardous waste:

- Household waste is the ordinary waste generated in the household or actually in the house from everyday activities. This involves food or kitchen waste, packaging, beverage containers, newspapers, magazines, advertisements, diapers, and sanitary towels, mail, flowers, broken household items and toys, small electronic waste, obsolete clothing, and the like.
- Bulky waste is an extraordinary waste, such as furniture, refrigerators, television sets, household machines, etc., appearing only occasionally.
- Garden waste is grass clippings, tree and hedge pruning, flowers, lawn turf and potting plants and soil from terraces, etc. Garden waste often also includes similar waste from community areas and parks.
- Household hazardous chemicals are solvents, oil, paints, batteries used in the household, and collected separately.

2.2.2 Municipal Solid Waste in Developing Economies

In developing economies, as found, for example in Asia and South America, the definitions of waste generated as presented in this is currently not very useful. First of all, because much waste, in the Western definition, never appears as waste because it is collected, cleaned, and recycled by family-scale entrepreneurs before it enters and becomes measured in a public system of waste collection. Secondly, private and commercial waste is often mixed when collected. Therefore, the softer definition of municipal solid waste is often used, but the majority of waste is a residential waste, and since bulky waste and garden waste are negligible it is close to household waste removed of recyclables. The majority of this waste would have been defined as “rest waste" by the terms used in this. The table 1 below provides typical data for "municipal solid waste" in China (PRC), Thailand and Sri Lanka. However large variations are observed because the economic development is not equally distributed in these countries (Visvanathan and Tr¨ankler. 2004 ; Huang, Wang, Dong, Xi and Zhou. 2006)

Table 1 Typical data estimated from data published (Visvanathan and Tr¨ankler. 2004)

Typical data estimated from data published by Visvanathan and Tr¨ankler (2004)	China (PRC)	Thailand	Sri Lanka
Unit generation rate (kg/person/year)	210-320	180-365	145-310
Composition (%)	100	100	100
- Kitchen waste/food waste	48	55	65
- Paper	7	10	12
- Plastic	9	10	7
- Glass	2	4	3
- Metal	1	3	4
- Wood	8	-	7
- Others (ash, textile, pottery, etc.)	25	18	2

Note; Data presented for Thailand (Visvanathan and Tr¨ankler. 2004) suggest that the moisture content of the waste due to the high content of kitchen waste is in the range 40-70 %. Huang, et al. (2006) suggest that in China (PCR) the moisture content is in the range 30-50 %. This characteristic is important in defining the proper management of the waste.

2.2.3 Household Waste

2.2.3.1 Unit Generation Rates

Unit generation rates for household waste vary significantly in space and time. For example, figure 4 shows the unit generation rates for household waste for five municipalities (totally about 200,000 inhabitants) in the southern part of Sweden for the period 1990-2003. The municipalities had almost similar waste collection systems. In 2003 the unit generation rates among the five municipalities varied between 320 and 415kg/person/year.

Fluctuations over time are significant and some of the fluctuations may be real, others of a more technical and statistical nature. Due to holidays or adverse the weather around New Year, one year may end up having more collection days than the neighboring year, or the statistical registration of glass and paper brought to central recycling centers may have been changed from one year to another.

Despite significant fluctuations, it shows an overall trend of about 1% increase per year, increasing the average unit generation rate from about 330kg/person/year in 1990 to 370kg/person/year in 2003. Such a slow increase is expected in a country like Sweden with a high gross domestic product (GDP). Growth rates of 2-4% per year may, however, be experienced in countries with developing economies.

Short-term variations in unit generation rates, for example, are based on monthly data, are expected for the single source, but are most likely moderate for a collection system if not subject to bad weather and other strong seasonal factors. Household waste is generated by everyday life activities and, as such is not subject to large seasonal variations. When seasonal peaks appear, the collection system may actually not be able to receive an increase in amount of waste per bin, forcing the resident to store the waste for later collection or to find alternative disposal routes. Spatial variations in unit generation rates for household waste are observed, but robust and generally applicable explanations have not been found that can account for variations among countries, among regions and within municipalities: some considerations and some myths about the unit generation rate.

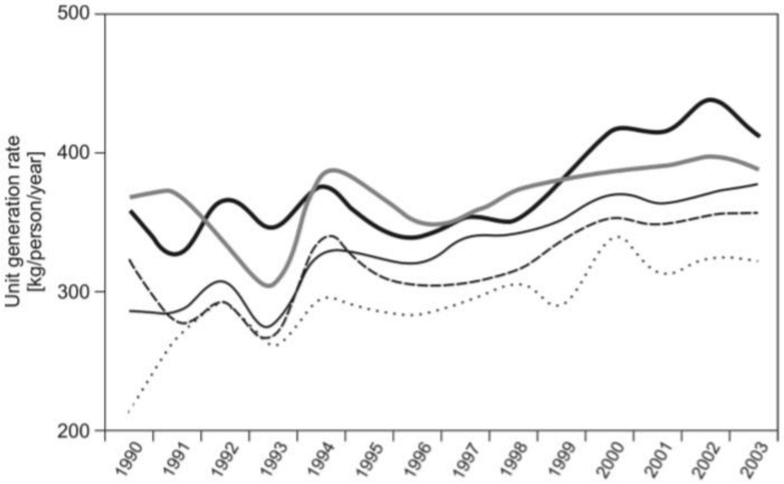


Figure 4 Household waste unit generation rates for five municipalities in southern Sweden for the period 1990-2003 (adapted after Domeij, Vukicevic, Meijer and

Lagerkvist. 2004). Reprinted with permission from Trends in Municipal Solid Waste Composition by A. Lagerkvist © (2004) Lulea University of Technology.

2.2.3.2 Composition

The average composition in terms of material fractions is shown for example countries in table 2 the data represent household waste prior to any recycling scheme. In general terms, household waste typically consists of one-third of organic kitchen waste, one-third paper, and paper products, and one-third of other waste. The composition is subject to national and regional conditions as to how other regulations and systems affect selected material fractions. For example, in the United States kitchen grinders (a small mill in the kitchen sink that allows solid vegetable waste to enter into the sewer) are common, reducing the content of vegetable waste in household waste. Another example is the long-established system for returnable beverage bottles and cans in Denmark, where high deposits on beverage containers bring these backs into the shops and hence reduce the content of glass bottles, aluminum cans, and plastic bottles in household waste.

Table 2 Composition (material fractions, %) of household waste in selected countries. The data presented are adjusted to shown material fractions and are not necessarily direct citations from the cited references.

Household waste (%)	Japan Own data	UK 1992 Adapted after Williams (1998)	USA 1990 Adapted after Tchobanoglous, G., Theisen, H., and Vigil, S. (1993)	DK 2002 Petersen and Domela (2003)
Vegetable food waste	36.0	18.1	8.4	22
Animal food waste				6
Newspapers and weekly papers	9.6	12.9		8
Advertisings and printed matter	4.2	6.8		8
Nappies, sanitary towels and cotton	7.5	7.1	35.8	6
Wiping paper	-			2
Other clean cardboard and paper	3.5	3.8		1
Cardboard and paper packaging	4.5	3.9	6.4	4
Other dirty cardboard and paper	1.2			3

Plastic packaging and containers	10.4	3.3	6.9	1
Other plastic	2.5	6.5		10
Flowers and yard waste	3.4	3.6	17.2	3
Other combustibles	6.2	11.9	3.9	9
Glass containers	5.4	9.7	9.0	8
Other glass	0.3			0.2
Iron and metal packaging	3.6	6.2	6.4	3
Other iron and metal	0.4	1.6	3.0	1
Other noncombustibles	1.3	4.6	3.0	5
Total	100	100	100	100

2.2.4 Garden Waste

2.2.4.1 Unit Generation Rates

Garden waste has existed as long as gardens have existed, but the collection of garden waste is in most countries a relative recent municipal service. For example, figure 5 shows the trend in unit generation rates for Denmark, showing an increase from about 55 kg/ person/ year in 1994 to about 90 kg/ person/ year in 2000. After 2000 the unit generation rates for garden seem to stay constant in Denmark. Some countries did not in the late 1990s register any garden waste in the municipal waste management.

Garden waste will, by nature vary a lot from place to place depending on the type of residential areas, level of public parks and recreational areas, climate, and type of garden vegetation, as well as on local tradition with home composting and the services provided. The more service provided, the more garden waste is collected. Also, the level of professional garden service is expected to influence the amount of waste collected because professional gardeners often will remove the waste they generate. Note that there is a distinct difference in the way we define household waste and garden waste. We address the generation of the household waste supposing that all waste generated shall be collected because there is no acceptable alternative disposal route (maybe except home composting of kitchen greens). In terms of garden waste, we focus on what is collected because there may not be any garden waste in a residential area and there are acceptable alternative ways of disposal of the garden waste (composting in the garden, use of wood in a fire place, but maybe not open burning in the yard).

The generation of garden and yard waste is highly seasonal, where climatic seasons exist. The monthly amount of garden waste received at the composting site in

Aarhus, Denmark. During the winter months, the generation may be less than 5 kg/person/month, while during the active garden season, the generation may exceed 15 kg/person/ month.

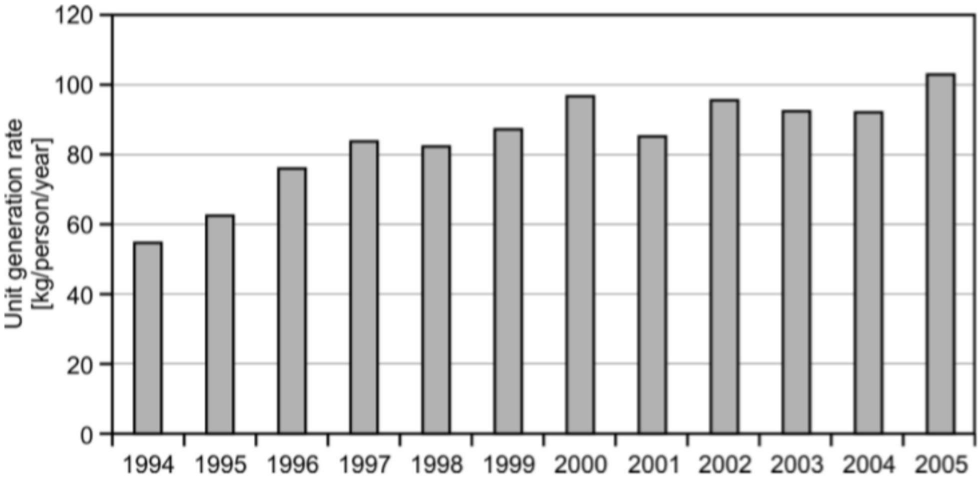


Figure 5 Garden waste unit generation rates for Denmark for the period 1994-2005 (based on DEPA. 2006)

2.2.4.2 Composition

Garden waste composition is also affected by season. Reports material fractions and chemical composition of Danish garden waste in summer and winter. It can be seen that the fraction of fine material (grass, flowers, leaves, soil, etc.) is predominant in summer when caretaking of the lawn is one of the main activities in gardens. This is also reflected in the C/N ratio, as shown during summer, the presence of nitrogen-containing material (grass, flowers, etc.) results in a C/N ratio around 35, while during winter the predominance of carbon-containing material (wood, branches, etc.) increases the C/N ratio to approximately 70 (Boldrin and Christensen. 2010)

2.2.5 Bulky Waste

Bulky waste is an irregular waste, typical with respect to size, so that it does not fit into the regular waste collection system. This may be furniture and white goods from the kitchen; waste that we all produce, but on a very irregular basis. Bulky waste is thus primarily collected by special collection systems, for example, 2-4 times annually on scheduled dates or upon request, or brought to collection or recycling centers by the citizen when convenient. What is considered bulky waste depends on local conditions and tradition. The bulky waste amounts to 120-130 kg/person/year in the two cities. Shows that the unit generation rates of bulky waste vary significantly among countries.

The material fractions of white goods and electronic waste are shown in considering the irregular appearance of the bulky waste and its ways of collection, bulky waste often also includes the special waste that cannot be collected by the regular waste collection system due to the composition of the material. This may be an electronic waste not covered by any producer's responsibility. Accordingly, bulky waste should, in many cases be named “bulky and special waste”. Bulky waste may, in some countries, also include building and demolition waste from households.

2.2.6 Household Hazardous Waste

Household hazardous waste is defined in different ways in different countries and in some countries, this waste type is not considered a regular part of residential waste. However, as the hazardous waste from commerce and industry becomes more strictly regulated, the hazardous waste from household starts playing a relatively larger role. Household hazardous waste originates from cleaning, maintenance, personal care, medicine, hobbies, and gardens. Household hazardous waste may contain some or all of these items (Gendebien, Leavens, Blackmore, Godley, and Lewin. 2002)

2.3 Collection

2.3.1 Waste Collection: Systems and Organization

Waste collection technology in terms of equipment and vehicles used in the waste collection has described the systems using this technology, and the organization and financing of the systems are described in this. Included are issues such as:

- Waste collection systems.
- Environmental aspects of waste collection (resources, emissions, social issues, occupational health).
- The role of public authority and private sector in waste collection.
- Organizing a collection of residential waste.
- Fee schemes.
- Public awareness programs.

2.3.1.1 Waste Collection Systems

The diversity of systems for waste collection exists around the world. The main factors determining a system are:

- Waste types at each source. The different waste types most likely will subscribe to different collection systems.

- Amount of waste at each source and its distribution over the year. A frequent and regular collection system is only economical for waste generated in significant quantities all year round. Thus, seasonal waste (e.g., garden waste) and irregular waste (e.g., discarded furniture) are usually collected by other systems than those used, for example, for household waste.

- Source-segregation systems introduced (mandatory, voluntary). This will affect the number of fractions to be collected separately and the technical systems introduced to affect the efficiency of the source segregation. The technical systems may vary for the different fractions depending on their quantity, storage ability, and value.

- Single-source (e.g., family) versus multi-source receptacles. The more people using a bin the more economical the collection is (large quantities collected each time). But users of multi-source (joint) receptacles are often less responsible than users of a single-family receptacle because eventual savings and costs (e.g. where pay, as you throw, has been introduced) are not directly related to the individual user, and any abuse (e.g. waste in the wrong container) is less traceable back to the user. This issue is, in particular, related to source segregation of certain fractions, e.g., recyclables and household hazardous waste.

- Physical placement of the receptacles. Waste placed in the street ('at the curb') with easy access for large collection trucks is easy to collect, while collection is slow and expensive if the receptacles are placed in the backyard and the waste collector must walk onto the premise to remove the full receptacles and furthermore may have to return the empty bin to the backyard. This collection system is often termed a full service.

- The degree of involvement of the waste producer in the waste collection. If the user can easily reach the right bin for a specific waste fraction, it is likely that the user will do so (for example if the bin is placed close to the kitchen door in a single-family house), while the user may seek alternative or incorrect ways of disposing of the waste if it is too demanding to bring the waste to the right point of collection. This issue also partly relates to the cases where the user has to bring the bin to the pick-up point, e.g., bring the garden waste collection bin to the curbside. If waste from apartment buildings is brought to the curbside by the building manager, this is considered a professional activity and is probably not subject to a lack of participation in organized waste collection.

- Collection schedule (fixed routine, infrequent schedule, upon request). Fixed routines are often used for regular and large quantities of waste; infrequent schedules are typically used for seasonal waste or smaller but storage fractions, while collection upon request is often used for irregular and bulky waste.

The most common waste collection systems may be categorized as:

- Full service, permanent (individual or joint). The receptacle for the waste is placed at a convenient location on the premises and the collection crew comes to the stand according to a fixed schedule and empties the receptacle (empty on location, empty at the truck, and return to stand, replace with the empty receptacle. This system has a high service level and requires no specific involvement of anybody but the collection crew. The system is common for mixed household waste in single-family residential areas and in apartment areas in cities. In apartment areas, the collection point may have large-capacity receptacles for several waste types, ranging from mixed household waste, over recyclables to hazardous waste. The system is also common in newer highrise areas where the collection trucks can drive to the collection point. Often a building manager or similar supervises the collection point and is the contact person to both the waste producer and the waste collectors.

- Full service, requested (individual or joint). The receptacle is placed at a convenient place on the premise and when close to full, the collection is requested by phone or email. This is a common system for commercial and industrial waste collected in large bins and containers but is also seen for less regular waste from apartment blocks (e.g., discarded furniture).

- Curbside collection, permanent (individual or joint). The receptacle is placed permanently at the curbside, and the collection crew has easy access to the receptacle, which is emptied according to a fixed schedule. This system is common for mixed household waste, recyclables, and maybe garden waste in single- family residential areas.

- Curbside collection, scheduled (individual or joint). The home-owner brings the receptacle or the waste according to a fixed schedule to the curbside for collection. The homeowner also returns the receptacle. The system is common in single- family residential areas for household waste, recyclables, and maybe garden waste, typically with weekly or biweekly collection days (e. g. Tuesday in odd-numbered weeks). The system is also common for apartment areas in cities for household waste (e. g. daily or twice a week) where the work typically is done by the building manager rather than by the individual citizen. This system may also be used for less frequent collection of bulky waste or hazardous waste on publicly announced days, for example twice in the spring and twice in the fall.

- Curbside collection, requested. This system may be used for infrequent waste, such as discarded furniture, white goods, etc. The waste producer requests the collection and brings the waste to the curbside ready for collection on a day specified by the waste collector. This system is common in single-family areas.

- Public collection points. This system may collect a limited number of fractions and is often equipped with robust equipment to resist abuse. Collection points are often placed at frequently traveled routes such as main roads, bus stops, supermarkets, and shopping centers. The relation between the waste producer and the waste collected is less apparent and less supervised than in the case of the joint collection point. This system is very common for the collection of recyclables like paper, glass, cans and partly also plastic packaging. The system is common for all waste types in areas with very dense housing with limited truck access or in sparsely populated areas, where distances are long between the individual houses. Collection points are also called collection islands, drop- off points, local bring systems, among other things.

The different systems have different levels of service or seen from the waste producers' point of view, requires his engagement and effort in different degrees. The different systems also have different costs. In general, the smaller the amount of waste per collection and the more involvement of the collection crew, e. g. difficult access for the collection crew to the receptacle in a full-service waste collection system, the more costly is the system. Designing a waste collection system is thus dependent not only on physical factors, as for example types of waste, source segregation, and housing structure, but is, to a large degree, a political issue as to wanted services and willingness to pay for the services.

2.3.1.2 Waste Transfer Stations

Collection and transport are usually the costliest part of any waste management system; and when waste is transported over a considerable distance or for a long time, transferring the waste from the collection vehicles to more efficient transportation may be economically beneficial. This involves a transfer station where the transfer takes place. These stations may also be accessible by private people, offering flexibility to the waste system, including facilities for bulky waste, household hazardous waste, and recyclables.

The waste transfer may also take place on the collection route from small satellite collection vehicles to large compacting vehicles that cannot effectively travel small streets and alleys within the inner city or in residential communities with narrow roads. However, mobile transfer is not dealt with in this, which focuses on stationary transfer stations (Tchobanoglous, et al. 1993)

1) Main Features of Transfer Stations

Waste transfer stations can be categorized according to three main features:

- Waste delivery.
- The waste transfers.
- The transportation of the reloaded waste. Several sketches of waste transfer stations are shown in figure 6

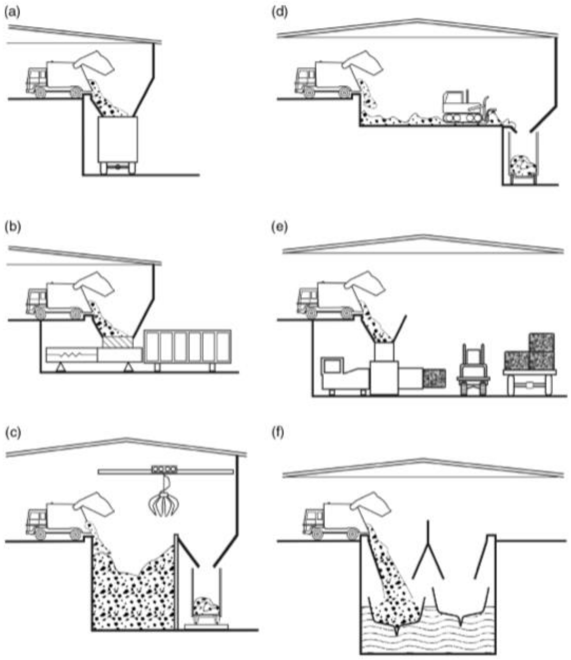


Figure 6 Sketches of waste transfer stations. (a) Direct transfer into open semitrailer. (b) Transfer via compacting into containers. (c) Transfer via bunker and reloading by crane into a railroad car. (d) Transfer via floor and pushing by dozer into open semitrailer. (e) Transfer by baling and hauling by truck. (f) direct transfer into barge.

(Source : Tchobanoglous, et al. 1993.)

2) Waste Delivery

The waste delivery is characterized by the type of waste accepted at the transfer station and those who have access to the station. A wide range of possibilities exists: (1) a waste transfer station where mixed residential and commercial waste is only brought in by authorized collection vehicles is fairly straightforward and serves to cut transport cost, (2) a transfer station which, in addition to the waste brought in by authorized collection vehicles, also accepts waste from private vehicles including recyclables, bulky waste and household hazardous waste, may also function as an integrated public service facility in the waste management system. These issues may affect the siting and the design of the station.

Waste deliveries by authorized vehicles and by small private trucks and cars usually are kept separate for many reasons (Tchobanoglous, et al. 1993)

- Efficiency: Efficiency must be high when authorized collection vehicles delivering waste to a transfer station, as any waiting in line to get access to the unloading area is costly. The delivery should not be disturbed by private people unfamiliar with the transfer station delivering small quantities of waste.

- Safety: Safety is important, and private people unfamiliar with the routines of professional waste collectors should not be present in the unloading zone. Backing and tipping trucks, as well as bunkers and silos, may be sources of danger to people unfamiliar with the situation.

- Inspection: While authorized trucks usually deliver waste of known origin and composition, private deliveries may contain waste that should follow other treatment or disposal routes. Unloading of private waste on a floor may provide inspection possibilities prior to mixing of the waste with other waste.

- Sorting: If recyclables, bulky waste, and household hazardous waste are also accepted at the transfer station, private cars often bring different kinds of waste in the same load, and thus time, space, and facilities may be needed for sorting this waste.

3) Waste Transfer

The transfer of the waste may be characterized as (Tchobanoglous, et al. 1993)

- Direct transfer by unloading directly into the body of the long-distance transportation system (trailer, rail car, barge) using only gravity. The lack of buffer in this system requires that the receiving transportation system has plenty of capacity and flexibility.

- Transfer via a floor, bunker or silo, which provides some flexibility with respect to capacity, possibility of inspecting the waste, and depending on the loading system (grab, dozer, modified backhoe) also some homogenization and compaction of the waste.

- Compaction of the waste during the reloading by means of stationary compactors compacting into containers, semitrailers or pull trailer (see figure 7) or by compacting equipment associated with the long-haul vehicles. Compaction is usually only done when containers, semitrailers or pull trailers are used for the long haul.

- Mechanical treatment in terms of shredding and baling may be introduced to increase the bulk density of the waste prior to reloading.

The main purpose of the transfer is to bring as much waste as possible into the units of the long-distance transportation system. This takes either a large volume carrier or mechanical means to increase the bulk density of the reloaded waste. The bulk density after compaction into a container may be about 0.6 t/ m^3 for mixed waste

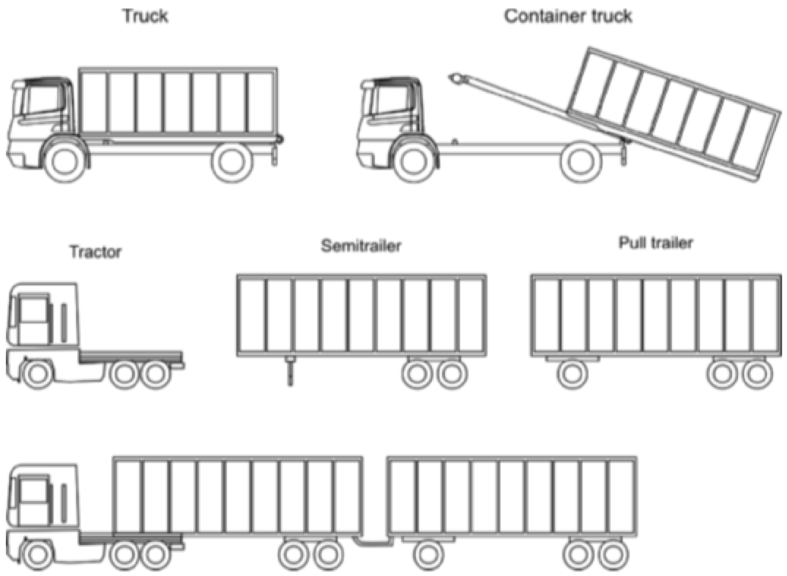


Figure 7 Sketches of long-haul transportation vehicles.

(Source : Tchobanoglous, et al. 1993.)

4) Waste Transport

The transport of the reloaded waste may be by road, railroad or waterways.

- Road Transport of waste takes place by truck, container, semitrailer, and pull the trailer. Containers are loaded onto trucks while semitrailers are pulled by a truck tractor.
- Railroad Transport of waste by railroad is used where large quantities of waste are being transported long distances. A railroad car may easily carry 50t of waste.
- Waterway Transport by barge is possible where large amounts of waste are transported in the vicinity of navigable water. A barge may contain 300t of the waste but moves at a moderate speed.

5) Siting and Design Issues

Several aspects should be considered in the siting and design of waste transfer stations.

- Siting

Siting of the waste transfer system may be guided by minimizing the cost of transporting the waste, including transport prior to transfer and transport after transfer. The ‘center of waste mass’ is not the optimal location of the transfer station as intuitively believed by some; some location between the ‘center of waste mass’ and the outskirts of the city in the direction of the final unloading place is most likely better from a theoretical and economic point of view. However, in practice many other factors control the siting of the transfer station: traffic patterns, distance to through roads, traffic noise and noise from the transfer operation may suggest that the transfer station is located in an industrial area, while the eventual use of the transfer station by private people may suggest a location closer to residential areas.

- Peak Hours

The waste does not arrive at the transfer station evenly distributed over its opening hours. In order to avoid unnecessary waiting time, the unloading area must be sufficiently large and organized in such a way that traffic jams do not develop. If the storage of waste is limited the long-distance transportation system must also be geared to accept peak loads. In some cases, containers are placed on a mechanical container-changing system so that a new container can be made accessible without having the truck available at the site. Sizing the station so that it can handle one-third of the daily average of waste within one hour should limit long waiting for unloading.

- Noise

The traffic related to a waste transfer station and the operation of the waste transfer station may be noisy if not properly addressed in the siting, design, and operation of the station. The latter may also involve restricted opening and operation hours.

- Operational Stability

Any additional technical process increases the vulnerability of the waste management system with respect to a breakdown. Therefore, the design of the transfer station must consider the stability of the system introduced and its suability to remediate any breakdown: This relates both to the reception of waste and to the facilities that receive the transferred waste; for example, an incinerator that needs waste continuously. Parallel lines of operation or the possibility of routing the collection trucks directly to the treatment or disposal facilities must be considered as part of the contingency plan.

6) Economic Considerations

Assessing the economic consequences of introducing a waste transfer station must be based on an integrated assessment of the actual waste management system, since the waste transfer may affect several elements in the system. Assuming that the waste transfer station will save on the cost of waste transport, it is very important to assess in each case whether any savings can actually be realized in the collection system because of less transportation of the waste after the collection vehicle has finished its collection route. This again depends on how much transportation time is saved and the possibility of using the saved time to make the collection more efficient and cheaper. The wage system for the collection workers may be an important factor here (Tchobanoglous, et al. 1993)

2.4 Thermal Treatment

2.4.1 Incineration: Process and Technology

Incineration of waste has been practiced for more than a century in the industrialized world. The incineration technology has developed dramatically from basic disposal units reducing waste volumes and hygienic problems to modern waste-to- energy plants with extensive process and emission control systems. Waste incineration is the thermal conversion of waste with a surplus of air. This releases energy and produces solid residues as well as a flue gas emitted to the atmosphere.

Waste is not an ideal fuel, and it is important, as described below, to link the fuel characteristics to the combustion process.

2.4.1.1 Waste as a Fuel

Waste incineration plants are designed to treat waste with great variation in the composition of the incoming waste. This is the primary difference between waste incineration and other combustion systems, and it has large implications on the design of the incineration plant.

The practical design of incineration systems, however, limits the allowable variations of the waste composition. For the design of a waste incineration plant, the best available data on the amount and composition of each waste type is needed, and the effect of expected future changes in the waste management system should be taken into consideration, for example, the introduction of source segregation or pretreatment.

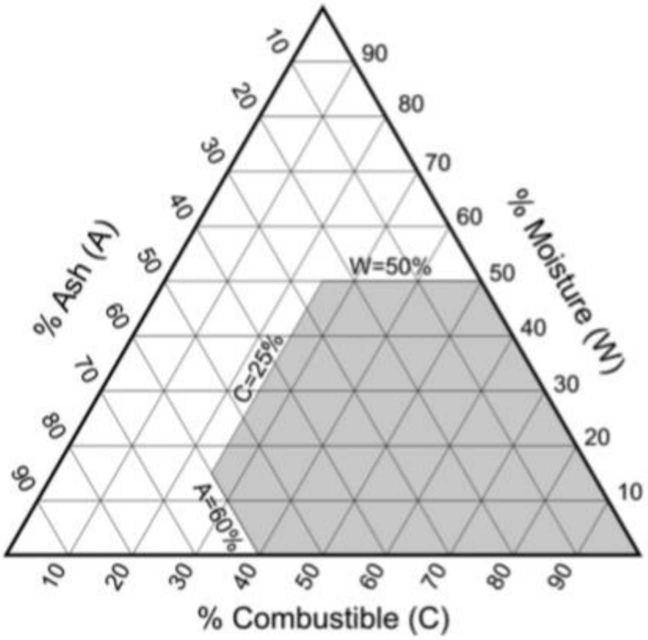


Figure 8 Tanner's diagram. Waste within the shaded area can be combusted without auxiliary fuel.
(Source : Kleis and Dalager. 2004)

The waste being led to the incineration plant often consists of several types of waste, such as household waste, some bulky waste, commercial and institutional waste, and some industrial waste. In some cases, also clinical waste and sewage sludge are incinerated. Street sweepings and construction and demolition waste containing a large fraction of incombustible matter are less suited for incineration. The different waste types received at the incinerator have significantly different characteristics, in particular in terms of heating value, moisture content and ash content. These are the three key variables in characterizing waste as fuel (Kleis and Dalager. 2004)

1) Waste Characteristics

The simplest way of characterizing waste as a fuel is to determine (based on wet waste) the moisture content, W (typically 15-35% when drying at 105◦C), and the (inorganic) ash content, A (typically 10-25% after ignition at for example 550°C) and then to calculate the combustible (organic) solids, C, as the difference between the dry solids and the ash content (typically 40-65%). Know characteristics, Tanner’s diagram can be used to examine whether or not the waste can be combusted without auxiliary fuel. If the data are located within the shaded area (W < 50%, A < 60%, C > 25%) it indicates that the combusting process does not need auxiliary fuel (see figure 8)

2) Heating Values

The lower heating value of the waste (the energy content available from complete combustion when assuming no energy losses) is the most important variable for determining whether the waste can sustain the combustion process without supplementary fuel. The theoretical maximum energy content is expressed by the higher heating value, which includes the heat of condensation of water vapor released in the combustion process.

The minimum lower heating value required for controlled incineration depends on the furnace design. Low-grade fuels require a furnace design minimizing heat loss and allowing for drying of the waste prior to ignition, and the air needed for the combustion process should be preheated. When the heating value is high, the furnace design should allow for extraction of heat from the furnace, e.g. by integrating the boiler in the furnace. The heating value is, therefore, an important parameter for the planning and design of a waste incineration plant.

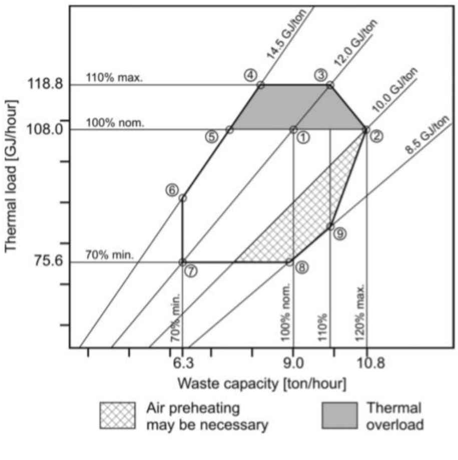


Figure 9 Plant capacity diagram. The nominal load point is indicated by (1).

(Source : Kleis and Dalager. 2004)

3) Plant Capacity

The typical (nominal) heating value and allowable variations are depicted together with the fired amounts in a so-called capacity diagram, illustrated by an example in Figure 9. For this specific furnace, the nominal heating value is 12MJ/kg, and the allowable variation is 8.5-14.5MJ/kg. This is a very broad interval compared to systems designed for combustion of a single type of fuel such as coal, straw, or wood chips.

The nominal load point figure 9 shows a nominal heating value of 12MJ/kg and a nominal waste capacity of 9 t/h. This corresponds to a nominal thermal capacity of 9×12=108 GJ/h = 108/3.6 = 30MW, 100% thermal load. In case the heating value increases (not higher than 14.5 MJ/kg), the control system will reduce the mass throughput so that the thermal load is maintained at 100%.

The nominal heating value should preferably correspond to the average value expected over the lifetime of the plant. In industrialized countries, where waste incineration plants often treat a mixture of wastes, the nominal heating value would typically be in the range of 10-12MJ/kg. If the plant treats only household waste or large quantities of market waste, the value may be lower; if the plant is to incinerate upgraded waste (refuse-derived fuel), it may be higher. As mentioned previously, due consideration should also be given to the effect of expected future changes in source segregation of certain waste fractions.

2.4.1.2 The Incineration Process in General

Figure 10 is a simplified cross-section of a typical waste incineration plant with a moving grate furnace and horizontal steam boiler generating energy in the form of both power and heat. It should be noted that the flue gas cleaning system is one of many potential layouts, cf. In the furnace, the overall result of the incineration process is that the combustible components react with the oxygen of the combustion air, releasing a significant amount of hot combustion gas. Furthermore, the moisture content of the waste is evaporated in the initial stage of the incineration process, and the incombustible parts of the waste form solid residues (bottom ash, fly ash). Through the incineration process in the furnace, the solid constituents of the waste undergo a range of processes as a result of exposure to heat and contact with the combustion air: drying, pyrolysis, and gasification (in which combustible gases are formed), ignition and combustion of these gases and burnout of the solids.

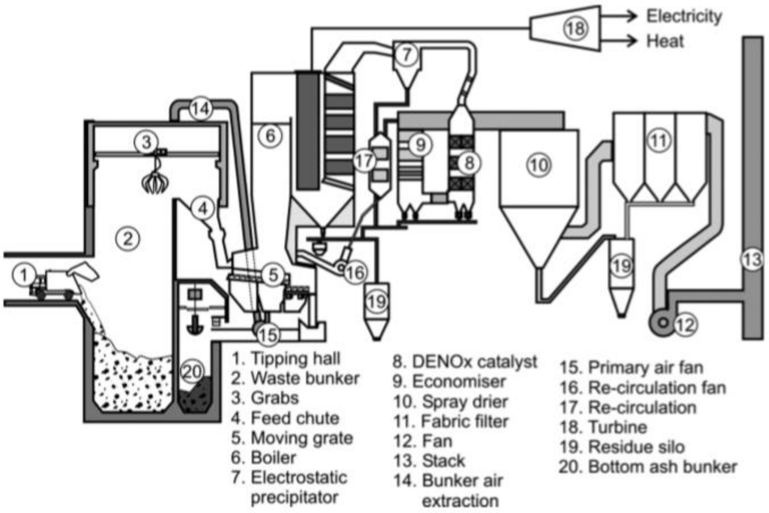


Figure 10 Cross-section of a typical waste incineration plant with a moving grate furnace.

(Source : Kleis and Dalager. 2004)

1) Processes and Energy Recovery

The combustion gases pass from the furnace to the afterburning chamber. For the purpose of ensuring complete burnout, legislation usually sets a minimum temperature for the combustion gases in the afterburning chamber (within the EU 850 ˚C for municipal waste and 1100 ˚C for certain types of hazardous waste). It is required that this temperature is maintained for a certain minimum of time (2 sin the EU) as measured from the last injection of combustion air. In the EU, it is furthermore a requirement that no waste is fed into the incinerator before the required temperature has been reached and that the feeding of waste is interrupted when the temperature drops below the required minimum temperature of 850 ˚C or 1100 ˚C.

Air emissions of CO and total organic carbon (TOC) relate exclusively to the quality of the combustion process. Improper furnace design or operation which results - even locally - in too low a combustion temperature, a lack of oxygen or too short a flue gas residence time at high temperature causes the limit values of CO and/or TOC to be exceeded. The content of CO and TOC (before the inlet to the flue gas cleaning system) is, therefore, a good indicator of the efficiency of the combustion process.

The flue gas is cooled by radiation and convection to the walls and other heating surfaces of the furnace and boiler. In the boiler, pressurized water is heated, and in the case of a high-pressure steam boiler it is evaporated, and the steam may be superheated (i.e. heated above its saturation temperature). The purpose is to exploit its energy content by expansion in a steam turbine, which is connected to a power generator. In a combined heat and power plant, typically 25% of the steam's energy content is transformed into electrical power. The remaining energy is regained by condensation of the exhaust steam from the turbine in a heat exchanger, thereby potentially generating hot water for district heating purposes. The condensate is transferred back to the feed water tank, from which the water is reused for the boiler, thereby generating a closed circuit. The water and steam circuit of the high-pressure boiler is called the Rankine process. Typical power generation efficiency would be 20-25% of thermal input for a combined heat and power waste to energy plant, increasing to 25-35% in the case of power production, only. This should be compared with efficiencies of up to 50% for coal fired plants.

In areas where the demand for heat is low, the energy from incineration of MSW is usually recovered as electricity or process steam or a combination of both. The surplus heat is not utilized and is cooled off instead, e.g. in cooling towers. A means for utilizing the excess heat and thereby increase the overall efficiency of the waste incinerator is by absorption cooling (Andersen. 2006)

Absorption cooling, sometimes referred to as absorption chilling or district cooling is comparable to the principles of a refrigerator. The main difference is that a refrigerator needs electricity to run a compressor driving the cooling system, whereas the absorption system utilizes a heat source to provide the energy needed to run the cooling system. Both units draw heat away, leaving the surrounding area cooler. Two commercially available absorption cooling systems exist: one uses water as refrigerant and lithium bromide (LiBr) as absorbent material. The other uses ammonia (NH_3) as refrigerant and water as absorbent.

An absorption cooler consists of the four main elements illustrated in the figure below: Generator, condenser, evaporator, and absorber. Other components needed are a pump, an expansion valve, a throttle valve, a heat exchanger, and a separator. The main features of the cooling process are the separation and re-absorption of the refrigerant and absorbent taking place in the evaporator and absorber, respectively. The key principles are:

- Heat, e.g., waste heat from an incinerator is lead to the generator, whereby the refrigerant is evaporated and lead to the condenser.
- In the condenser, the refrigerant turns into a liquid again, releasing heat (heat of condensation) to the ambient air. This takes place at high pressure and high temperature.
- The refrigerant is subsequently via an expansion valve lead to the evaporator. The expansion valve reduces its pressure and boiling point temperature. In the evaporator, the refrigerant is boiled hereby, absorbing heat from the ambient air. This creates the chilled water applicable for e.g. district cooling.
- From the evaporator, the refrigerant is lead to the absorber where it dissolves while releasing heat. Finally, the solution constituted by refrigerant and absorbent is pumped back to the starting point by means of a heat exchanger. The circle is closed and the process can start again (DEA. 2007)

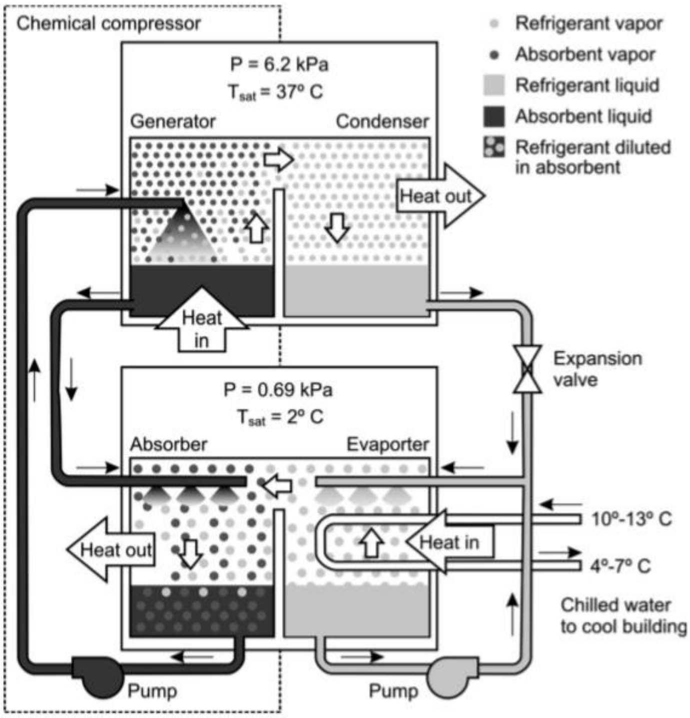


Figure 11 The process is dependent on a heat source and that heat can be removed from the system by cooling water or a cooling tower.

(Source : DEA. 2007)

2) Solid Residues

The main part of the ash content of the waste leaves the furnace as a solid residue, i.e., bottom ash or slag. In order to ensure proper burnout, immobilization of heavy metals, etc., legislation usually requires the bottom ash to hold a certain maximum of remaining organic matter, measured as loss on ignition (LOI) or total organocarbon (TOC). Within the EU, the content of LOI and TOC may not exceed 5% and 3%, respectively (EU. 2000) However, the possible use of bottom ash may pose stricter requirements.

The remaining ash leaves the furnace as fly ash. The fly ash is normally separated from the flue gas in three different places in the boiler and the flue gas treatment system:

- In the boiler, the first fraction of the fly ash is separated by gravity at the bottom of the vertical second radiation pass of the boiler. This fly ash fraction is normally separated as an independent fraction, i.e. separated from the remaining boiler ash; cf. below. It is relatively coarse and has physical and chemical properties similar to the bottom ash. It is, therefore, often mixed with and made use of together with the bottom ash.

- The second boiler ash fraction is deposited on the heating surfaces of the boiler, from which it is removed by an automatic system. This fraction has physical and chemical properties similar to the fly ash removed in the flue gas cleaning system and is therefore normally mixed and managed together with that fraction.

- The third fly ash is separated from the flue gas after the boiler in the flue gas cleaning system in an electrostatic precipitator or baghouse filter. The flue gas cleaning system may (and normally does) also generate other solid residues and wastewater, cf.

3) Flue Gas Volume

The incineration of municipal solid waste generates large volumes of flue gases. The raw flue gases carry a wide range of pollutants harmful to nature and human health. The pollutants present and their concentration depend on the composition of the waste incinerated as well as on the combustion conditions. Ash, heavy metals, and a variety of organic and inorganic compounds, however, are always found. The volume of flue gas is closely related to the thermal input to the incinerator and the excess air level and is a major factor in dimensioning the air pollution control measures.

As a rule of thumb, all fuels may be assumed to produce a dry, stoichiometric flue gas quantity of some 0.26Nm3/MJ thermal input. Stoichiometric refers to the hypothetical condition that the fuel is burned completely with only just the quantity of combustion air (oxygen) theoretically needed for the combustion process. Consequently, the oxygen content in the resulting flue gas is zero. The volume of the water vapor formed by evaporation of water in the waste and from the combustion process should be added.

In order to ensure complete burnout of the flue gas and bottom ash, a certain excess air level is needed, represented by oxygen in the flue gas. Optimization of the furnace should, however, keep the excess air level as low as possible for the purpose of minimizing the dimensions of the main components of the plant and maximizing the energy production.

2.4.1.3 Combustion Technology

It is illustrated above that the combustion technology shall be designed and dimensioned with due consideration of, amongst other things, the waste characteristics, desired capacity and legislative requirements on burnout and the flue gas residence time and temperature.

The heart of an incineration plant is the combustion system. The combustion system can be categorized as:

- Mass burning of inhomogeneous waste as received.
- Burning of homogeneous waste of limited particle size.

In systems designed for mass burning of inhomogeneous waste, little or no pretreatment, such as size reduction, shredding, or sorting, is required. This is true even though different types of waste are delivered to the plant, e.g. residential, commercial and industrial waste. Mass burning systems are typically based on a moving grate technology. It is technically robust and able to accommodate large variations in waste composition and heating value. Another not so common mass burning alternative is the rotary kiln.

Systems for incinerating homogeneous waste normally require pretreatment and homogenization through size reduction, shredding, and/or manual sorting or even production of ‘refuse-derived fuel,’ which are demanding complications when they are to receive inhomogeneous waste.

The design of the combustion system must, as far as possible, aim at preventing the formation of pollutants, especially NO_x and organic compositions such as dioxins. Appropriate measures to ensure an efficient combustion process (complete burnout of the bottom ashes and the flue gases, low dust content in the raw flue gas etc.) comprise a long flue gas retention time at high temperature with an appropriate oxygen content, intensive mixing and recirculation of flue gases, optimal supply of combustion air below the grate and before inlet to the after combustion chamber, as well as proper mixing and agitation of the waste on the grate.

1) Depending on the quality of the waste and the incineration system, some kind of pretreatment may be necessary. Pretreatment involves sorting and homogenization before the waste is incinerated.

For mass burning incinerators pretreatment may involve (EU. 2000):

- Removal or shredding of bulky or heavy items, which may block the feeding systems or cause damage to the mechanical parts of the plant. This may be done on the floor of the reception hall or in the bunker, where the overhead crane can remove bulky items.

- Mixing of low and high heating value waste is typically carried out in the bunker by the overhead crane in order to achieve the best possible basis for controlling the energy input and the combustion process.

For fluidized bed incineration pretreatment may involve:

- Shredding to homogenize the waste.
- Screening in order to further narrow the particle range-fed to the fluidized bed.
- Removal of metallic iron with magnets.

2) Moving Grate Incineration

The conventional mass-burn incinerator based on a moving grate consists of a layered burning of the waste on the grate that transports the waste through the furnace. Figure 9 shows a moving grate incinerator. An overhead crane feeds the waste into the hopper, where it is transported via the chute to the grate in the furnace. On the grate the waste is dried and then burned at high temperature while air is supplied. The ash (including noncombustible waste fractions) leaves the grate via the ash chute as slag/bottom ash. The main advantages of the moving grate are that it is well proven technology, can accommodate large variations in waste composition and in heating values, and can be built in very large units (up to 50t/h). The main disadvantage is the investment and maintenance costs which are relatively high.

The grate forms the bottom of the furnace. The moving grate, if properly designed, ensures an efficient transportation and agitation of the waste and an even distribution of combustion air. The grate is usually sectioned into individually adjustable zones, and usually there is a possibility of preheating the combustion air in order to accommodate the variations in the lower heating value of the waste. Several alternatives for the design of the grate are available.

3) Rotary Kiln Incineration

The mass burning incinerator based on a rotary kiln consists of a layered burning of the waste in a rotating cylinder. Figure 12 shows a rotary kiln incinerator. The material is transported through the furnace by the rotations of the inclined cylinder. The rotary kiln is usually refractory lined but can also be equipped with water walls. The diameter of the cylinder may be 1-5m and the length 8-20m. The capacity may be as low as 2.4t/day (0.1t/h) and is limited to a maximum of approximately 480t/day (20t/h). The kiln rotates with a speed of typically 3-5 rotations/h.

The excess air ratio is well above that of the moving grate incinerator and the fluidized bed. Consequently, energy efficiency is slightly lower and may not exceed 80%. As the retention time of the flue gases usually is too short for complete reaction to take place in the rotary kiln itself, the cylinder is followed by an afterburning chamber, which may be incorporated in the first part of the boiler.

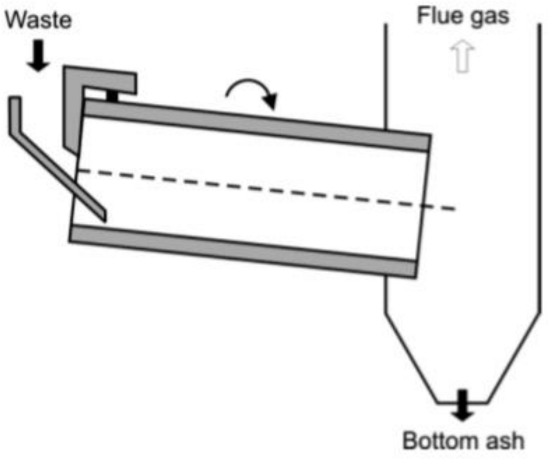


Figure 12 Rotary kiln furnace.

(Source : EU. 2000)

The rotary kiln may also be used in combination with a moving grate where the moving grate forms the ignition part, and the rotary kiln forms the burning out section. A very low level of unburned material in the slag may be achieved with a rotary kiln for the burning out section. It has, therefore, often been used in cases with waste of low heating value. The slag leaves the rotary kiln via the ash chute.

The main advantages of the rotary kiln are similar to the moving grate incineration system, except that the maintenance is slightly higher and the energy efficiency slightly lower. The investment cost and particularly the maintenance cost are, however, relatively high. The rotary kiln is therefore rarely used for new MSW incineration plants with high heating value wastes. Its most common use is for burning waste with special characteristics, for example, hazardous/ chemical waste where confinement of the waste matters or for low heating value waste such as animal waste/carcasses.

4) Fluidized Bed Incineration

Fluidized bed incineration is based on a principle where solid particles mixed with the fuel are fluidized by air. Figure 13 shows a fluidized bed incinerator. By fluidization, the fuel and solids are suspended in an upward air stream, thereby behaving like a fluid. The reactor usually consists of a vertical refractory- lined steel vessel containing a bed of granular material such as silica sand, limestone, or ceramic material. The fluidization of the bed is ensured by air injection through a large number of nozzles in the bottom of the incinerator. This causes a vigorous agitation of the bed material, in which the incineration of waste takes place in close contact with the bed material and combustion air. This allows for relatively low excess air level, thereby allowing for a high thermal efficiency, up to 90%.

The fluidized bed technology has a number of appealing characteristics in relation to combustion technique, reduction of dangerous substances in the fluidized bed reactor itself, flexibility regarding low-quality fuels, costs, etc.

A main disadvantage of the fluidized bed for waste incineration is the usually very demanding pretreatment before the fluidized bed. The waste must be treated in such a way that it meets the rather stringent requirements for size, heating value, ash content, ash composition, etc. Because of the heterogeneous composition of municipal solid waste, it can be difficult to produce a fuel that meets the requirements at any given point in time. The fluidized bed incinerator is, therefore, primarily useful for homogeneous waste types, including liquid waste. One such waste type is municipal sewage sludge; fluidized bed incinerators have become the generally preferred choice for sludge-only incinerators (Albertson, Bergstedt, Bruno, Copeland, Crumm, Haney, Homoki, Low, Noriega, Okey, Seiler, Semon, Wester, Wood and Zang, R.B. 1992)

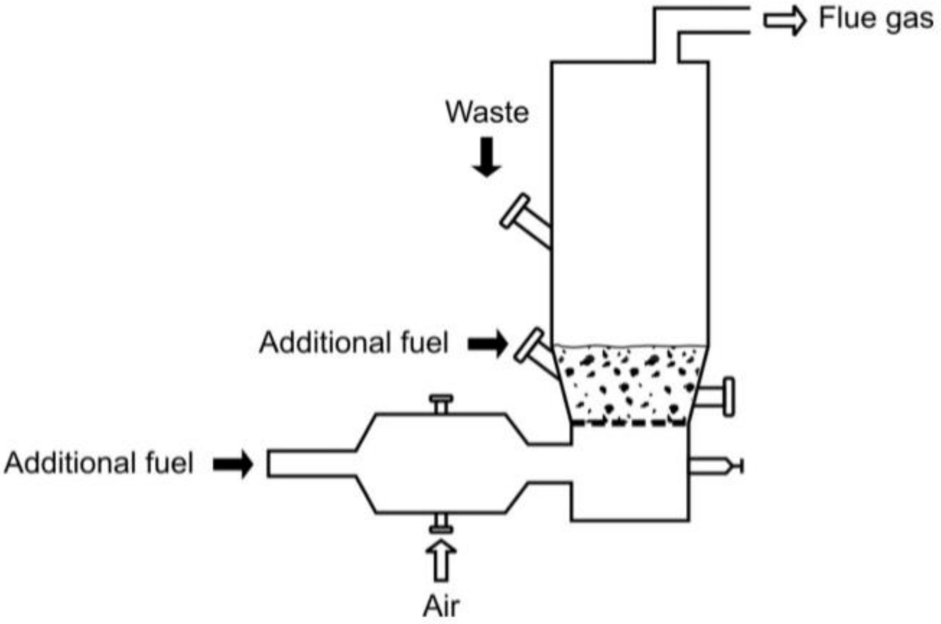


Figure 13 Fluidized bed furnace.
(Source : Albertson et al. 1992)

2.4.1.4 Design and Layout of Moving Grate Incineration Plant

Selected main design criteria and layout data, particularly related to mass burning by moving grate incineration technology, are presented below.

1) Grate

The grate has two principal purposes:

- Transportation, mixing, and leveling of the ‘fuel’/waste.
- Supply and distribution of primary combustion air to the layer of waste.

Various grate designs are available, usually characterized by their respective principles of ‘fuel’ transportation. These principles include horizontal forward and reverse pushing grates, roller grates, rocking grates, etc. Some of these grates are schematically illustrated in figure 14

The grate performance is of decisive importance to the entire plant, and in the choice of grate and grate design one should pay attention to its suitability for the waste to be incinerated, robustness to variations in heating value, ability to function also at less than full load, and be fully automatic from feeding to slag extraction without obstacles/clogging of any kind and without requiring manual intervention at any time.

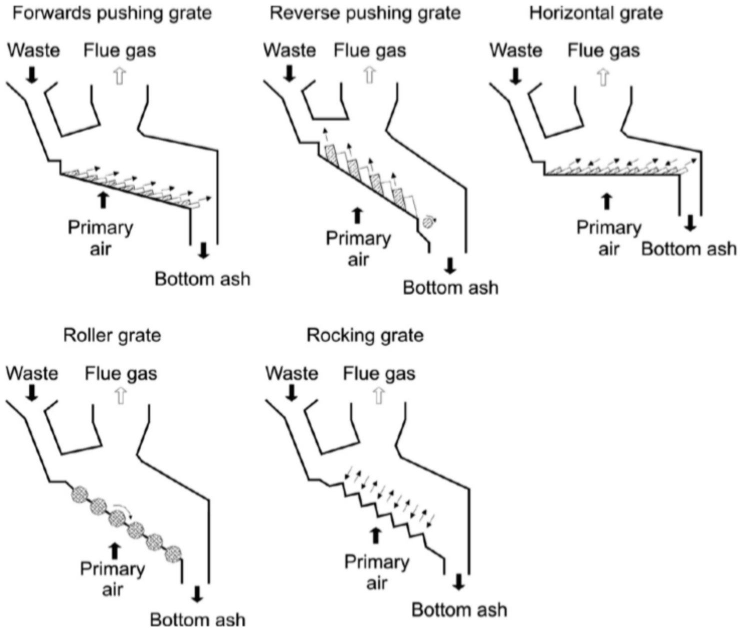


Figure 14 Moving grate technologies.

(Source : Albertson et al. 1992)

2) Grate - Air Supply

It is a decisive factor that the grate should be capable of performing the required intensive agitation, mixing and leveling of the waste layer for the purpose of creating the largest possible ‘fuel’ surface and, thus, efficient drying, ignition, combustion and final burnout of the slag/ash.

The expectedly high variations in load and heating values require a very flexible primary air supply system in respect to both the amounts supplied and the supply spots, as it should be possible to change the extent and location of the drying and primary combustion zones in relation to the waste composition and the waste load. Consequently, a relatively great number of adjustable air zones should be established under the grate. Depending on the specific type of grate, four to six longitudinal adjustable air zones should be established. The primary combustion air should be supplied to the waste layer through small slots in the front side of the grate bars or through 1-2 mm slots between the grate bars. Experience shows that the air supply area should as a maximum be 1.5-2.0% of the total grate area to ensure satisfactory air distribution. The rate of air supply through the slots will typically be 10-15 m/s.

3) Furnace

In principle, the furnace and the secondary combustion chamber, the afterburning zone, are designed, so that along retention and reaction time of the flue gases at high temperatures is ensured. Most important is the secondary combustion chamber, which is also the first radiation pass of the boiler, which needs a large volume and height so that all processes/reactions in the flue gas are terminated before they reach the unprotected boiler walls. Moreover, the size/volume and geometry of the furnace must be designed to minimize the risk of slag deposits and ash fouling on the furnace walls, which requires an adequately low thermal furnace load and as well as a relatively low flue gas velocity in the furnace.

The flue gas velocity in the furnace is usually maintained at a level lower than 3.5-4.0 m/s. It should be possible to control the furnace temperature in such a way that undesired peaks can be avoided. The furnace sections depend to a great extent on the chosen flue gas flow, which may basically be the so-called co-flow, counterflow, or midflow principle, as illustrated in figure 15. The choice of flue gas flow in the primary combustion chamber depends to a great extent on the prevailing type of waste, the heating value and the specific grate concept. The furnace temperature is usually in the interval 1000-1200 °C. It is determined by the combination of the heating value of the waste, the excess air level and the cooling caused by the furnace walls.

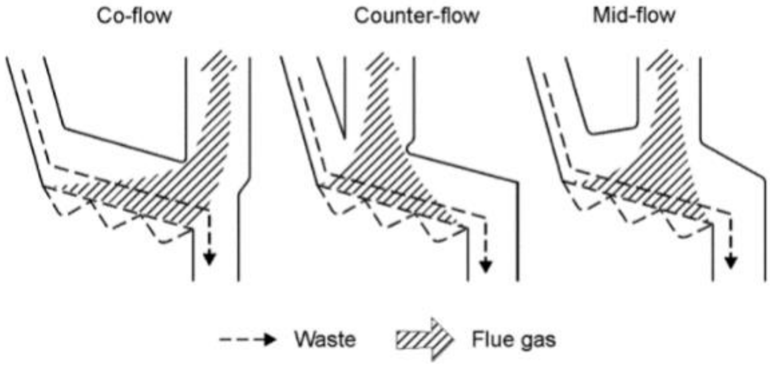


Figure 15 Examples of flue gas flow in the furnace.

(Source : Albertson et al., 1992.)

2.4.1.5 Energy Recovery Technology

The main benefit of solid waste incineration is the possibility of recovering the energy in the waste and by its utilization substitute energy production from other sources, preferably fossil fuels. The flue gases carrying the energy released in a waste incineration furnace have to be cooled in a boiler before the air pollution control system. The boiler is also a necessary technical installation for energy recovery. The type of boiler, however, depends on the intended energy use (Albertson, et al. 1992):

- Hot water for district heating.
- Process steam for various types of industries.
- Electricity or combined heat and power.

The choice between the various end-use possibilities depends on the local energy market conditions, including:

- Existing infrastructure for energy distribution, e.g., the availability of a power grid and a district heating network.
- Annual energy consumption pattern (the energy output from MSW incineration plants is usually determined from waste disposal requirements and is therefore fairly constant over the year).
- Prices of the various types of energy and possible agreements with the consumer (s).

The overall thermal efficiency of an MSW incineration plant equipped for energy recovery depends on the end use of the energy recovered. The production of electricity only has a low thermal efficiency, resulting in expensive energy, whereas hot water for district heating is considered cheap energy, but the overall thermal efficiency of hot water generation is high, and the complexity and the costs of the necessary technical installations are relatively low.

1) Boiler Technology

Energy is released from the incineration and leaves the furnace with the flue gas at a temperature of approximately 1000- 1200 °C. The hot flue gases from the incineration must be cooled down before they pass on to a flue gas cleaning system. Cooling of the flue gases is obtained with a boiler where the energy released from incineration is initially recovered as hot water or steam. The end uses are power, district heating or steam, depending on the type of boiler. The boilers are divided into three categories:

- The hot water boiler allows the production of heat only (hot water). The boiler producing hot water is also used if no heat recovery is possible (cooling of the surplus heat).

- The low pressure (LP) boiler allows the production of LP steam, only. This steam can be used in industry or exchanged to hot water.

- The high-pressure boiler producing steam allows power generation and combinations of power and process steam or heat.

2.4.1.6 Energy Conversion Technology

The energy recovery from a steam producing boiler is known from conventional power plant technology as the Rankine process (figure 16). The Rankine process allows for energy outputs in the form of power, steam and various combinations of power, steam and hot water. The energy from the hot flue gases is recovered via the boiler and passed to the internal circuit of steam. The steam energy may be converted to power by means of a turbine/generator set. The superheated and high-pressurized steam from the boiler expands via the steam turbine and the energy content of the steam is hereby transformed to kinematic (rotation) energy, which is further transformed into electrical energy by the generator. The excess heat of the low-pressure steam is via the heat exchanger (condenser) converted to hot water and passed to a district heating network or cooled away.

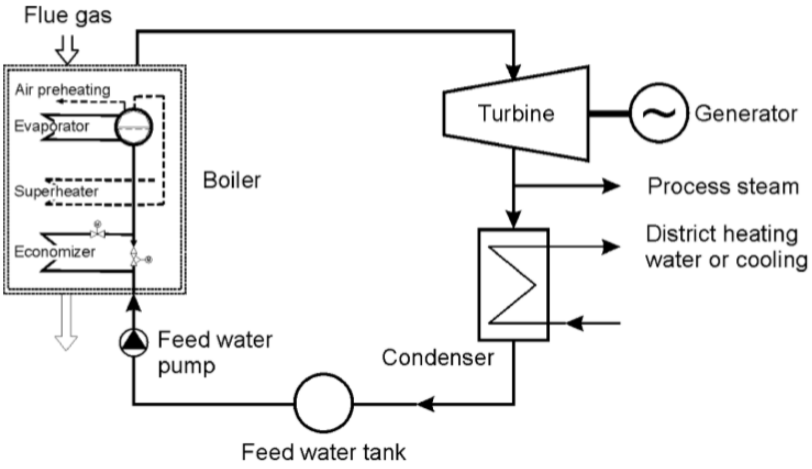


Figure 16 The energy recovery system of a waste fired combined heat and power plant.

(Source : Albertson, et al. 1992)

1) Electrical Power Only

When producing electrical power only, it is possible to recover an output of up to 35% of the available energy in the waste as power. The surplus heat has to be cooled in a condenser or a cooling tower. This option is attractive if the plant is situated far from district heating consumers or process steam demanding industries. For power only production, a fully condensing turbine is employed. The excess heat produced in the condenser for this turbine is produced at such a low-temperature level that it is not attractive for recovery. The cooling medium for the condenser of the fully condensing turbine is most likely to be seawater or air.

2) Combined Heat and Power

When producing a combination of heat and power (CHP), also called co-generation, it is possible to utilize more than 90% of the energy of the waste. With a boiler designed for waste incineration (moderate steam parameters) an output of electricity of up to 27 % and an output of heat of 60-65 % can be achieved, depending on the flow and return temperatures of the district heating system. For combined production of power and district heating, a so-called backpressure turbine is used. The backpressure is determined by the temperature and the flow of the coolant, which is most likely to be water of a district heating network.

3) Process Steam and Power

When producing both process steam and power, the electrical output may be found somewhere between the abovementioned values for combined heat and power production and power production only, i.e., 20% and 35%, depending on the amount of process steam extracted from the turbine. For production of both process steam and power, a certain minimum amount of the steam has to be passed all the way through the turbine. This means that a minimum of approximately 10% of the low-pressure steam has to be cooled away. A so-called extraction turbine is used which is a combination of the two above-mentioned concepts. It may be operated as a fully condensing turbine cooled by seawater or air and then, when needed, steam is extracted from a bleed in the turbine at relevant conditions (pressure, temperature).

2.4.1.7 Energy Recovery in the Flue Gas Cleaning System

The risk of corrosion and the sizing of the boiler set a limit to the cooling of flue gas in the boiler and hence, a limit to the energy recovery. More energy may be recovered downstream, the boiler (and downstream a particle separator) in a corrosion protected heat exchanger, thereby bringing the total thermal efficiency well above 90%. Such a system yields low temperature (< 100◦C) energy use for heating purposes such as air preheating, preheating of the condensate from the turbine, and district heating.

A significant amount of energy, adding approximately 10% to the thermal efficiency, may further be recovered at a low-temperature level through condensation of water vapor from the flue gas. Such a recovery system may be integrated with a wet scrubber by circulating the scrubbing liquid through a heat exchanger. As the temperature of the heated media would typically be in the range 40-50◦C, this may be used for preheating district heating water. If the district heating return temperature is too high to use the low temperature, a heat pump can be used to increase the temperature level - at the cost of electricity or steam to operate the heat pump.

It appears that by flue gas condensation, the total thermal efficiency may exceed 100%, which seems to conflict with basic physical laws. This is not the case. The explanation is that the thermal efficiency is calculated on the basis of the lower heating value, for which it is a precondition that water leaves the process in its evaporated state. In other words, the flue gas condensation system exploits an energy resource not accounted for in the lower heating value.

2.4.1.8 Overall Energy Balance for an Incineration Plant

The overall energy balance of the furnace/boiler is depicted in figure 17 The thermal input by waste is the mass flow rate (t/h) times the lower heating value (GJ/t), cf. the description of the capacity diagram in figure 8. If the combustion air is heated above the chosen reference temperature (usually 25◦C), its energy content may also be considered a thermal input. The thermal efficiency is the thermal output (steam) relative to the thermal input. It is typically some 85%, and it can be above 90% for a highly optimized system (Albertson, et al. 1992)

The largest loss is the flue gas loss, representing the energy content of the flue gas when it leaves the boiler, i.e. the potential additional energy extraction in the boiler had the flue gas been cooled to the reference temperature. It is calculated from flue gas flow rate (Nm3/h) times density (kg/Nm3) times heat capacity [kJ/(kg*˚C)] times flue gas temperature (◦C), minus 25 ˚C (because 25◦C is the chosen reference temperature). The flue gas loss may be reduced by reducing the amount of flue gas through optimization of the incineration process so that the excess air level can be reduced and by supplementing the boiler with a corrosion-proof economizer (heating, for instance, district heating water) or air preheater, which cools the flue gas to for instance 100 ˚C. Thereby, the loss may be reduced to approximately 5% of the thermal input.

The bottom ash causes a loss determined as the sum of the energy content of the bottom ash when it drops from the grate to the cooling water and the energy content represented by its remaining content of organic matter. The radiation and convection loss is the heat loss from the surfaces of the furnace and boiler. For a large, well-insulated incinerator, this loss may be as little as 1% of the thermal input.

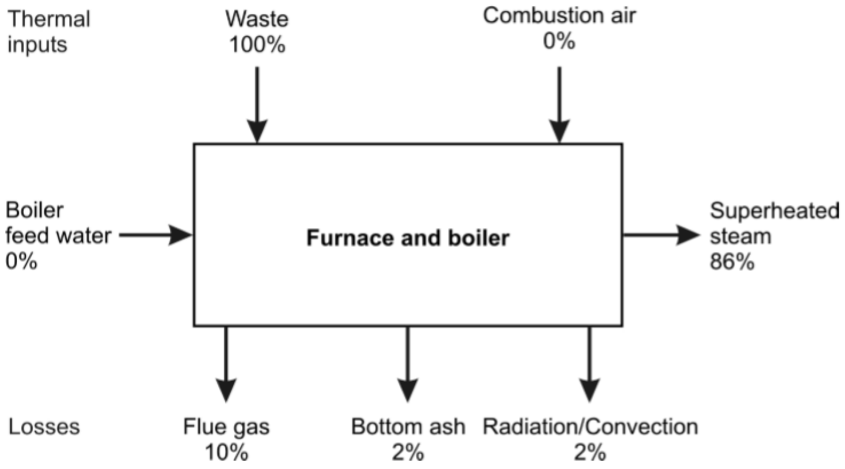


Figure 17 Energy balance of the furnace/boiler with typical values.

(Source : Albertson, et al. 1992)

2.4.2 Incineration: Flue Gas Cleaning and Emissions

In the waste incineration process, about 80 % of the waste is transferred into the flue gas. This flue gas must be extensively cleaned before being released to the atmosphere through the stack of the plant. The most problematic components in the flue gas are dust/particles, acidic gases (HCl, HF, SO2), NOx, heavy metals, and organic pollutants (e.g. dioxins, furans, PCDD/F). Flue gas cleaning aims at bringing the release of these components down to an acceptable level. This describes the most important strategies and technologies for flue gas cleaning associated with municipal waste incineration.

2.4.2.1 Combustion Products

The high temperature and oxygen surplus in the combustion chamber, regardless of the type of furnace, convert all input species into the most chemically stable products under oxidizing conditions. Furthermore, a partitioning takes place between the species remaining in the fuel bed and those entering the gas phase.

Mineral materials, as well as lithophilic heavy metals like iron, manganese, titanium and nickel and their compounds, leave the combustion chamber as bottom ash at the back end of the grate. A certain amount of salts like alkali or earth-alkali chlorides and especially sulfates stay in this residue as well. Also traces of products of incomplete combustion (PIC) are found in the bottom ash.

The stable oxidation product of all carbon compounds is CO_2. Hydrogen is always oxidized to H_2O. Both enter the gas phase. Sulfur forms both the gaseous SO2 and solid sulfates, which remain in the bottom ash. The waste-bound nitrogen is partly oxidized to NO, with small amounts of other oxides present as NO_2 and N_2O. Depending on the operation mode, more or less particulate matter leaves the furnace as dust (fly ash) in the flue gas.

Although the carbon in the waste is almost totally oxidized to CO_2, minor amounts of products of incomplete combustion such as CO, TOC, polyaromatic hydrocarbons (PAH), and soot particles are formed as well. Soot particles are known to be a source of toxic low-volatility halogenated organic micropollutants, especially PCDD/F (Van den Berg, Birnbaum, Denison, De Vito, Farland, Feeley, Fiedler, Hakansson, Hanberg, Haws, Rose, Safe, Schrenk, Tohyama, Tritscher, Tuomisto, Tysklind, Walker and Peterson. 2006)

2.4.2.2 Flue Gas Cleaning Systems

The reduction of pollutants from the levels found in the raw gas down to concentrations well below the respective air emission limit values can be achieved in many ways. According to the chemical properties of the pollutants, different types of cleaning technologies, also known as air pollution control (APC) technologies, have to be implemented for the efficient removal of particulate matter, acid gases, mercury, and other metals, organic micropollutants and nitrogen oxides. Two main strategies prevail:

- Wet flue gas cleaning consisting of up to five individual treatment steps.
- Dry and semidry flue gas cleaning, in which the fly ash, the metals, the acid gases, and PCDD/F are removed in one common treatment step.

The selection of the most appropriate gas cleaning strategy depends to a great extent on local conditions. Important factors are administrative regulations regarding the resulting waste streams (liquid effluent discharge, disposal of solid residues), options, and markets for recovered products (gypsum) and, last but not least, the investment and operating costs of the entire system.

The following sections present technologies used for the cleaning of specific types of pollutants:

- Removal of dust and heavy metals.
- Acid gas neutralization.
- Abatement of PCDD/F and related organic micropollutants.
- Reduction of nitrogen oxides.

The various technologies differ in their pressure loss (i.e., the drop-in pressure that the flue gas experiences when passing the process equipment). As the power consumption of the fan transporting the flue gas is proportional to the pressure loss, a low-pressure loss should be preferred. Hence, a key component in the flue gas treatment plant is the induced draught (ID) fan, which ensures the transport of flue gases from the furnace through all the process steps of the flue gas treatment plant to the stack. The ID fan also ensures that no polluted flue gas escapes from the process equipment by providing a reduced pressure therein. The flue gas transport is quite demanding in terms of power consumption, and the ID fan is the largest single power consumer in the entire waste incineration plant.

1) Dust Removal

In all incineration plants, it is necessary to have a high-efficiency dust collection system to remove the fly ash from the combustion process as well as the solid reaction products formed by the addition of various chemicals.

In wet flue gas cleaning, the first treatment step is the separation of the fly ash. The fly ash particles carry, condensed on their surfaces, almost all the heavy metals that are volatilized in the combustion process. The fly ash also contains products of incomplete combustion like soot, PAH, and PCDD/F. The PAHs and dioxins are mainly bound to the particulate carbon matter or soot in the fly ash. In most cases an excellent fly ash removal not only results in compliance with the air emission limit value for particles but also with the limit values for heavy metals other than mercury.

An important parameter for the removal of fly ashes is the size distribution of the fly ash particles, which differs from plant to plant and is depending on the mode of air supply, the flue gas velocities, and the type of boiler. Figure 18 shows the mass related size distribution of fly ashes from two incineration plants. The fly ash particles range mainly between 1 µm and1 mm, with the major fraction smaller than 100 µm. The median particle size for the two plants is 40 and 75 µm, respectively. Modern incineration plants, which prefer more gentle combustion with low gas velocities, generate fewer and smaller fly ash particles.

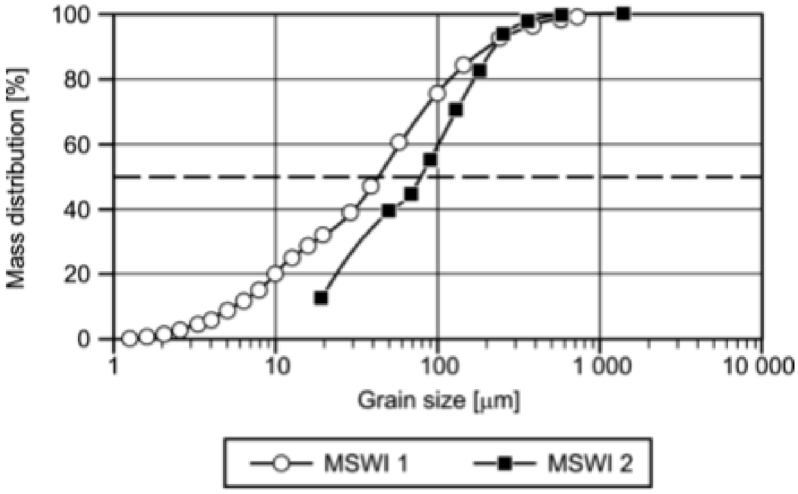


Figure 18. The size distribution of fly ash at two incineration plants.
(Source : Brunner and M¨onch, 1986; Reimann, 1989; Belevi and M¨onch, 2000; Vehlo. 2000)

In dry and semidry flue gas cleaning, the first step is to bring the acid gases to react with an alkaline chemical under formation of solid reaction products (see below). These products are then collected together with the fly ash in a subsequent dust collector. The removal of particles from flue gas can be achieved by applying different physical mechanisms:

- Force of gravitation.
- Inertial impaction.

- Centrifugal force.
- Diffusion.
- Electrostatic force.

The gravitational force is of minor importance and only for the removal of coarse fly ash particles, e.g., in the furnace and the boiler. The action of the other forces is schematically shown in figure 19 whereas a gas stream easily finds its way around a solid target, a large particle (>1µm) transported in that gas may not be able to follow the gas flow and can collide with the target due to its inertia. This is shown as case (a) in figure 19 Newton's law of motion can describe the movement of the particle. A special application of the principle of inertial impaction is the effect of the centrifugal force. A small particle (<1µm) may be able to follow the gas stream around the target. Its movement, as shown as case (b), however, is an irregular path driven by the thermal movement of the gas molecules (Brownian molecular movement). Such small particles may hit the target by diffusion, even at its rear side. Fick's diffusion law can describe this process. If a particle carries an electrical charge, it will interact with an electrostatic field and be forced to hit a target with zero or opposite charge. This is indicated by case (c) in figure 19

The main types of dust removal systems used in waste incineration are (Green Facts. 2007):

- Cyclones.
- Electrostatic precipitators (ESPs).
- Fabric or baghouse filters.
- High efficiency venturi scrubbers.

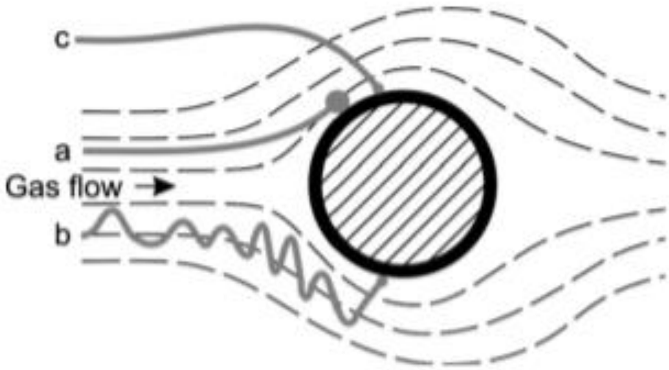


Figure 19 Mechanisms of particle deposition used in fly ash removal from incineration flue gas: a = inertia, b=diffusion, c=electrical field (static electricity).

(Green Facts. 2007)

1.1) Cyclones

A cyclone uses inertial impaction for fly ash separation. The gas enters a cylindrical chamber tangentially at high velocity and thus is forced into a cylindrical path. The centrifugal force acting on the particles causes them to collide with the walls, where they impinge and settle down into the discharge hopper. The gas is extracted through a central tube. A sketch of a cyclone is shown in figure 20

The removal efficiency of cyclones is in the order of 50 to >90% for particles >10µm. For fine particulate matter (<5 µm), the removal efficiency is rather low. Ingrate fired waste incineration plants today cyclones are, if ever, only used for preparation. But as they can be used at temperatures up to 850 ◦C or more, a common application is their integration in a fluidized bed combustion system, forming the so-called ‘circulating fluidized bed.’ In other industrial sectors, e.g. in the wood industry, a number of small cyclones in parallel (multi cyclones) are used to improve dust removal efficiency (Hagenmaier, Kraft, Brunner and Haag. 1987; Schwarz, Stieglitz and Roth. 1990)

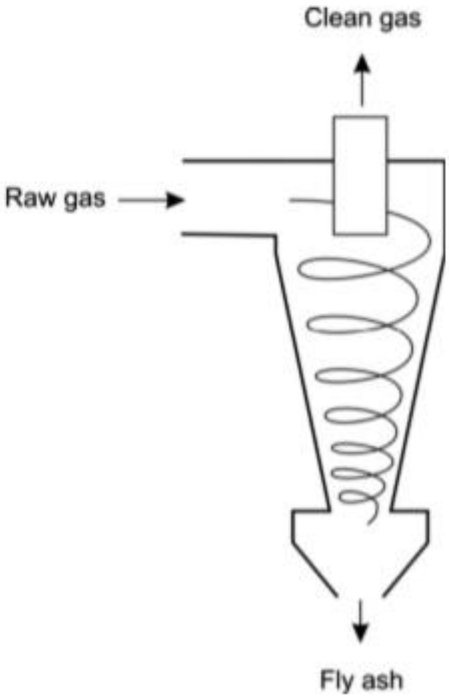


Figure 20 Sketch of a cyclone for fly ash removal.

(Green Facts. 2007)

1.2) Electrostatic Precipitators

Due to their simple design, low-pressure loss (typically 0.1-0.3kPa), and easy operation, ESPs are most widely used for fly ash separation in waste incineration and also in other combustion processes, like in coal fired power plants. They may be used at temperatures up to 400◦C. Sketches of the de-dusting principle and of a technical design are shown in figure 21

In the ESP, an electrical field is established between grounded metal plates and central wires, which are negatively charged to 30-100 kV by rectified AC power. The flue gases pass the aisles between the plates at low velocity (0.5-1.5 m/s). The fly ash particles are ionized by corona discharge and start to move (migrate) along the lines of the electric field until they impinge upon the plates. At certain times the deposited particles are removed from the plates by rapping (mechanical vibration of the plates) and collected in the discharge hopper.

ESPs are sized to obtain a certain efficiency, and the art is to determine the achievable particle migration velocity towards the collecting plates. The higher the velocity, the easier the precipitation, and the smaller the ESP.

A modern ESP, which comprises at least two and often three sections in series assures fly ash removal down to 20 and 5mg/ m3, respectively (daily average values). In a few installations a wet ESP is implemented at the back end for polishing purposes. In these ESPs the collecting plates are cleaned with water instead of rapping. The residue from a wet ESP is a solution or suspension and its disposal may require specific precautions.

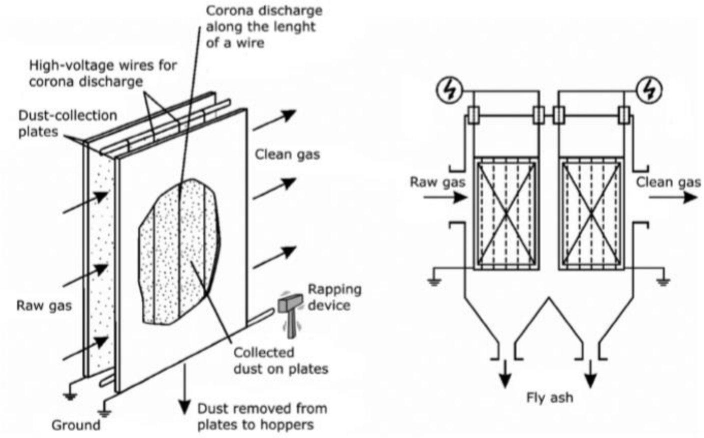


Figure 21 Electrostatic precipitator. Sketches of the removal principle (left) and a full-scale configuration of a two-field electrostatic precipitator (right) for fly ash removal. (Source : Green Facts. 2007)

1.3) Fabric Filters

Due to their very nature, fabric filters (also named bag house filters) always achieve low emission levels, often lower than those of ESPs. In a fabric filter, the raw gas passes through fabric bags, which are supported by metal cages. The gas flow is commonly from the outside to the inside. The dust stays on the outside of the bags and is periodically removed by an air pulse opposite to the filtration direction. This cleaning releases the particles, which fall into the discharge hopper. A sketch of a fabric filter is shown in figure 22

Several fabric materials are used, depending on the actual operating conditions. In all fabric filters, it is important to avoid condensation on the bags. The upper-temperature limit depends on the fabric but rarely exceeds 250 °C. The removal efficiency of a fabric filter does not only depend on the pore size of the cloth, because impingement of fine particles by diffusion has an important effect, since the gas velocity in a fabric filter is very low (only a few cm/ s). Hence fabric filters have high removal efficiencies also for fine particles. In waste incineration the dust content of the cleaned gas is typically in the order of 1mg/ m3 or below. The pressure loss is typically in the order of 0.5-2.0 kPa.

The risk of ignition by hot particles is the reason why fabric filters rarely are installed directly downstream of the boiler. Their main use is in dry or semidry scrubbing systems following a spray absorber or another reagent injection system. They are also the preferred particle removal technology after a carbon injection for final polishing (Brunner and M¨onch. 1986 ; Reimann. 1989 ; Belevi and M¨onch. 2000 ; Vehlow. 2000)

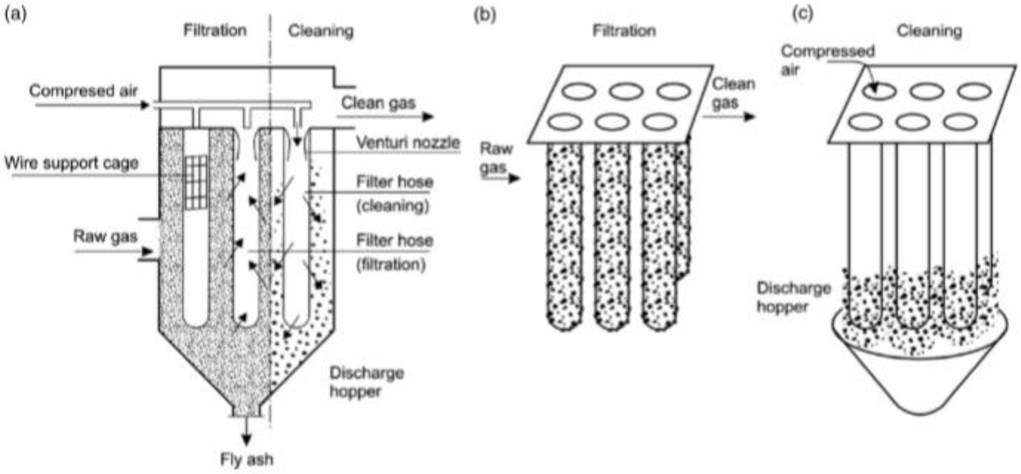


Figure 22 Sketch of a fabric filter (with the cleaning by air pulse) for fly ash removal. (Source : Brunner and M¨onch. 1986 ; Reimann. 1989 ; Belevi and M¨onch. 2000 ; Vehlow. 2000)

1.4) Venturi Scrubbers

Wet scrubbers, especially venturi scrubbers, have some potential for particle removal. Figure 23

shows a sketch of a venturi scrubber. The flue gas is accelerated to a high velocity by passing a funnel with a reduced cross-sectional area (the venturi), where also water is injected and atomized. The water aerosols, caught by the flue gas, pick up a large fraction of the ash particles. The principle is that the larger water aerosols are more easily removed from the flue gas in the subsequent cyclone than the particles. The particles are removed with the water from the cyclone. The removal efficiency is depending on particle size and pressure loss (typically 3-20kPa).

If present, HCl is transferred to the water aerosols, making them low in pH, creating corrosive conditions, and demanding treatment prior to discharge or reuse. These issues have limited the use of venturi scrubbers as a main fly ash removal technology.

A special design is an electrodynamic venturi (EDV), which is, in fact, a wet electrostatic precipitator built into a venturi scrubber. In a number of waste incineration plants, the EDV is used as an aerosol and fine particulate eliminator at the back end of a wet scrubbing system.

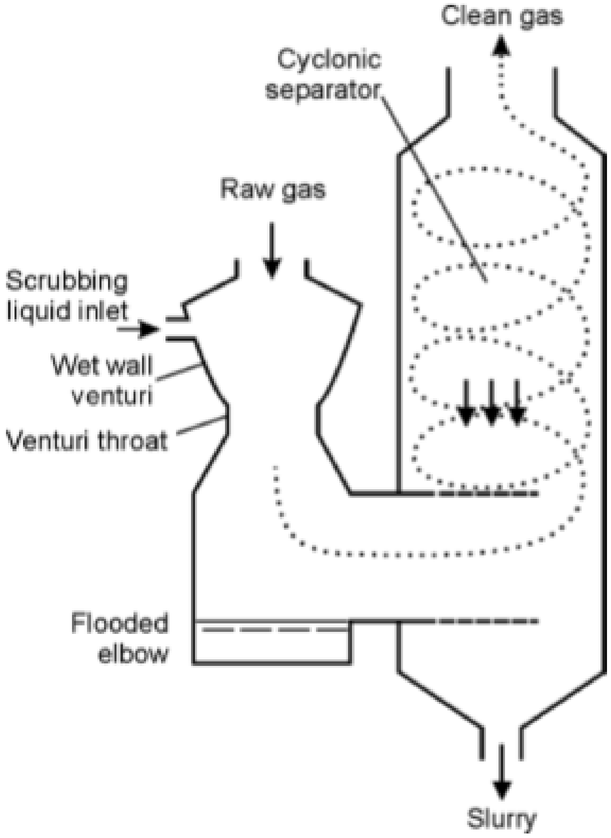


Figure 23 Venturi scrubber.
(Source : Brunner and M¨onch. 1986 ; Reimann. 1989 ; Belevi and M¨onch. 2000 ; Vehlow. 2000)

2) Acid Gas Neutralization

Acid gases can be removed by a number of technologies that can be categorized as:

- Wet systems with and without liquid discharge.
- Dry and semidry systems with different neutralizing agents.

2.1) Wet Systems

Wet scrubbing is normally applied after the fly ash has been removed, typically in an ESP.

The principle of wet scrubbing is the absorption of gaseous components into a liquid. The efficiency of such absorption processes depends first on all on the available surface area of the liquid, which controls the mass transfer from the gas into the liquid phase. Different techniques are used to achieve large surface areas:

- Jet and spray scrubbers spray the liquid into the gas flow by special spray nozzles to establish a large surface of the scrubbing solution. Common types, mainly used for acid scrubbing, are open and packed scrubbers.
- Packed tower scrubbers are filled with packings, which provide a large surface of the scrubbing solution drizzling down from the top while the gas flow is a counter-current from the bottom. An example of the design is shown in figure 24.
- Plate and tray towers contain flooded perforated plates or trays, through which the gas passes from below, forming bubbles and ensuring an efficient mass transfer in the turbulent zone.

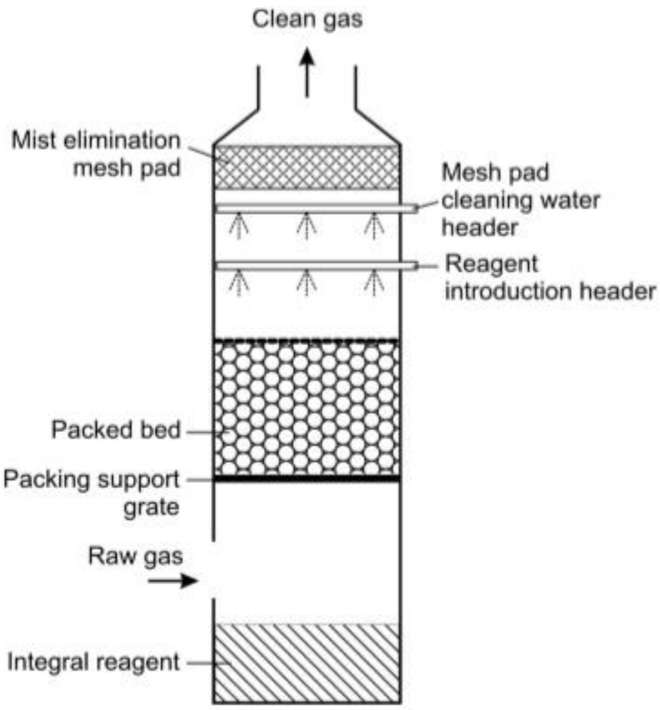


Figure 24 Packed column scrubber (wet scrubbing technology) for acid gas cleaning at waste incineration plants.

(Source : Braun. 1992)

- Acid Scrubbing. In the first scrubber HCl, HF and HBr are absorbed in water, forming the respective acids.

- Alkaline Scrubbing. The second scrubber is intended for SO_2 removal. SO_2 is first absorbed in the liquid, but unlike HCl its dissociation into ions is a two-step reaction.

- Wet Scrubber Wastewater. Wet scrubbers are often operated with the discharge of liquid effluents (100-300l/t waste), which require neutralization to neutral pH and an efficient removal of any heavy metal or other toxic contaminants.

- Wet Process Residues. The main residue from the wet process is the fly ash, which amounts to approximately 20kg/ t waste incinerated. From the wastewater treatment comes at least the dewatered hydroxide sludge; it amounts to approximately 1kg DM/t waste. At 40% DM, the quantity is approximately 2.5kg/t waste.

The easiest way of evaporation is to spray the liquid after neutralization into the hot flue gas downstream of the boiler. This can be done in a spray dryer or directly in the gas duct. The dried scrubbing residues are removed from the gas flow in a subsequent filter. This filter may, for economic reasons, be the same filter that removes the fly ash from the flue gas. A typical configuration of a wet scrubbing system without liquid effluents is shown in figure 25 an alternative way to evaporate the scrubbing solutions is to dry them in steam-heated external devices.

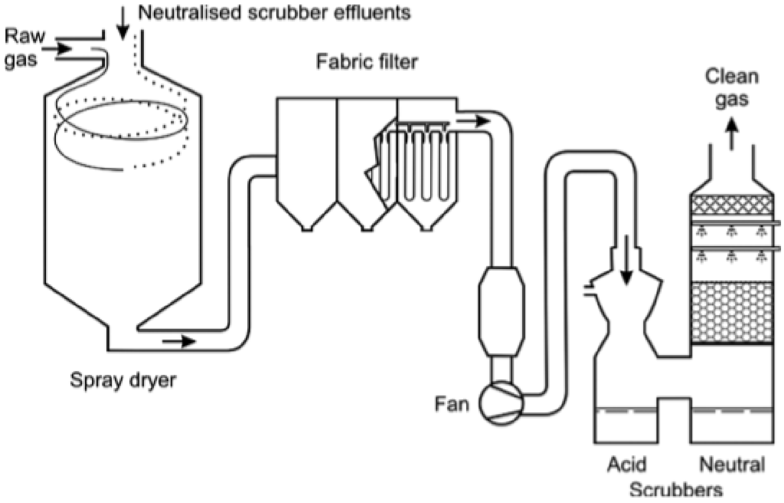


Figure 25 Example of a wet scrubbing system with the evaporation of the neutralized scrubbing solutions in a spray dryer
(Source : Zaw-Coburg. 2007)

2.2) Dry and Semidry Systems

Dry and semidry flue gas cleaning processes are used in many plants all over the world. They can be performed with different reagents, the most common being lime ($Ca(OH)2$) and sodium hydrogen carbonate (sodium bicarbonate, $NaHCO_3$), which are injected into the flue gas for neutralization of the acidic gas components. In the dry process, the agent is injected as a dry powder, maybe together with water, while in the semidry system, the agent is injected as a slurry that dries in the flue gas. In a semidry system calcium oxide (CaO) may be purchased instead of $Ca(OH)_2$, provided that is slaked in the slurry preparation installation. The reaction products are in most cases removed together with the fly ash from the flue gas by a fabric filter. Calcium-Based Processes. The neutralizing reactions of calcium-based systems are rather slow. For enhanced reactivity, the additives should have a large specific surface or the reactions should happen at high humidity. A commonly applied technology is the semidry scrubbing with the injection of $Ca(OH)_2$ in an aqueous suspension (slurry).

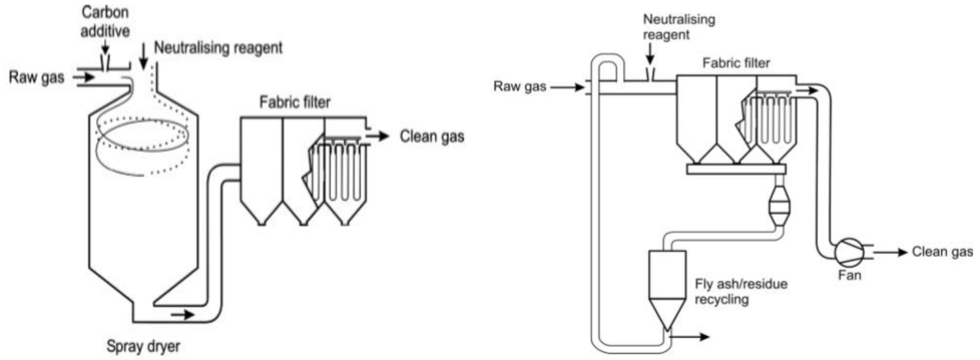


Figure 26 Example of a dry scrubbing system with an injection of the neutralizing agent via a spray dryer Example of a dry scrubbing system with injection of the neutralizing agent via a spray dryer. (modified from Figure 25.)

- $NaHCO_3$- Based Dry Process. This scrubbing technology is based on the injection of dry NaHCO3, which- directly before the injection - is finely ground in a hammer mill to make a fresh and large surface available for neutralization reactions. The reagent - with or without a separate carbon additive injection - is either dosed directly into a gas duct or into a reactor, which is similar to the spray dryer in the calcium-based processes.

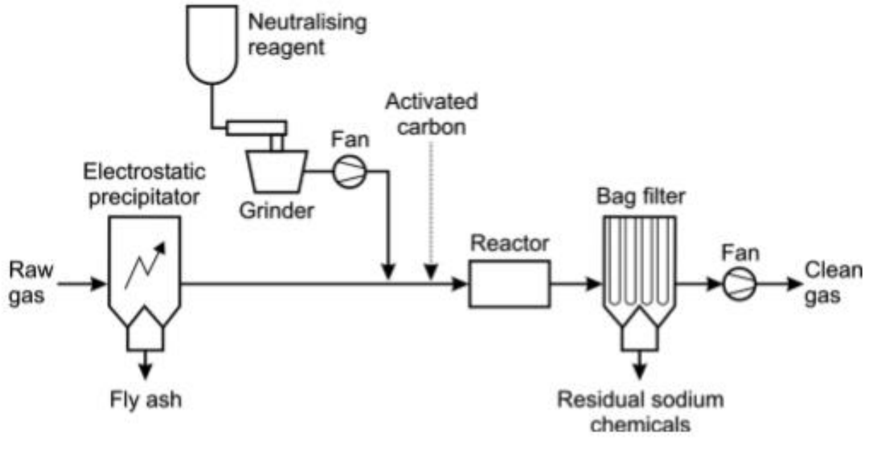


Figure 27 Example of a dry scrubbing system using NaHCO3 as a neutralizing agent. Adapted from http;//www.neutrec.com/process/recycling/0, 5330, 1614- EN, 00.html. © (2010) Neutrec.

2.4.3 Incineration: RDF and SRF - Solid Fuels from Waste

The energy content in waste can be utilized either by direct combustion (waste incineration), by biological conversion of organic matter to biogas (anaerobic digestion) or by producing a solid fuel that can be used in power plants, cement kilns, and other combustion plants. The latter was developed in the 1970s during the time of the energy crisis under the name ‘refuse-derived fuel’ (RDF). By 1984, 53 RDF plants had been built in Europe, most of them in the UK and in Sweden (Bilitewski, Härdtle, and Marek. 1997) Due to the high concentrations of chlorine and heavy metals, the processed fuel could not create sufficient demand in the intensive energy sectors. In Germany, the last of about 10 plants were closed in 1997 because of unsolved pollutant problems in co-combustion processes.

Refuse-derived fuel (RDF) is defined differently across countries. RDF usually refers to the segregated, high calorific fraction of municipal solid waste (MSW), commercial or industrial wastes. Learning from experiences from the first market failure of RDF, today, the quality of the fuel is receiving significant attention during the production process in order to fulfill market requirements. The term solid recovered fuel (SRF) today refers to waste derived fuel meeting defined quality specifications, while the terminology RDF nowadays is more used for unspecified waste after basic processing to increase the calorific value.

RDF and SRF are much more uniform fuels than unprocessed MSW with regard to particle size, calorific value, water, and ash content. This uniformity results in higher efficiency of energy recovery in an incineration process. In addition, most of the noncombustible material is removed from the RDF and SRF before the fuel is fed into the furnace, reducing the size of both the fuel and the ash handling system.

2.4.3.1 Production of RDF/SRF

According to its origin, three sources of waste relevant for the production of RDF can be distinguished: Residential waste from private households and small enterprises, commercial waste, and industrial waste.

Commercial and industrial waste usually has a homogeneous but very producer-specific composition. Recyclable, combustible and noncombustible fractions are often segregated already at the source. For fuel processing, the main components are paper, plastic, and wood. The content of inert material and food or garden waste is negligible.

Due to the segregation at source, no initial segregation of high calorific fractions is necessary at the beginning of the processing.

The residential waste consists of many different material fractions. It has a more heterogeneous but at the same time, predictable composition. RDF from residential waste is produced in MBT plants according to two main concepts, as illustrated in Figure 28:

- The separation which seeks to split the waste into ‘biodegradable’ (that may be composted and afterward landfilled) and ‘high calorific’ fractions. Dry stabilization which is less concerned with the splitting into fractions, and more focuses on the use of heat from a ‘composting’ process to dry the waste (bio drying) and increase its calorific value, thereby making it suitable for use as a fuel as well as facilitating the separation of fractions. As alternative to bio drying, drying with natural gas, landfill gas or biogas can be used (physical drying).

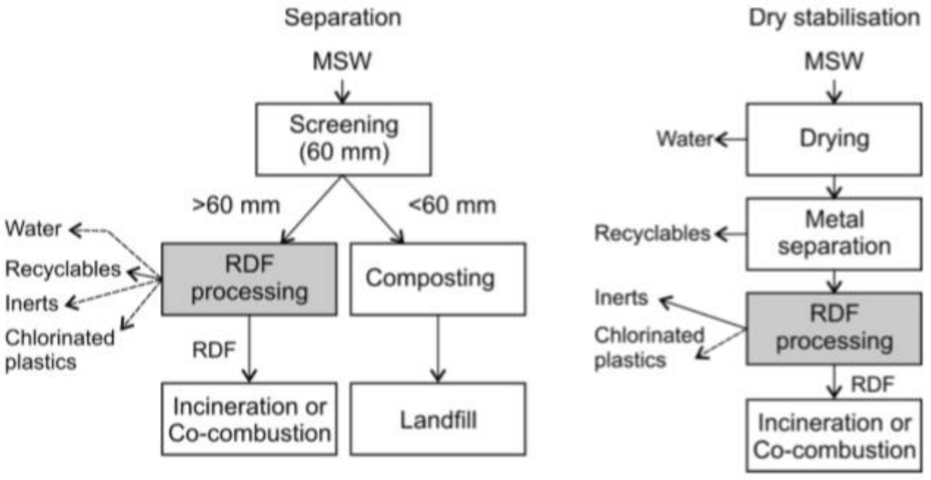


Figure 28 Combination of process units in MBT plants and integration of RDF processing

(Source : Rotter, S., Ma, W., Hoffmann; G. and Schirmer, M. 2007)

The objectives of the RDF/ SRF production process are (Pretz, Khoury, Uepping, Glorius, and Tubergen. 2003):

- Removal of water and inert components in order to improve calorific value.
- Removal of chlorine, aluminum, and zinc in order to avoid corrosion and other fuel-related technical difficulties in furnace and boiler.

- Reduction of volatile substances that have a negative environmental impact when combusted.
- Reduction of substances that have a negative impact on the quality of byproducts such as ashes and gypsum from flue gas desulfurization.

Furthermore, mechanical properties like grain size, bulk density, and thermal stability of the fuel are important for the fuel feeding system of the combustion plant.

2.4.3.2 RDF Characterization and Quality Assurance

Quality of RDF and SRF fractions is the key to success on the market and hence, for the plants producing these fractions. The basic concepts of quality.

Since RDF and SRF increasingly are becoming a commodity that is traded internationally, international standardization of quality assurance measures is required to improve the business environment and to assure environmental standards. In 2003, the European Committee for Standardization (CEN) established a Technical Committee ‘TC343 - Solid recovered fuels’ to develop standards and technical specification on solid recovered fuels for European markets. This work is harmonizing existing national activities for the quality assurance of SRF and RDF.

The production of RDF requires a stepwise approach for the implementation of quality assurance systems including: (1) parameters describing the quality of RDF, (2) reliable methods for analyses, (3) criteria expressing the ‘customer’s’ expectation, (4) procedures for continuous quality monitoring and documentation.

1) Parameters for the Characterization of RDF/SRF

Fuel characteristics summarize the properties of waste that influence the use of waste as a fuel. Parameters describing these characteristics have to be defined considering specific customer needs. The European standard CEN/TS15359:2006 ‘Solid recovered fuels - Specifications and classes’ defines a set of parameters and the related analytical methods and conditions for determination as a specification for solid recovered fuel.

In general, six groups of parameters can be defined to describe the characteristics of the specific fuel:

- Calorific and incineration properties.
- Feeding and storage properties.
- Corrosion potential.

- Properties related to financial incentives of its use.
- Properties related to the environmental impact of the usage.
- Properties are affecting the byproducts of the process.

In choosing the specific parameters for fuel characterization, the significance of the parameter has to be balanced with the complexity of analysis and with the precision and reproducibility of the measurement. The continuous control of the product quality requires simple, fast and robust test methods (Hoffmann, Lehmann, Marzi, M¨ohle, Rotter and Schingnitz. 2008) For basic process design more, detailed information on the fuel characteristics is necessary. Since these investigations are not done routinely, it is possible also to consider parameters that require a complex determination or particular skills in interpretation of the results. Marzi, Mrotzek, and G¨oner. 2007) described a method to determine the depending temperature release of volatile matter including its composition and its calorific value. (Marzi, et al. 2007) shows how results with this method can be combined with thermodynamic models describing the temperature distribution in grate firing systems.

2) Physical and Chemical Properties of Waste and RDF/SRF

An exact insight into the distribution of relevant physical properties, energy content and contaminants in the input material is a prerequisite for optimizing mechanical sorting processes for the production of quality RDF/SRF (Rotter, Kost, Winkler, and Bilitewski. 2004)

Specifically, the parameter chlorine is one of the limiting factors for the marketability of RDF/SRF due to a large number of chlorine-containing material fractions in household and commercial waste and the strict limitation defined by the end-users of RDF/SRF because of technical problems caused by chlorine during combustion. Studies by Maystre and Viret (1995), Kost (2001) and Marb, Przybilla and Weigand (2003) have identified plastics and packaging waste as main sources of chlorine in MSW. Especially nonpackaging plastic products, electronic waste, shoes, composite material, rubber and leather show a total chlorine content significantly higher than 2% (w/w dry basis). This is due to the use of polyvinylchloride (PVC) in these products. The production of chlorinated plastics has decreased in the last few years. But since most of the PVC containing products have a lifetime of 5-30 years, the reduction of chlorine in MSW is not expected within the next decades. Also, other sources like sodium and potassium chloride in household kitchen and yard waste contribute significantly to the total chlorine content.

Figure 29 shows results from two different investigations that determined the chlorine content in components of MSW. In addition to the total chlorine content the speciation of the chlorine was determined by a subsequent leaching procedure (Schirmer, Janz, Bilitewski and Rotter. (2005). ; Hoffmann, Schirmer and Bilitewski. (2007); Rotter, et al. 2007) As expected, the chlorine content of fractions like organics, paper and fines can be dissolved completely by leaching, because only inorganic chloride is found in these fractions. But even packaging plastics, films and packaging composite materials like beverage cartons separated from mixed waste contain soluble inorganic chlorine originating from food adhesions.

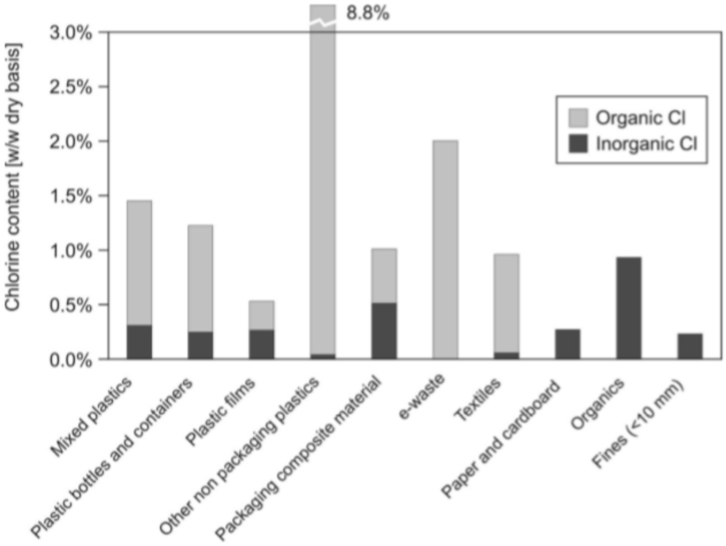


Figure 29 Calorific value, chlorine and mercury content of the fuel quality 'RDFI' in the production period 2006 at the RDF plant in Neuss, Germany

(Source : Roos and Peters. 2007.)

3) Classification and Quality Assurance of RDF/SRF

A first systematic approach to classify RDF was developed by the American Society for Testing and Materials (ASTM), defining seven classes of RDF depending on the type of processing (Alter. 1996) This classification does not include any chemical or physical parameters.

On a national basis, statutory standards regulate the use of RDF in cement kilns like in Switzerland (BUWAL. 1998), and in the Flemish Region, Belgium (EURITS. 1996) Focusing on environmental impacts of the utilization of RDF, the limited heavy metal concentration in the RDF is chosen due to their environmental relevance.

2.4.3.3 Utilization of RDF/SRF

The following options are available for the utilization and conversion of RDF/SRF to energy:

- Co-combustion in cement kilns.
- Co-combustion in coal fired boilers (lignite or hard coal).
- Mono- combustion in RDF- fired boilers (grate firing or fluidized bed technology) for district heating or industrial supply of steam and electricity.

Quality standards for co- combustion are usually set on the basis of the properties of the substituted primary fuel. In particular, the technical specifics of the thermal unit and the subsequent use of energy determine requirements on the fuel. In the following text, the main characteristic of these three options is described with regard to their fuel requirements.

1) Co-combustion in Cement Kilns

The cement industry has a very high energy demand as the process requires a temperature of about 2000° C. Specifically in Germany, Austria, Belgium, the Netherlands and France the cement industry already substitutes primary fuels up to 40% of its firing thermal capacity with those high calorific waste fuels (Gendebien, Leavens, Blackmore, Godley, Lewin, Whiting, Davis, Giegrich, Fehrenbach, Gromke, Del Bufalo and Hogg. 2003) The substitute fuel can be used at two spots in the cement process. The primary firing system at the furnace requires a calorific value of the fuel higher than 20MJ/kg to assure the necessary combustion temperature. That explains the interest of the cement industry in waste fuels like old tires, used oils or plastics. Alternatively, fuel can be added to the process in the secondary firing system for preheating the raw materials. Here a lower calorific value is acceptable for the process. That opens this application for a wider range of waste-derived fuels.

Due to the obligation of the cement industry in the CO_2 emission trading scheme, interest in fuels with a low fossil carbon content is increasing. Most of the used primary and waste-derived fuel in the cement process is based on fossil carbon. Biomass-based fuels have a calorific value ranging from 15 to 18MJ/kg, thus these fuels can only be used in the secondary firing system.

2) Coal-Fired Power Plants

Coal combustion systems for power generation can be generally categorized into Pulverized coal combustion (PCC), fluidized bed combustion (FBC), grate firing and stoker firing. Public power generation is usually based on PCC and FBC, using hard coal and lignite as a fuel. Grate and stoker firing systems typically are used in small combustion units for unprocessed and low-quality coal.

The specific fuel properties and reaction conditions in coal fired power plants with pulverized coal combustion (PCC) and fluidized bed combustion (FBC). FBC power plants allow a higher rate of substitution of the primary fuel coal. Also, the quality requirements regarding calorific value, grain size, and ash content are lower. In addition, general fuel requirements for co-combustion are determined by operational and emission-related factors. (Thiel, Neulinger, Staufenberger, Schmaljohann and Imhoff, 2007) identified the main barriers for the utilization of RDF operational problems included:

- Insufficient burn out of the organic matter.
- High-temperature chlorine corrosion.
- Alkali salt deposits on the boiler surface.
- The increased chloride concentration of the gypsum as a byproduct of combustion gas desulfurization.
- Oxidation of metallic aluminum particles in the boiler associated with hydrogen production and local temperature increase at the boiler surface.
- Increased gaseous mercury emissions.
- Increased ash production.

Due to these problems, the operators of coal fired power plants have very specified acceptance criteria for SRF. While a broad range of the calorific value is acceptable in the process (lower limit 12-14 MJ/kg), the accepted chlorine content is usually limited to <1 % or <0.5 % (w/w dry basis). In addition, according to the Waste Incineration Directive (2000/76/EC) heavy metals are limited in their total concentration in the fuel. In addition, some plants require a limited aluminum and alkali metal content in the fuel.

3) RDF Mono-combustion

Multi-fuel power plants, based on different types of waste fuels, are becoming increasingly popular. all dedicated RDF combustion plants need permission according to the waste incineration directive. Their legal status and in particular corresponding technical requirements and limitation of emissions are not different from those for classical mass-burn waste incineration of unprocessed waste. Hence, the flue gas cleaning system of plants for RDF mono-combustion is comparable to the one of waste incinerators for untreated waste. Distinguishing features are more how they are integrated into the energy supply system and how the combustion unit is adapted to the specific fuel properties.

Specifically energy-intensive industries with own electricity or combined heat and power (CHP) supply like pulp and paper and the food industry are integrating RDF boilers in their energy supply concept. But also, for district heating those boilers can replace the use of natural gas and oil.

The firing system is adapted to the homogeneous features of the fuel. Fluidized bed combustion (FBC) plants are finding widespread application for RDF combustion. They have advantages in terms of ease of emission control over mass-burn incinerators. They are also less sensitive to variations in the calorific value of the incoming fuel. Burn out, energy recovery, and operations, in general, can be more efficient. In addition, as the particle size of the waste is small, combustion equipment can be smaller, less robust and, therefore, less expensive (Gendebien, et al. 2003)

4) Market situation

The market for RDF or SRF in Europe is still not fully developed. Until now only in Germany and Austria has a sizable amount of RDF actually been produced. In 2007, in Germany the offer of RDF/SRF clearly exceeded the demand for this product (Bilitewski, Hoffmann, Wagner, and Wienhold. 2007)

Due to the limited demand and the ban on landfilling, the surplus of RDF/SRF is put into intermediate storage as baled RDF in old landfills, is further processed for improving fuel quality and is sometimes incinerated in mass-burn processes.

2.5 Anaerobic Digestion Process

Anaerobic digestion may be defined as a biological conversion process without an external electron acceptor. That is, there is no overall supplied electron acceptor such as oxygen (in aerobic processes such as composting oxygen is the overall electron acceptor), or nitrate and sulfate (in anoxic processes such as denitrification and sulfate reduction respectively). This definition determines some of the most obvious technological characteristics of anaerobic digestion. Combined end products have the same oxidation/reduction state as the waste degraded. The final catabolic end products are the carbon dioxide and methane, the most oxidized and least oxidized forms of carbon, respectively. The relative composition of the two gases in the biogas produced in anaerobic digestion is determined by the oxidation state of the waste. The energy available from anaerobic conversion processes is relatively low compared to aerobic or anoxic reactions. Therefore, biomass produced from anaerobic digestion during anabolism is limited and very little energy is released as heat. An increase in temperature due to anaerobic digestion is not observed in anaerobic digesters; it has only been observed in large well-insulated landfills. Because of the limited energy available and specialized reactions occurring during anaerobic digestion, different reactions within anaerobic digestion are mediated by different groups of microorganisms. This is why anaerobic digestion is often termed ‘structured processes. The different digestion processes are generalized in figure 30. Fermentative organisms convert simple sugars and proteins to organic acids, alcohols, hydrogen, and carbon dioxide, and produce enzymes that hydrolyze complex particulates to dissolved substrates. Acetogenic organisms produce acetate from organic acids and waste electrons as hydrogen. This hydrogen is converted by hydrogenotrophic methanogens, while the acetic acid is converted to methane by acetolactic methanogens.

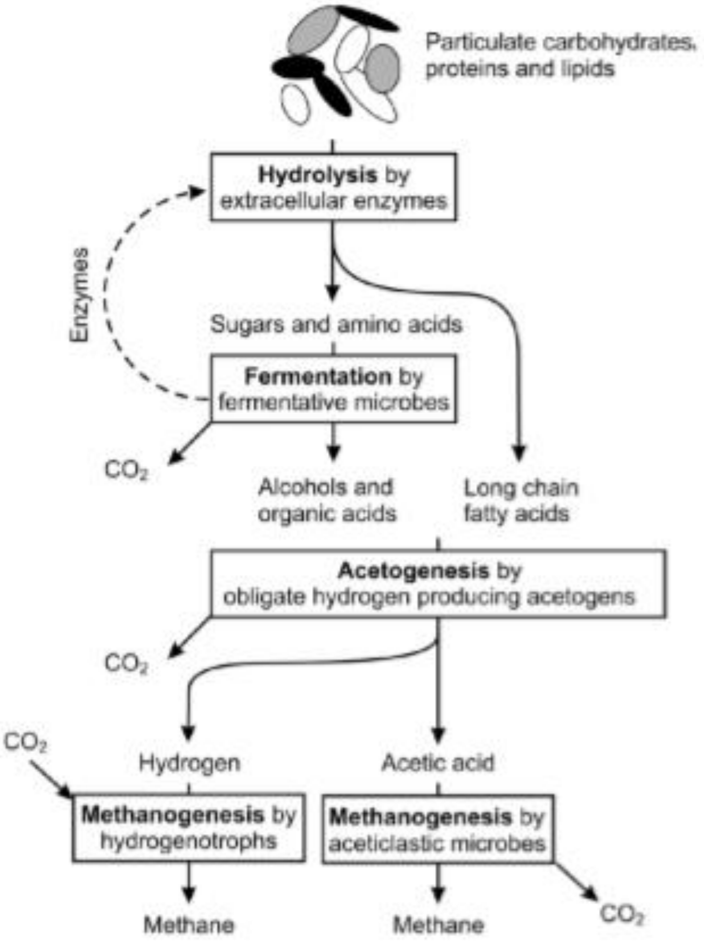


Figure 30 Stepwise degradation of organics to CH_4 and CO_2.

(Source : Lepisto and Rintala. 1999)

The main components in the biogas, CO_2, and CH_4 are determined by the composition of the waste digested. Electron-rich (energy-rich) waste such as fats produces a biogas high in methane, while electron-neutral substrates such as carbohydrates produce biogas with equal amounts of carbon dioxide and methane. CO_2 is partially soluble in water, and the biogas from anaerobic digestion of waste usually contains 55-65% CH_4 and 35-45% CO_2. Ammonia, H_2S, and numerous volatile organic compounds usually constitute only less than 1% of the biogas.

2.5.1 The Structure of Anaerobic Digestion Process

The different biochemical processes - hydrolysis, fermentation, acetogenesis, and methanogenesis - active in anaerobic digestion are described in the following sections.

1) Hydrolysis

Hydrolysis of particulates to soluble molecules is the first step in anaerobic digestion. Hydrolysis is extracellular because microbes cannot accept particles. In anaerobic digestion, hydrolysis is used as a lump term for solubilization of solids. There are three main classes of compounds that can be hydrolyzed: Carbohydrates, proteins, and lipids. There are also recalcitrant organic compounds such as lignins, keratin, plastics, waxes and mineral compounds. Inert organic compounds are generally included in mass balances, while mineral compounds often are excluded. Different groups of fermentative bacteria are capable of excreting the extracellular enzymes that are needed for the hydrolysis of complex polymeric compounds in the waste into oligomers and monomers that can be taken up by the microorganisms. The proteolytic bacteria produce proteases that catalyze the hydrolysis of proteins into amino acids. The cellulolytic and xylanolytic bacteria produce cellulases and/or xylanases that degrade cellulose and xylan (both are carbohydrates) to glucose and xylose, respectively. The lipolytic bacteria produce lipases that degrade lipids (fat and oils) to glycerol and long-chain fatty acids. Carbohydrates are plant material formed from long-chain, branched polysaccharides and are the main component in food waste, paper, cardboard, and wood in municipal solid waste. By definition, they have a generalized empirical. Proteins and lipids are main components of food waste. Both compounds are relatively more reduced compared to carbohydrates and therefore produce larger amounts of CH_4 than CO_2. They are also the source for inhibitory compounds; proteins produce ammonia when the amino acids are degraded, and lipids produce long-chain fatty acids. Both ammonia and long-chain fatty acids inhibit aceticlastic methanogenesis. Most proteins are relatively rapidly hydrolyzed. The rate of lipid hydrolysis varies, depending on whether it is a liquid (oil), or a solid (fat). Most animal-based fats are hydrolyzed slowly in comparison to proteins. The products from hydrolysis are simple sugars, amino acids, and long-chain fatty acids. The process is also called acidogenesis since the main outcome is acids.

2) Fermentation

Sugars and amino acids are converted to volatile fatty acids (VFA), alcohols, hydrogen, and CO_2in, a process called fermentation. The amino acids release ammonium during fermentation. This process is not obligated to use an external electron acceptor. Electrons from oxidative processes can be directly utilized in coupled reductive processes. This often means that multiple products are produced. Long-chain fatty acids from the hydrolysis of lipids are not converted into fermentation but instead are oxidized during the following acetogenesis. Generally, fermentation is a rapid process involving many pathways, intermediates and end products. The versatility of the process is illustrated with the fermentation of glucose in figure 31. The fermentation of monosaccharides (nominally glucose) has two main branches. One may produce propionate via pyruvate, which overall, is an electron consuming reaction, while the other may produce a variety of products via acetyl-coenzyme A (CoA), including acetate, butyrate, and ethanol, which are generally (net) electron producing. If the overall reaction is electron producing, the excess electrons must be wasted to produce hydrogen or formate. Formate and hydrogen are energetically interchangeable as final electron acceptors. Examples of some balanced reactions, with net adenosine triphosphate (ATP) generation, there are also many alternative products from acetyl-CoA (Madigan, Martinko, and Parker. 2000), but the major products are butyrate and acetate. Ethanol may also be produced under low pH conditions (Ren, Wan, and Huang. 1997) Lactate is also an important potential intermediate that may be produced and released with the same overall oxidation state as glucose, but which is very quickly consumed.

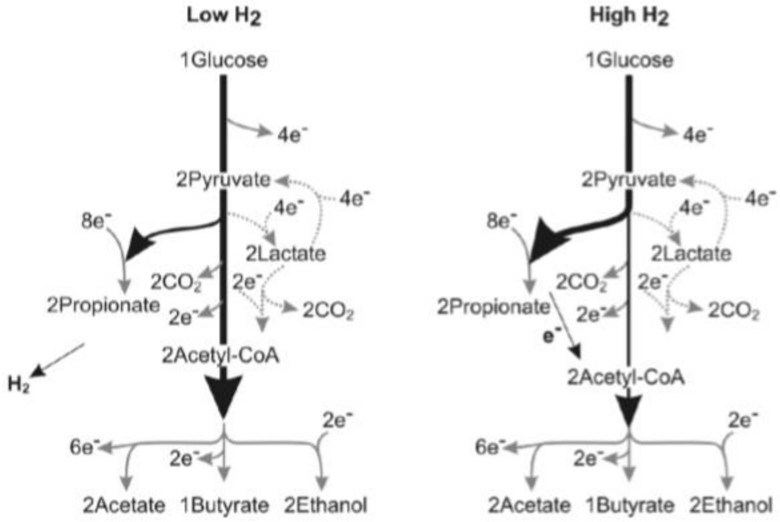


Figure 31 Major degradation pathways for glucose in anaerobic digestion, showing major directions of energy flow under low and high H_2 conditions.

(Source : Madigan, et al. 2000)

Fermentation has under most conditions a considerable energy yield when producing both highly oxidized products such as acetate and more reduced products such as propionate and butyrate. When the reactor is operating under stable conditions, the most substrate is converted to acetate and hydrogen directly, rather than passing through the reduced products. Production of mainly acetate and hydrogen is an oxidative pathway, as electrons are wasted to hydrogen ions (to form dissolved H_2). However, when the reactor is overloaded, either through excessive production of acetate and hydrogen, or pH extremes, fermentation directs to coupled pathways to form larger amounts of less oxidized products such as propionate, butyrate, and ethanol. Proteins may also form higher organic acids, such as valerate and aromatic organic acids. These higher organic acids need to be oxidized by organic acid-oxidizing bacteria, which are also subject to hydrogen and pH inhibition, and the reactor can easily move into an organic overload situation.

3) Acetogenesis

The VFA (such as propionate and butyrate) and alcohol (such as ethanol) produced during the fermentation step are oxidized to acetate by obligate hydrogen-producing acetogens. Electrons produced from this oxidation reaction are wasted to hydrogen ions to produce H_2. By obligate, it is meant that there is no coupled reaction or external electron acceptor available, as wasting electrons by producing hydrogen is generally energetically unfavorable. The free energy of reaction for fatty acid oxidation is positive at standard conditions, and therefore the reaction needs very low hydrogen concentrations to achieve negative free energy (and thereby yield energy for anabolism). Hydrogen consuming methanogens, which convert H_2 and CO_2 to CH_4, help in balanced biomass to keep H_2 concentrations low. However, it is only in a very narrow band of H_2 concentrations that it is favorable for both H_2 producers (acetogens) and H_2 consumers (methanogens). H_2 is the most important end product with respect to determining the free energy of the reaction since more H_2 is produced (stoichiometrically) than other products. Acetate is also important, as it is also an end product, but acetate is stoichiometrically produced at lower levels. This is demonstrated in figure 32, which indicates the ‘operating regions’ for different acetogenic reactions, the major aceticlastic reaction to methane, and the methanogenic, H_2- consuming reaction. As demonstrated, the range in which the reaction is possible (shaded for propionate) is far smaller for H_2 than acetate. Because of the critical levels of H_2 concentration, H_2 transfer between the H_2 producers and H_2 consumers is very important, and most likely they live in syntrophic consortia. Because they have no alternative pathways apart from direct oxidation of the organic acids, fatty acid-oxidizing organisms may be referred to as having a linear metabolism.

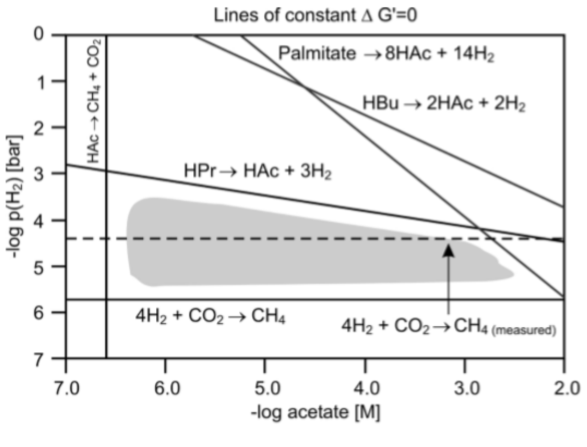


Figure 32 The shaded portion shows regions where all reactions are possible. The measured hydrogen-utilizing threshold and corresponding line (-)
(Source : Ruwisch, et al. 1988)

4) Methanogens

Methane is generated primarily by two pathways: Hydrogen trophic methanogens, which converts H_2 and CO_2 into CH_4, and the aceticlastic methanogens, which converts acetate into CH_4 and CO_2.

Hydrogen trophic methanogens are, as previously discussed, takes place in close coexistence with acetogenesis and typically accounts for 30-40% of the CH_4 according to this overall reaction:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \ \Delta G_0 = -130 \text{ kJ/mol } CH_4$$

Aceticlastic methanogenesis typically generates 60-70% of the CH_4 and is one of the most sensitive processes in anaerobic digestion to a number of factors. It is also a highly specialized reaction and is mediated by two groups of Archaea, specifically the Methanosarcinaceae and Methanosaetaceae within a single-family Methanosarcinales. The overall reaction is as follows:

$$CH_3COOH \rightarrow CH_4 + CO_2 \ \Delta G_0 = -31 \text{ kJ/mole } CH_4$$

There are several important differences between the two groups, mainly related to the transport and reaction pathways. Methanosarcinaceae convert 1 mol ATP/mol acetate activated, while Methanosaetaceae convert 2 mol ATP/ mol acetate. Consequently, Methanosaetaceae achieve an overall yield of approximately 0.25 mol ATP/mol acetate converted, while Methanosarcinaceae achieves an overall yield of between 1.0 and 1.25 mol ATP/mol acetate converted. As a negative, higher acetate concentration levels are required for the active transport mechanism used by Methanosarcinaceae (Zinder. 1993)

In practical terms, this means that Methanosarcinaceae can outcompete Methanosaetaceae at high acetate concentrations, while Methanosaetaceae dominates at low acetate concentrations. It also means that Methanosarcinaceae has a higher maximum growth rate and also a lower minimum acetate level. Additionally, Methanosaetaceae is more susceptible to load shocks and inhibition (as there is less energy available to maintain cellular stasis). Therefore, while Methanosarcinaceae can achieve higher conversion rates, Methanosaetaceae can achieve lower effluent acetate concentrations.

Acetate oxidation is also an alternative route for converting acetate. In this process, acetate is oxidized directly to CO_2 and H_2, with the same thermodynamic considerations as for acetogenesis. This pathway mainly occurs in thermophilic (high temperature) digesters, where the acetate ion oxidation reaction becomes more thermodynamically favorable (Petersen and Ahring, 1991). It has recently been found that in the absence of Methanosaeta this reaction is the dominant reaction for acetate conversion (Karakashev, Batstone, Trably, and Angelidaki. 2006)

Finally, it should be mentioned that acetoclastic methanogenesis may be suffering by competition for acetate if sulfate enters the digester. Oxidation of acetate by sulfate reduction is thermodynamically a more favorable process leading to the generation of CO_2 and HS^-. The latter may precipitate as sulfides, for example with iron, but may also contribute to odor formation.

2.5.2 Important Parameter on Anaerobic Digestion Process

In an operational composting system, each part of the composting mass is working as a micro composting unit with each unit being based on an individual particle. The mass transfer rates, both within the particle and at the surface, determine the conditions which exist around the particle. The principal factors involved are: temperature, moisture content, oxygen availability and nutrient availability. 1) Temperature

Whilst we have the variation in temperature within the composting mass being dependent on microsite activity, the general variation of temperature with time is represented in figure 33 The two temperature/time curves shown in figure 33 represent a system with no temperature control (system 1) and one with temperature feedback control (system 2). Despite the apparent difference in the two curves, their main features are the same: Increasing temperature, static temperature, and decreasing temperature. The difference in the two systems is the middle phase; in the controlled system a relatively constant (generally lower) temperature is maintained for an extended period to maximize the rate of biodegradation (stabilization). In the uncontrolled system there is no attempt to optimize the system and, in most cases, the high temperatures restrict the rate of degradation, as shown in figure 33

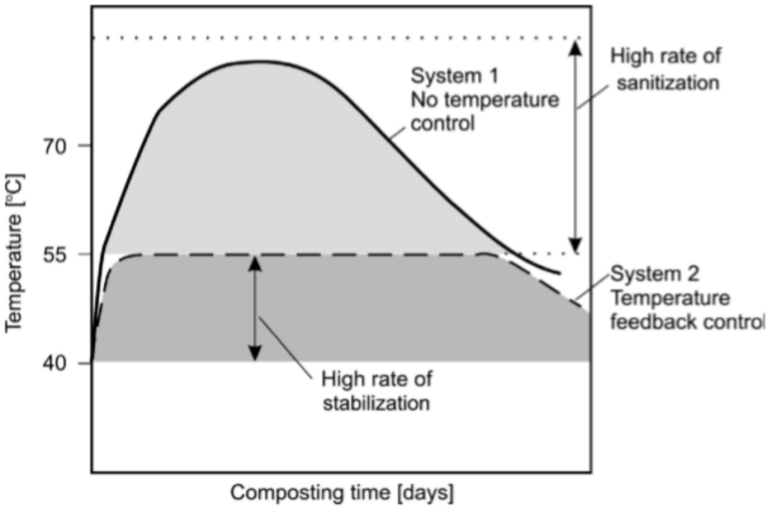


Figure 33 Typical temperature/time profiles for two composting systems. System 1: No temperature control. System 2: With temperature control.
(Source : Adani, Confalonieri, and Tambone. 2004)

However, in all cases, the same fundamental process of adjusting the heat loss to achieve the required temperature is behind the operation. The heat loss can be controlled by controlling the air flow and the moisture content. In relation to the heating phase of the process it is worth bearing in mind that if elevated temperatures in excess of 55 ◦C cannot be reached within one day there is something fundamentally wrong with the system and/or operating protocol.

4) Nutrient Availability

A wide range of nutrients is required to ensure the optimum performance of a particular biological community. In the composting context the issue which raises most concern is the balance of carbon and nitrogen: The C/N ratio. For bacterial cell formation the typical C/N requirement is in the 10-15 range; however, in order to support the energy requirements of the process, additional carbon is required. The ideal starting value for the C/N ratio varies depending on the materials used, but it is generally agreed to be in the 20-35 range (Haug. 1993) Problems during processing can occur if the initial value of the C/N ratio is outside this range:

- C/N is too high: The rate of degradation is restricted because of the lack of N, which is needed by the microorganisms.
- C/N is too low: Excess nitrogen is given off as ammonia, which not only represents loss of nutrients but also causes potential odor problems.

CHAPTER 3

Materials and Methodology

3.1 Equipment Apparatus and Chemicals

3.1.1. Autoclave (Model LS-24 “REXALL”)

3.1.2. Crucible

3.1.3. Hand Crimper

3.1.4. Nitrogen Gas (N_2)

3.1.5. Water Bath

3.1.6. Gas Chromatography

3.1.7. pH Meter

3.1.8. Silicone Cap and Aluminium cap

3.1.9. Erlenmeyer Flask size 1000 mL

3.1.10. Serum Bottle size 500 and 1000 mL

3.1.11. Beaker size 100, 500 and 1000 mL

3.1.12. Bottle size 30 mL

3.1.13. FURNACE (CARBOLITE ELF 10/6)

3.1.14. TE Buffer (10 mM Tris 1.21 g, 0.1 mM EDTA 0.027 g, Deionized Water 1000 mL)

3.1.15. Deionize Water (Invitrogen)

3.1.16. Master Mix (Gene Direx)

3.1.17. Agarose (Invitrogen)

3.1.18. DNA Marker (Invitrogen)

3.1.19. Loading Dye (Invitrogen)

3.1.20. SYBR Gold (Invitrogen)

3.1.21. 10X TAE Buffer (Invitrogen)

3.1.22. Ammonium Persulphate (Amresco)

3.1.23. TEMED (Amresco)

3.1.25. Primer 27f (GAGTTTGATCCTTGGCTCAG)

3.1.26. Primer 1525r (AAGGAGGTGWTCCARCC).

3.1.27. Primer 21f (TTCCGGGTTGATCCYGCCGGA)

3.1.28. Primer 958r (YCCGGCGTTGAMTCCAATT)

3.1.29. Primer 357f (CTCCTACGGGAGGCAGCAG) with CG clamp

3.1.30. Primer 518r (GTATTACCGCGGCTGCTGG)

3.1.31. Primer 340f (CCTACGGGGYGCASCAG) with CG clamp

3.1.32. Primer 519r (TTACCGCGGCKGCTG)

3.1.33. Solution A 0% Denaturant (Bis-Acrylamide 20 mL, 10X TAE 5 mL, Deionized Water 100 mL)

3.1.34. Solution B 100% Denaturant (Bis-Acrylamide 20 mL, 10X TAE 5 mL, Deionized Formamide 40 mL, Urea 42 g)

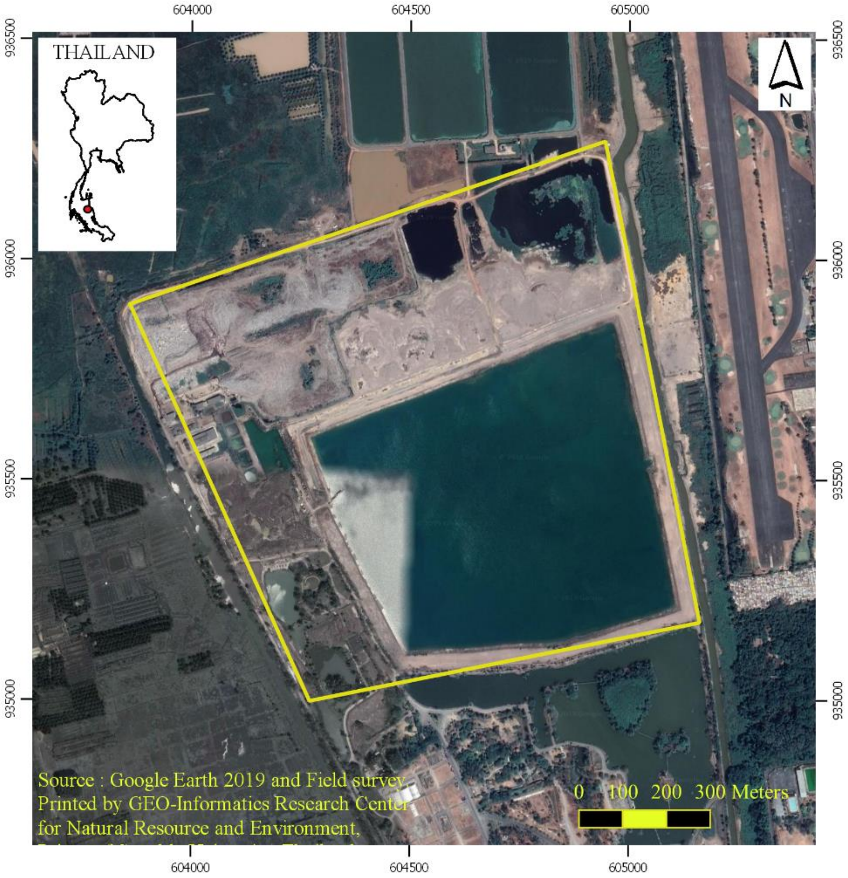
3.2 Methodology

3.2.1 Substrates and Inoculum

OFMSW in this research, municipal waste from municipal waste disposal sites of Nakhon Si Thammarat Municipality. Southern of Thailand (Coordinate position: 8.4634554, 99.9431729). (Figure 34)It is classified by the quartering method (Park and Bell. 2002) to sample as a good representative. The survey covers a total of 7 days and all day on weekends. And each day should be surveyed at least 2 times. That is probably now Example 2 and an average of 1 and 2 in the afternoon, and then the sample was 2nd. After the survey, each day, the data was derived for the average of the components throughout the week. If there is a large quantity of solid waste from 50 tons per day, sampling should be done at least 3 times. OFMSW was oven-dried at 60-80°C in a convection oven to less than 10% moisture, ground with a hammer mill to pass through a 5 mm screen, and stored in airtight containers prior to use. Anaerobic digested Sludge from Biogas production from PUME was used as inoculum in methane production

3.2.2 Biogas production by the one-state anaerobic digestion process

Methane production from OFMSW was examined using a one- stage mesophilic liquid-state anaerobic digestion. The experiments were carried out in batch conditions, and the hydrogen production was tested an initial pH of 5.5. Subsequently, methane effluent was investigated for methane production under initial pH of 7 control By ashes from the incinerator. In the methane reactors, OFMSW was mixed with 10,20,30,40 and 50 % of methane inoculum, according to (Mamimin, Thongdumyu, Hniman, Prasertsan, Imai and O-Thong., 2012) And then added IFA 0.5 and 1% for pH control. The inoculum and OFMSW were mixed by a hand-mixer and flushed with nitrogen gas to generate anaerobic conditions. The serum bottles were closed with butyl stoppers and incubated at mesophilic conditions (35°C) for 55 days in order to evaluate the methane production. The reactor size was 500 ml with an effective volume of 200 ml for the methane stage. All of the treatments were done in triplicate. Biogas production was determined through the use of the water replacement method and Check biogas composition by gas chromatography. (Yan. 2015)



Source : Google Earth 2019 and Field survey
Printed by GEO-Informatics Research Center
for Natural Resource and Environment,

Figure 34 The municipal waste collection area of Nakhon Si Thammarat Municipality was sampled for municipal waste.

3.2.3 Biohythane production in the two-stage anaerobic digestion process

Biohythane production (hydrogen and methane) from OFMSW was examined using a two-stage mesophilic liquid-state anaerobic digestion. The experiments were carried out in batch conditions. The hydrogen production was tested an initial pH of 5.5. Subsequently, hydrogen effluent was investigated for methane production in the second stage under initial pH of 7. In the hydrogen reactors, OFMSW was mixed with 10,20,30,40 and 50 % of hydrogen inoculum, according to Mamimin et al. (2012). And then added IFA 0.5 and 1% for pH control. The inoculum and OFMSW were mixed by a hand-mixer and flushed with nitrogen gas to generate anaerobic conditions. The serum bottles were closed with butyl stoppers and incubated at mesophilic conditions (35°C) for 15 days. When the hydrogen production ceased, the reactors were opened, and 80 % of anaerobic digestion sludge was introduced into the reactors. The reactors were incubated at mesophilic conditions for 55 days in order to evaluate methane production. The reactor size was 500 ml with an effective volume of 200 ml for the hydrogen stage and 500 ml for the methane production stage. All of the treatments were done in triplicate. Biogas production was determined through the use of the water replacement method. (Yan. 2015)

3.2.4 Methane production in one-stage solid-state anaerobic co-digestion

Methane production from OFMSW between green waste (GW) was examined using a one-stage solid-state anaerobic digestion (SS-AD). The OFMSW: GW ratios (1:1 and 2:1 base on dry VS) on the performance of methane production via SS-AD were investigated. The experiments were carried out in batch conditions. The methane production was tested an initial pH of 7. The ratios of F:I was mixed 10,20,30,40 and 50% with added IFA 0.5 for pH control. The inoculum and OFMSW: GW was mixed by a hand-mixer and flushed with nitrogen gas to generate anaerobic conditions. The serum bottles were closed with butyl stoppers and incubated at mesophilic conditions (35°C). The reactors were incubated at 45-55 days in order to evaluate methane production. The reactor size was 500 ml with an effective volume of 200 ml for the methane production stage. All of the treatments were done in triplicate. Biogas production was determined through the use of the water replacement method. (Yan. 2015)

3.2.5 Heating value analysis

Experimental heating value measurements using a bomb calorimeter (GE-5055 Compensated Jacket Calorimeter, Parr) were carried out according to ASTM D5468-02 (2007). The experimental procedure was performed to burn the sample in a high-pressure oxygen atmosphere within a metal vessel, called a bomb, which was placed in a bucket filled with exactly two kilograms of water. A sample size of 0.5–1.0 g was used for each measurement. After firing, the sample would be completely consumed in the bomb and was followed by a temperature rise of the water in the bucket. The heat of combustion was then calculated by multiplying the temperature rise of the water by a previously determined energy equivalent with standard material (benzoic acid). This calculation process was automatically completed by the calorimeter. At the end of each measurement, the bomb needed to be opened to check whether the sample had been completely combusted; if not, the measurement had to be repeated. Around 0.1–0.5 g mineral oil (high purity, Alfa Aesar) was used as spike material to enhance the combustion performance. The bomb calorimeter was designed to allow this introduction of spike material and able to output the sample's heating value by taking the mineral oil's heating value into consideration during calculations. The ground wool-like paper/textile/carpet samples were observed not able to achieve complete combustion due to their non-compact structure. A portion of these ground samples was blown out of sample holder during combustion and left as residues in the bomb. However, other ground samples achieved complete combustions successfully. Thus, unground dry samples of paper/textile/carpet were used for their heating value determination. They were cut into 1 × 1 cm squares to fit the dimension of sample holder in the bomb.

3.2.6 Analytical methods

The chemical and physical composition of OFMSW, inoculums, and digestated were analyzed for pH, Total Solid (TS), Volatile Solid (VS), Alkalinity, Total carbohydrate, Volatile Fatty Acid, % Gas Contain, and alkalinity according to APHA (1998). And the chemical composition of the waste material with regard to the elements C, H, O and N according to Lesteur, et al. (2010) The TS content of each sample was measured after drying 20 g of fresh sample at 95°C for 48 h, followed by 3 h of calcinations (550ºC) for VS content determination (Motte, Vereecke, Geelen and

Werbrouck, 2014) Volatile fatty acids (VFAs) were measured at the start and at the end of each experiment. At the end of the experiment, 0.5 g of sludge samples were diluted in 9.5 ml of deionized water and mixed for 10 minutes. Solutions were centrifuged at 12,000 rpm for 10 min. The supernatant was collected and filtered through 0.2 µm nylon membrane. Filtrated samples were used to measure the VFAs. Volatile fatty acids concentrations were determined with a gas chromatograph Shimadzu GC-17A with a stabilwax®-DA fused silica 30 m column connected to a flame ionization detector at 240°C and helium at 30 mL min^{-1} as the carrier gas. The daily biogas production for each experiment was recorded using the water displacement method (Yan, et al. 2015). The biogas composition was measured by gas chromatography equipped with thermal conductivity detectors (TCD). Methane, carbon dioxide, hydrogen, and nitrogen were analyzed by GC-TCD fitted with 1 m stainless steel column packed with Shin Carbon (60/80 mesh). Argon was used as the carrier gas at a flow rate of 14 ml min^{-1}. The temperatures of the injection port, oven and detector were at 120, 40 and 100°C, respectively. The gas sample of 0.5 ml was injected in duplicate. The theoretical methane potential was calculated according to Bushwell's formula that is derived from the stoichiometric conversion of the organic compound to CH_4, CO_2, and NH_3. It was assumed that the averaged chemical compositions of VS in MSW. The energy yield from biogas was calculated by using an energy factor of 36 MJ per m^3 CH_4 described by O-thong et al. (2012) Eq. (3.1).

$$\textbf{Energy yield (mJ tone}^{-1}\textbf{VS)} = \frac{\textbf{Methane yield (m}^3\textbf{CH}_4\textbf{ tone}^{-1}\textbf{ VS}}{\textbf{36(mJ m}^3\textbf{ CH}_4\textbf{)}} \qquad 3.1$$

The modified Gompertz equation (3.2) was used for estimating the methane yield, methane production rate and lag phase time of SS-AD process (Lui, et al. 2016) Where $Y(t)$ is the cumulative methane yield based on VS added (ml CH_4 g^{-1} VS) at digestion time. Y_{max} is possible maximum methane yield based on VS added (ml CH_4 g^{-1} VS) at the end of digestion time, t (day) is digestion time of SS-AD process. R_{max} is the methane production rate (ml CH_4 g^{-1} VS d^{-1}). λ is the lag phase time (day), and e is equal to 2.7183. The three parameters Y_{max}, R_{max} and λ were estimated by nonlinear curve fit in SigmaPlot 11.0 (Lui, et al. 2019)

$$\mathbf{Y(t) = Y_{max} \times exp\ (-exp\ (\frac{R_{max} \times e}{Y_{max}} \times (\lambda - t) + 1))} \qquad 3.2$$

The first-order model was used for the determination of the hydrolysis constant Eq. (3.3) during the anaerobic digestion of MSW. Where B_{∞} is cumulative methane yield (ml CH_4 g^{-1}VS), B is daily methane yield (ml CH_4 g^{-1}VS d^{-1}), t is time of anaerobic digestion (day), and k_h is hydrolysis constant (d^{-1}).

$$\mathbf{In\ \frac{B_{\infty} - B}{B_{\infty}} = -k_h\ t} \qquad 3.3$$

3.2.7 Microbial community analysis in biohythane production system

Nested polymerase chain reaction-denaturing gradient gel electrophoresis (nested PCR-DGGE) was used to study microbial community structure in the two-stage solid-stage anaerobic digestion. The genomic DNA was extracted from sludge samples from each stage of fermentation by using QIAamp DNA mini kits, QIAGEN®. First, genomic DNA was used as a template for PCR reactions with a specific primer pair (Arch21f and Arch958r followed with 340f-GC and 519r for archaea population and 1492r and 27f followed with 357f-GC and 518r for bacteria population) according to Stackebrandt and Goodfellow. 1991 and Keyser, et al. 2006 DGGE analysis of the amplicons obtained from the second PCR was performed as previously described by Muyzer and Smalla. 1998 and Zoetendal, et al. 2001 The 8% polyacrylamide gel running in the D-Code system (Bio-Rad Laboratories, Hercules, CA) with a denaturant gradient ranging from 40-60%. Most of the bands were excised from the gel and re-amplified. After reamplification, PCR products were purified and sequenced by Macrogen Inc. (Seoul, Korea). Closest matches for partial 16S rRNA gene sequences were identified by database searches in GenBank using BLAST.

3.2.8 Data collection

The sources used in the research came from 15 sources from 5 districts of Nakhon Si Thammarat, consisting of Sichon District, Lansaka District, Thasala District, Phrom Khiri District, Mueang District, and Chawang District. The waste transport to the collection and disposal of waste. Nakhon Si Thammarat Province. Data collection by interview and questionnaire. Officers of the municipal government and the sub-district administration organization regarding types of trucks used for collecting solid waste, distance, fuel information, and Include solid waste.

3.2.9 The system of Municipal Waste Management

Waste Management System of Nakorn Sri Thammarat Municipality It can be divided into 3 parts: a collection of household waste. Transport to waste disposal and disposal sites. The collection of three cars is divided into 5 districts, 15 areas. Municipal Waste collectors will collect 2-3 days at a time. Transportation of waste from the collection to the waste disposal site with the distance from 1 to 160 km. And the removal is a grip that is not properly sanitary. The municipality carried out only weighing and pouring it into layers. In 2017, Nakhon Si Thammarat Province The amount of garbage accumulated to 1,093,057 tons.

3.2.10 GHG emissions from MSW waste source

On the basis of the GHG emission and mitigation, an estimate on the GHG emissions from MSW waste source from System boundary of the interrelations among the Municipal Waste Management in this study using Eq. (3.4) below

$$\mathbf{Emission_{Degradation} = E_{CH4} \times GWP_{CH4} + E_{N2O} \times GWP_{N2O}} \qquad 3.4$$

Where GHG emissions from MSW waste source equals, $\text{Emissions}_{\text{Degradation}}$ means Emissions of trash from organic waste (KgCO_2/organic carbon), E_{CH4} means Methane emissions from organic waste degradation The program uses a default value of 4, Program users can switch to the specific value of the fertilizer compartment if data is available, GWP_{CH4} means Potential for global warming (methane is 21 times carbon dioxide over 100 years) 2, E_{N2O} means Nitrous oxide emissions from organic waste degradation and GWP_{N2O} means Potential for Global Warming

3.2.11 Contribution of GHG emissions from MSW transportation

On the basis of the Contribution of GHG emissions from MSW transportation, an estimate on the GHG emissions from MSW waste source from System boundary of the interrelations among the Municipal Waste Management in this study using

$$\mathbf{Emissions_T = \frac{Fuel(units)}{Waste\ (tones)} \times Energy\ (MJ/units) \times EF(kgCO_2/MJ)} \qquad 3.5$$

Contribution of GHG emissions from MSW transportation equals, Emissions $_T$ means Greenhouse gas emissions (KgCO$_2$ / tonne of transported solid waste), Fuel means the amount of fossil fuel used in transportation per month. (L / kg) Waste means the amount of solid waste shipped per month (Tons of solid waste / month), Energy means the net heating value of fossil fuels. (MJ / l / kg), EF means emission factor of fossil fuel (Kilograms of carbon dioxide / MJ)

3.2.12 Contribution of GHG emissions from disposal in landfall

On the basis of the Contribution of GHG emissions from MSW transportation, an estimate on the GHG emissions from MSW waste sourced from the System boundary of the interrelations among the Municipal Waste Management in this study using Eq. (3.6) below

$$\mathbf{CH_4\ emitted\ in\ year\ T = (\Sigma CH_4\ generated_{X,(T)} - R_{(T)}) \times (1\text{-}\ OX_{(T)})} \qquad 3.6$$

Where the Contribution of GHG emissions from disposal in landfall equals, Greenhouse gas emissions from the landfill / dump. (Kg of CO$_2$ equivalent to tons of solid waste) means CH$_4$ emissions / tons of solid waste (KgCH$_4$ / tons of waste) × GWPCH$_4$ + Greenhouse gas emissions from landfill activities (KgCO$_2$equivalent / tons of solid waste)

CHAPTER 4

Results

4.1 The composition of municipal solid waste and green waste

The summaries of the Composition of municipal solid waste in Nakhon Si Thammarat landfill are presented in Tables 3 The main ingredients are vegetables, about 37.04±0.31% paper, 11.87±0.46% plastic, 25.06±0.31% clothing, 9.36±0.14% wood, 4.58±0.14% rubber and Leather 0.68±0.08% glass, 7.73±0.22% metal, 0.74±0.04% bone stone, 1.38±0.68% and 1.48±0.17% foam., The percentage is calculated from the weight of each type of waste. Corresponding to the data. Central Statistical Office. (2009) municipal wastes were produced in Poland in 2008. The municipal wastes consist of kitchen wastes, paper, and cardboard, plastics, textiles, glass, metals, mineral wastes, dangerous wastes, etc. classified by moisture content. The low moisture content included paper, plastic, clothing, rubber, leather, foam, wood around 44% of MSW. For, the high moisture content included Paper, Fruits, vegetables, food waste around 56% of MSW.

Table 3 The Composition of municipal solid waste in Nakhon Si Thammarat landfill.

Composition of Municipal waste	Percentage by weight per day							Average	S.D.
	1	2	3	4	5	6	7		
Fruits, Vegetables	37.36	36.50	37.50	37.10	36.90	37.00	36.90	37.04	0.31
Paper	11.52	12.00	11.65	11.78	11.39	12.00	12.77	11.87	0.46
Plastic	25.20	24.99	25.03	25.67	24.98	24.67	24.87	25.06	0.31
Clothing	9.49	9.34	9.55	9.23	9.16	9.43	9.30	9.36	0.14
Wood	4.74	4.56	4.71	4.38	4.59	4.67	4.44	4.58	0.14
Rubber, Leather	0.79	0.67	0.64	0.76	0.65	0.56	0.67	0.68	0.08
Glass	7.63	7.53	8.00	7.45	7.89	7.64	7.98	7.73	0.22
Metal	0.73	0.67	0.78	0.75	0.76	0.73	0.78	0.74	0.04

Table 3 (Continued)

Composition of Municipal waste	Percentage by weight per day							Average	S.D.
	1	2	3	4	5	6	7		
Stone, Bone Tile	1.14	2.10	0.70	1.20	2.30	1.70	0.49	1.38	0.68
Foam	1.40	1.50	1.45	1.34	1.29	1.60	1.80	1.48	0.17
Total percentage	100	99.86	100	99.66	99.91	100	100	99.92	0.13

The sources used in the research came from 15 sources from 5 districts of Nakhon Si Thammarat, consisting of Sichon district, Lansaka district, Thasala district, Phrom Khiri district, and Mueang district. The waste transport to the collection and disposal of waste. Nakhon Si Thammarat province. The data collection by interview and questionnaire. The officers of the municipal government and the sub-district administration organization regarding types of trucks used for collecting solid waste, distance, fuel information and Include solid waste. Waste sorting by dividing the garbage into 2 types: wet waste (organic waste) and dry waste (inorganic waste). And when the garbage is separated from the origin and was brought to finding the heating value energy by bomb calorimeter. For municipal waste heating value, the samples collected in the landfill of Nakhon Si Thammarat municipality were collected at 5 points shown in Table 4

Table 4 Heating value from municipal waste in the landfill of Nakhon Si Thammarat

municipal waste source	Wet waste (organic waste) (MJ/tonne)	Dry waste (inorganic waste) (MJ/tonne)
Sichon district	10,275±95	7,356±14
Lansaka district	17,315±21	15,776±19
Thasala district	13,158±25	6,658±10
Phrom Khiri district	17,204±89	6,614±11
Mueang district	13,911±11	4,706±11
Chawang district	15,388±21	2,277±17

As observed, the moisture content of the MSW varied significantly, depending on the type of material. As expected, paper and wood samples had the highest moisture content due to their stronger water sorption ability. Other materials have a high moisture content of 73.64%. The hard-plastic foam all textiles and carpets have little moisture due to the properties. They do not like water. They accounted for 37.26%. In addition, waste sources influenced the moisture content significantly. For instance, the MSW plastic-rigid sample has a moisture content of 0.23%, whereas the residential plastic-rigid sample contains higher moisture (15.02%) due to the moisture-rich impurities (such as shampoo or laundry detergent) attached to the residential samples. As a general trend, the moisture contents of residential wastes are remarkably higher than those of MSW wastes (except the similar values of paper and carpet). And characteristics of the municipal solid waste High moisture content of MSW dominate by carbohydrate 1020 mg/L, protein 12 % and lipid 20.9% indicate high carbon content around 51%, it is high potential convert to biogas. For low moisture content of MSW had total solid 62%, it is not technically economical to use as fuel for biogas production. And characteristics of the green waste dominate by TS, about 33.70% VS, 24.30% Fatty acid, 0.40% pH, 5.1 Moisture, 66.30% Ash, 7.19% Lipid, 1.17% Protein, 1.67% Alkalinity, 0.15% Cellulose, 53.03% Hami Cellulose, 5.36% Lignin, 41.61% C, 49.11% H, 6.44% O, 43.42% and 1.03% N., (Table 5).

Table 5 Characteristics of high and low moisture content of the municipal solid waste and green waste.

Parameter	HMC-MSW	LMC-MSW	Green waste
pH	5.59	-	5.1
TS (%)	26.36	62.76	33.70
VS (%)	18.34	-	24.30
Ash (%)	8.02	8.63	7.19
Moisture (%)	73.64	37.24	66.30
C (%)	51.05	-	49.11
H (%)	6.58	-	6.44
O (%)	40.28	-	43.42
N (%)	1.97	-	1.03

Table 5 (Continued)

Parameter	HMC-MSW	LMC-MSW	Green waste
S (%)	0.13	-	-
Protein (%)	12.3	-	1.67
Carbohydrate (mg/L)	1020.06	-	-
Alkalinity (%)	-	-	0.15
Cellulose (%)	-	-	53.03
Hami Cellulose (%)	-	-	5.36
Lignin (%)	-	-	41.61
Lipid (%)	20.9	-	1.17

Table 6 shows the incinerator fly ash. The fly ash consisted primarily of sodium oxide (Na_2O), Magnesium oxide (MgO), Aluminium oxide (Al_2O), Silicon dioxide (SiO_2), Phosphorus pentoxide (P_2O_5), Sulfur trioxide (SO_3), Potassium oxide (K_2O), Calcium oxide (CaO), Titanium dioxide (TiO_2), Chromium (III) oxide (Cr_2O_3), Manganese (II) oxide (MnO), Iron (III) oxide (Fe_2O_3), Copper (II) oxide (CuO), Zinc oxide (ZnO), Bromos (Br), Rubidium oxide (Rb_2O), Strontium Oxide (SrO), Tin (IV) oxide (SnO_2), Antimony (III) oxide (Sb_2O_3), Lead (II) oxide (PbO) were identified on the diffractogram for fly ash.

Table 6 Composition of ash from incinerators

Parameter	Intensity (%)	Parameter	Intensity (%)
Na_2O	8.351	Fe_2O_3	0.432
MgO	1.175	NiO	0.007
Al_2O	0.663	CuO	0.055
SiO_2	1.658	ZnO	0.427
P_2O_5	0.689	Br	0.108
SO_3	3.229	Rb_2O	0.026
Cl	22.080	SrO	0.050
K_2O	4.955	CdO	0.021

Table 6 (Continued)

Parameter	Intensity (%)	Parameter	Intensity (%)
CaO	39.625	SnO_2	0.048
TiO_2	0.367	Sb_2O_3	0.026
Cr_2O_3	0.014	PbO	0.103
MnO	0.023		

4.2 Biological methane potential of OFMSW via one-stage anaerobic digestion

The accumulative methane yield obtained from OFMSW under mesophilic conditions one-stage anaerobic digestion process at different TS contents (10, 20, 30, 40, and 50% TS) was shown in Figure 35 and 36. In the accumulative methane yield from OFMSW was gradually increased until 15 days of incubation. The methane yields of OFMSW at 10, 20, 30, 40, and 50 %TS with IFA 0.5 and 1%. For IFA 0.5% were 44, 143, 179, 21, and 25 and for IFA 1% were 48, 134, 218, 33, and 27 ml/gVS, the BMP under by one-stage anaerobic digestion process. This result indicated the 30% of MSW had maximum methane yields 218 ml/gVS with IFA 1%. And Biodegradation of MSW around 38%, when compared with theoretical methane yield**.** The total alkalinity after one-stage anaerobic digestion process showed that the highest Alkalinity content was 14 grams per liter, reflecting that the system was stable. And Total volatile fatty acids remained the highest at only 267.25 milligrams per liter. Ash fills 0.5 percent and 50 percent waste. (Figure 37**)** Estimated parameters of modified Gompertz equation for one-stage methane production are showed in Table 7. The low lag times of one-stage AD process were achieved 6.07-6.66 day of 10%(w/w) MSW with fly ash addition 0.5-1% (w/w).

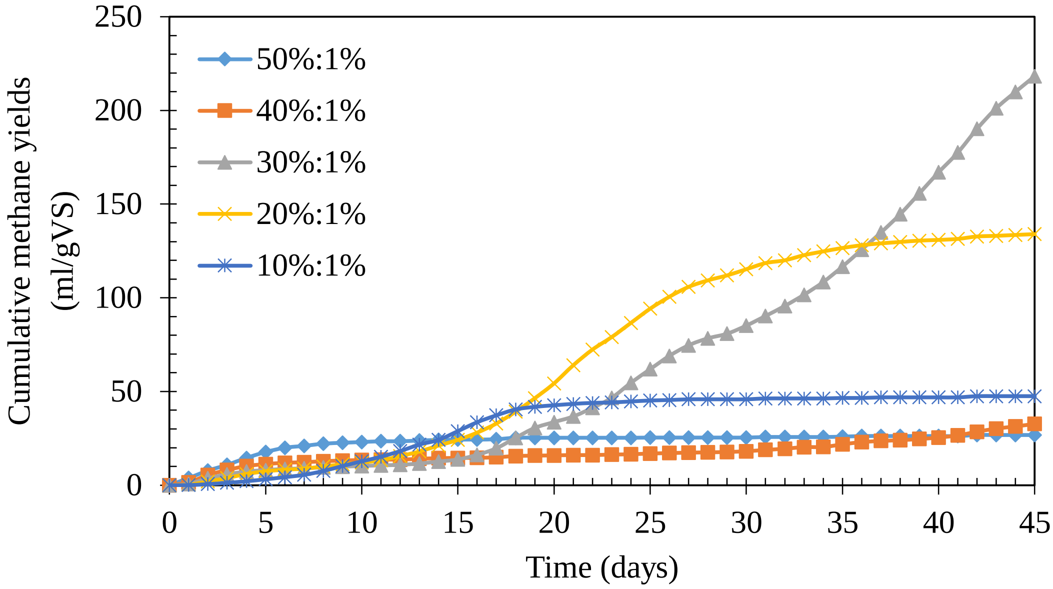


Figure 35 Cumulative methane production from the one-stage anaerobic digestion process at 1% of IFA

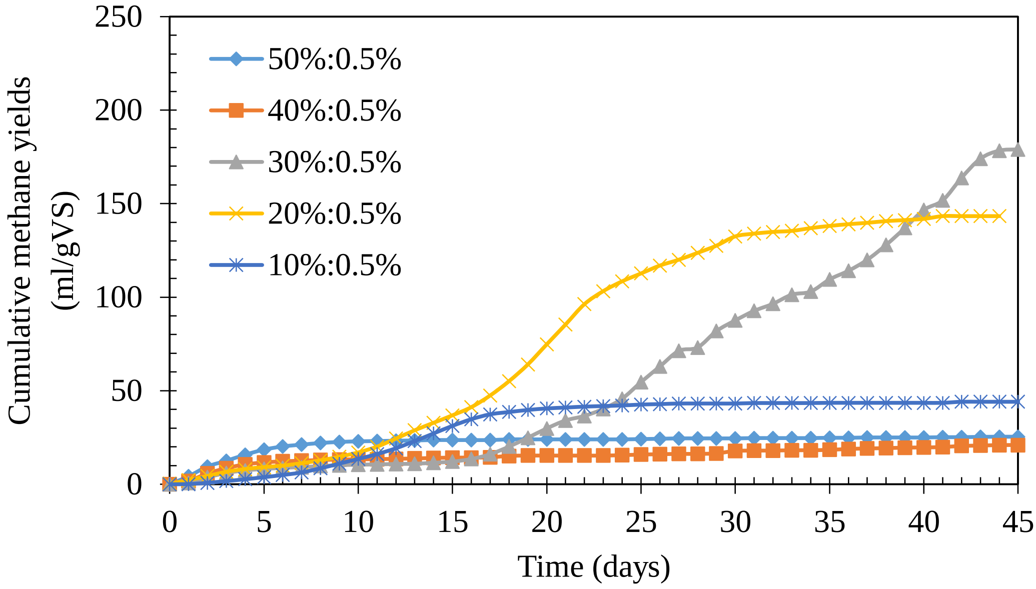


Figure 36 Cumulative methane production from the one-stage anaerobic digestion process at 0.5% of IFA

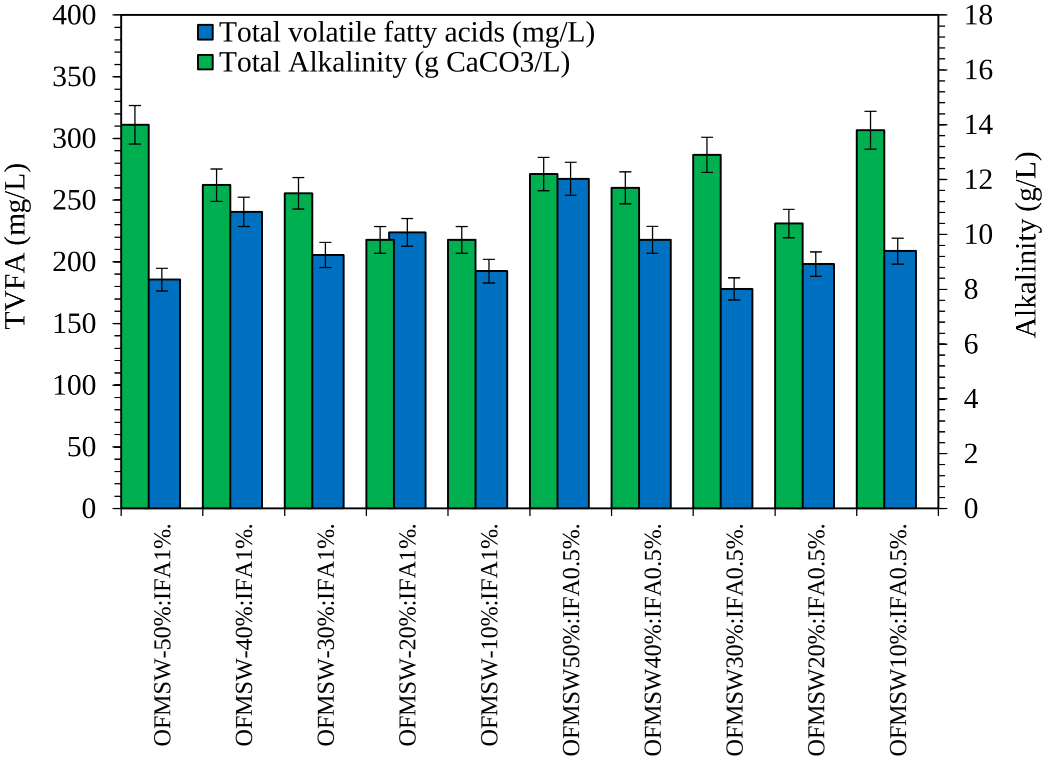


Figure 37 Total volatile fatty acids and Total alkalinity after One-Stage Anaerobic Digestion Process.

Table 7 Estimated parameters of modified Gompertz equation for one-stage methane production

MSW	Fly ash	Y_{exp}	Y_{max}	R_{max}	Lag times	K_h
(%w/w)	(%w/w)	ml-CH_4 /gVS	ml-CH_4 /gVS	ml-CH_4 /gVS/d	day	day^{-1}
50	1	26.8	26.0	0.59	-	0.081
40	1	32.7	31.4	0.73	-	0.027
30	1	218.3	216.1	4.85	30.9	0.031
20	1	134.0	131.3	2.98	11.6	0.097
10	1	47.5	46.6	1.06	6.66	0.128
50	0.5	25.4	24.4	0.56	-	0.085
40	0.5	20.9	20.0	0.47	-	0.054
30	0.5	179.0	170.1	3.98	18.8	0.036
20	0.5	143.3	137.3	3.19	10.6	0.108
10	0.5	44.1	42.2	0.98	6.07	0.137

4.3 Biohythane production in two-stage anaerobic digestion

The accumulative methane yield obtained from OFMSW under mesophilic conditions Two-Stage Anaerobic Digestion Process at different TS contents (10, 20, 30, 40, and 50% TS). In the accumulative methane yield from OFMSW was gradually increased until 55 days of incubation. The cumulative hydrogen yields of OFMSW at 10, 20, 30, 40, and 50 %TS with IFA 0.5 and 1%. For IFA 0.5% was 48.8, 47.7, 46.5, 43.3, and 42.6 and for IFA 1% was 16.5, 41.4, 43.1, 36.1, and 47.4 ml/gVS, the BHP under by two-stage anaerobic digestion process (Figure 38a and 38b). The BHP test, the maximum hydrogen yields of MSW was 47.7 ml gVS^{-1} obtained from 0.5% of IFA. Estimated parameters of modified Gompertz equation for hydrogen production are shown in Table 8. Lag times of hydrogen production were not significantly different from 10-50% (w/w) of MSW and fly ash addition 0.5-1%(w/w).

And the methane yields of OFMSW at 10, 20, 30, 40, and 50 %TS with IFA 0.5 and 1%. For IFA 0.5% was 399, 397, 401, 362, and 320 and for IFA 1% was 349.0, 369.0, 375.0, 341.0, and 364.0 ml/gVS (Figure 39a and 39b). The BMP under by two-stage anaerobic digestion process can improve methane production 45%. When compared with the one-state anaerobic digestion process, the maximum methane yields of two-stage anaerobic digestion process was 401 ml/gVS obtained from 30% of MSW and added 0.5% of IFA. And biodegradation of MSW can increase to 70% when compared with theoretical methane yield. Estimated parameters of modified Gompertz equation for methane production are shown in Table 9. Lag times of methane production were not significantly different from 10-50% (w/w) of MSW and fly ash addition 0.5-1%(w/w).

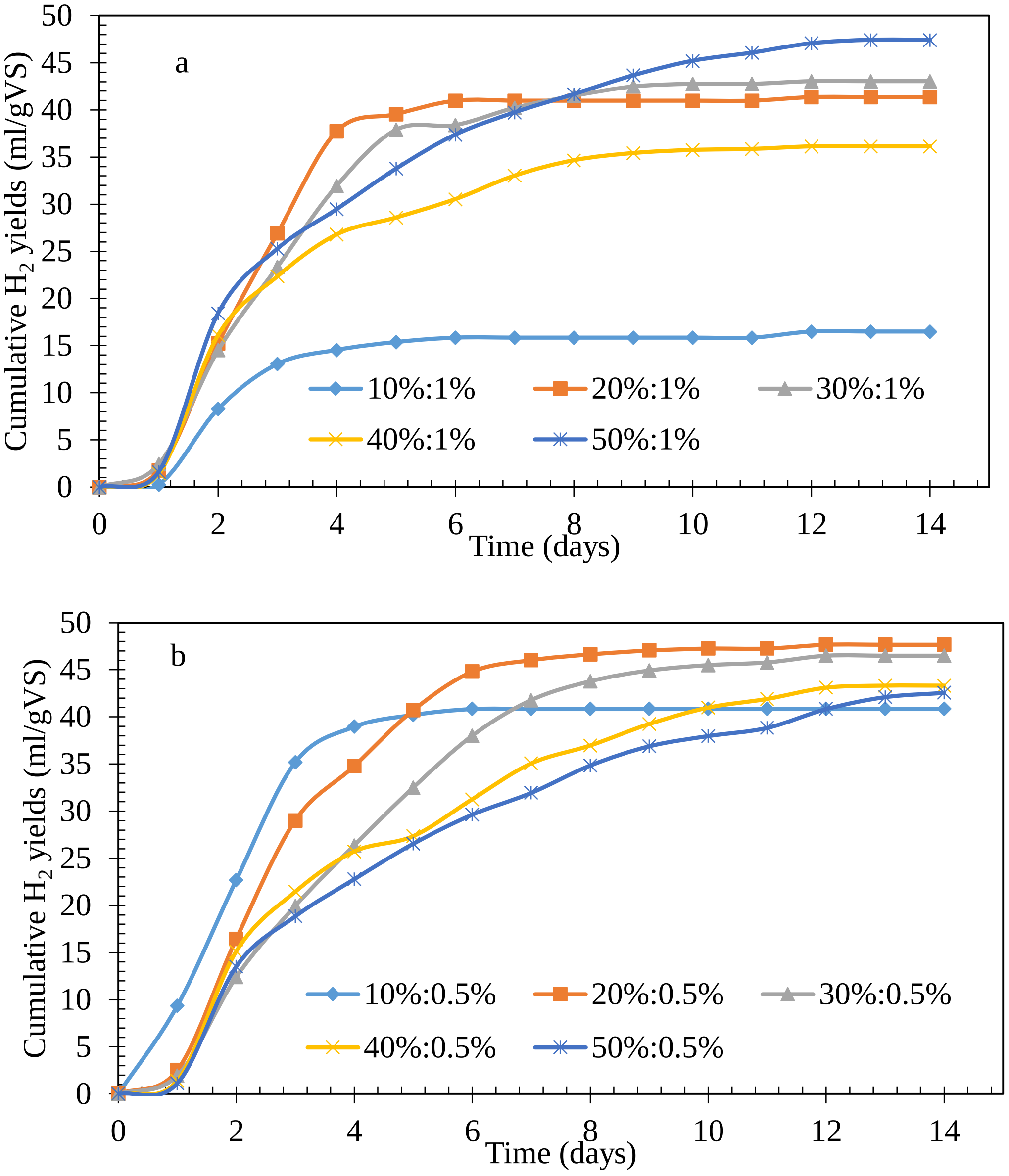


Figure 38 Biological hydrogen potential by two-stage anaerobic digestion process at 1% IFA (a) and 0.5% IFA (b)

Table 8 Estimated parameters of modified Gompertz equation for hydrogen production

MSW	Fly ash	Y_{exp}	Y_{max}	R_{max}	Lag times	K_h
(%w/w)	(%w/w)	ml-H_2 /gVS	ml-H_2 /gVS	ml-H_2 /gVS/d	day	day^{-1}
50	1	47.4	46.5	8.11	0.24	0.358
40	1	36.1	35.5	8.45	0.47	0.463
30	1	43.1	42.7	11.0	0.81	0.504
20	1	41.4	41.3	15.9	1.08	0.522
10	1	16.5	16.0	7.96	1.02	0.331
50	0.5	42.6	41.9	5.65	0.14	0.229
40	0.5	43.3	43.7	6.33	0.14	0.301
30	0.5	46.5	46.7	8.58	0.78	0.412
20	0.5	47.7	47.3	12.7	0.79	0.502
10	0.5	40.8	40.9	16.2	0.48	0.871

Table 9 Estimated parameters of modified Gompertz equation for methane production

MSW	Fly ash	Y_{exp}	Y_{max}	R_{max}	Lag times	K_h
(%w/w)	(%w/w)	ml-CH_4 /gVS	ml-CH_4 /gVS	ml-CH_4 /gVS/d	day	day^{-1}
50	1	363.7	352.7	33.7	1.91	0.103
40	1	341.5	327.8	33.6	1.61	0.103
30	1	375.1	371.4	42.9	1.71	0.114
20	1	369.4	362.0	41.4	1.37	0.121
10	1	348.6	341.6	36.7	0.85	0.106
50	0.5	319.7	306.6	30.7	1.85	0.101
40	0.5	362.4	346.8	36.4	1.83	0.106
30	0.5	400.7	380.7	45.1	1.86	0.113
20	0.5	396.9	380.2	47.3	1.61	0.129
10	0.5	399.2	382.1	46.2	1.24	0.133

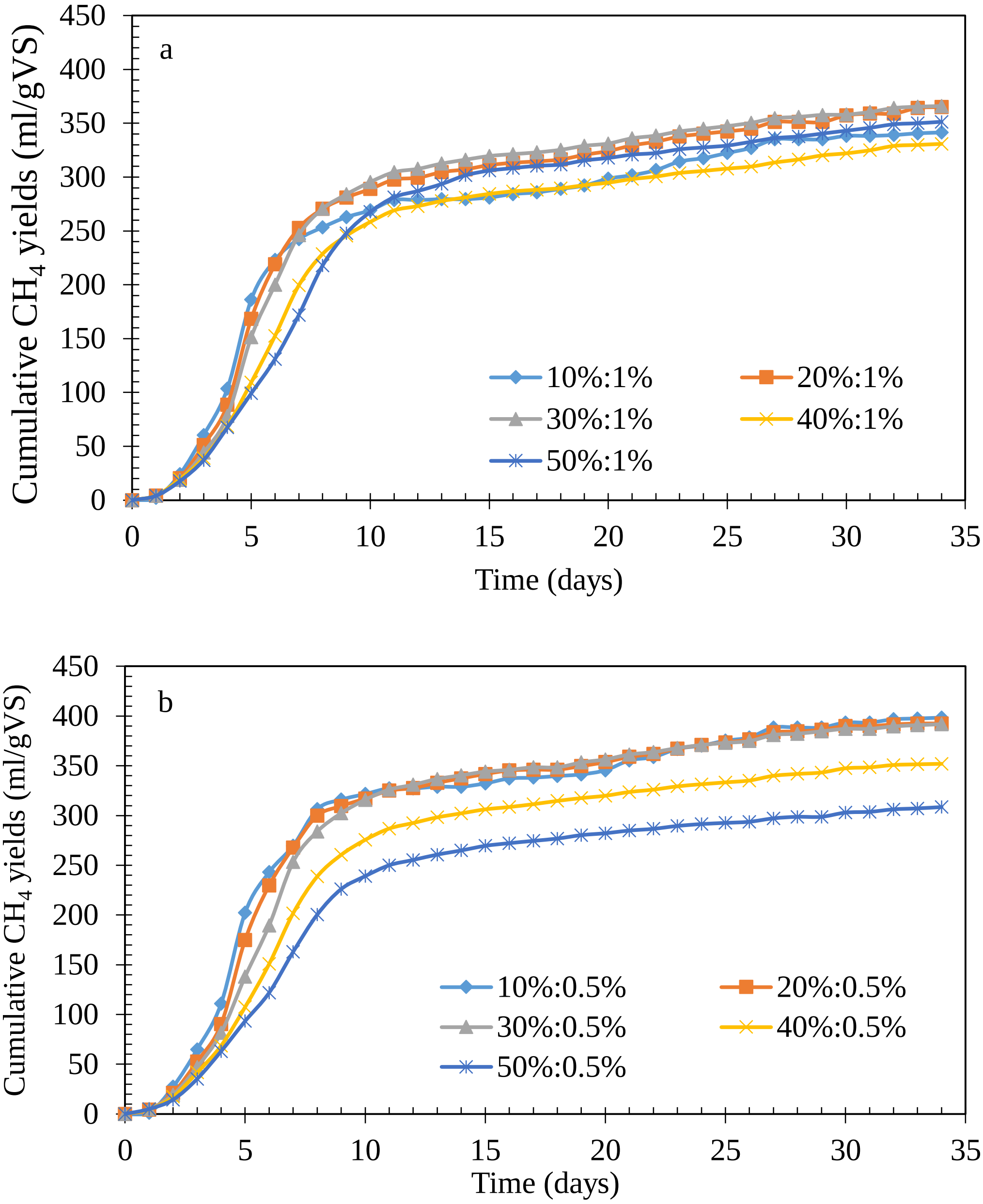


Figure 39 Biological methane potential by two-stage anaerobic digestion process at 1% IFA (a) and 0.5% IFA (b)

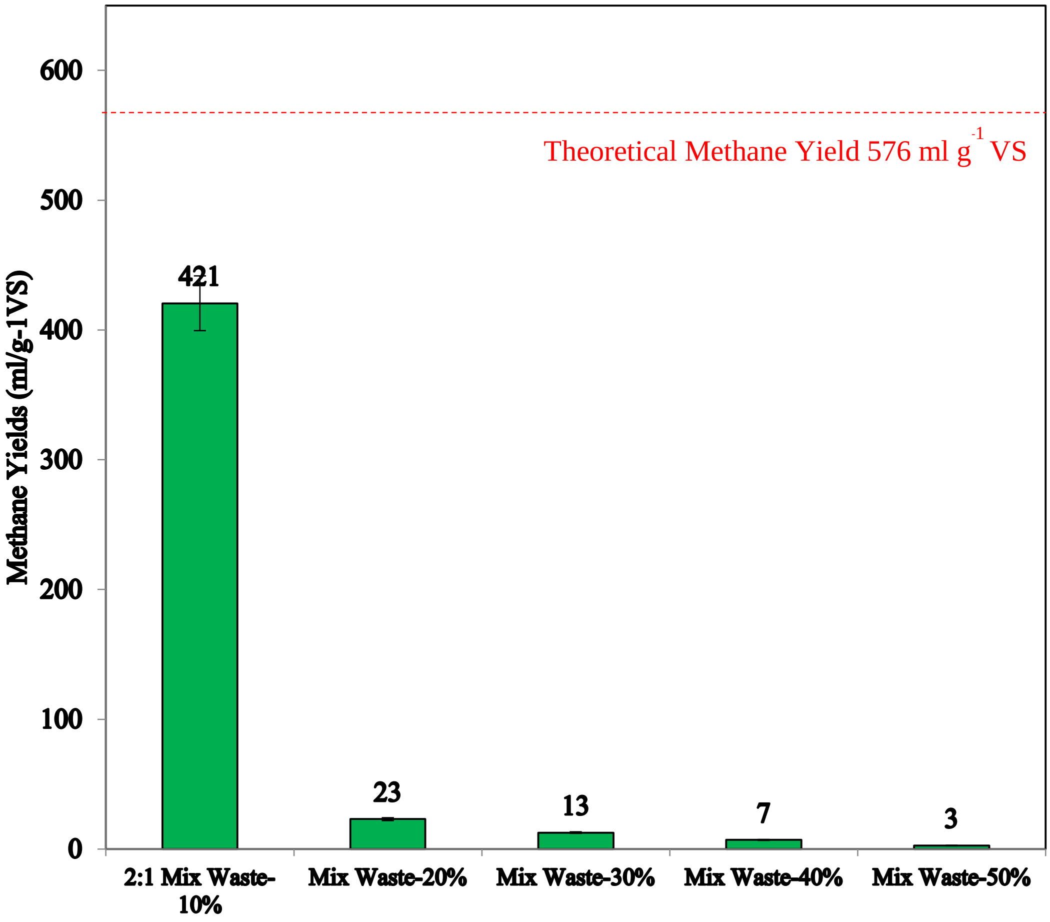


Figure 40 Biological Methane Potential (BMP) by One-Stage Anaerobic Co-Digestion Process.

4.4 Microbial community of two-stage anaerobic digestion process

Denaturing gradient gel electrophoresis (DGGE) was conducted to characterize the microbial community structures in the two-stage anaerobic digesters (Figure 41). Both bacterial and archaeal PCRs were performed with DNA samples collected from hydrolysis stage, and methanogenic stage of OFMSW 20% with IFA0.5% was at steady state. The bacterial communities were dominated by *Clostridium* sp. *Sphingobacterium* sp. *Eubacterium* sp., and *Lactobacillus* sp. in the hydrolysis stage. These genera are very versatile and participate in the degradation of several complex organic residues, such as lipids, carbohydrates, and proteins. This study indicates the main compositions of OFMSW were 1020 mg/L of carbohydrates, 12.3% of proteins and 20.9% of lipids. *Clostridium* sp. could utilize cellobiose, xylose, glucose, and sucrose, and produce acetate, lactate, and hydrogen. Also, the heavy metals of IFA were possibly metabolized as trace nutrients in the first stage of hydrolysis by the three groups of anaerobic microorganisms such as hydrolytic and fermentative microorganisms, obligate proton reducers.

The archaeal community of the methanogenic stage was clearly dominated by members of the genus *Methanobacterium* sp. and *Methanothermus* sp. The *Methanobacterium* sp. can grow with H_2/CO_2 or formate as substrates for methanogenesis. In accordance with (Luo, Wang, J., Wang, Z. and Yue., 2015), who reported that biochar could enrich hydrogenotrophic *Methanobacterium* sp. when adding biochar, *Methanobacterium* sp. was mainly concentrated in the tight sludge absorbed on biochar. An increase in pH occurred in the methanogenic stage and caused an increase in all methanogens group detected; the populations of *Methanosaeta* sp., Methanobacteriales, *Methanobacterium* sp., Methanococcales increased by 208%, 133%, 50%, and 144% respectively.

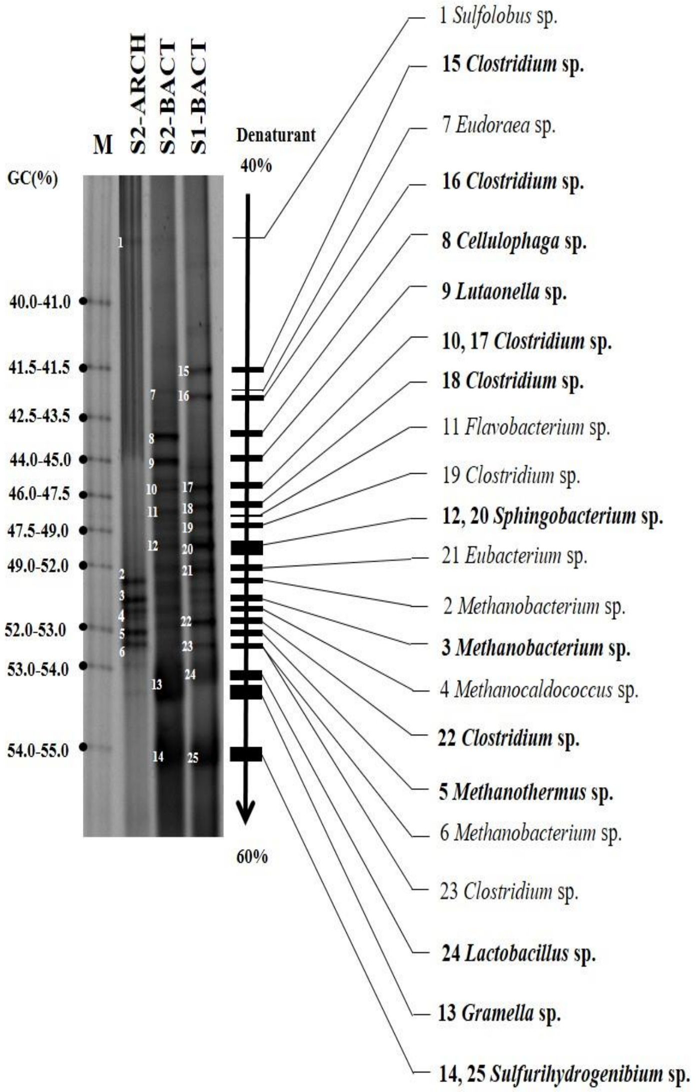


Figure 41 Microbial community of two-stage anaerobic digestion process with using OFMSW as substrates (S1-BACT; bacteria in first stage H_2 production, S2-BACT; bacteria in second stage CH_4 production, S2-ARCH; archaea in second stage CH_4 production)

4.5 Biomethane production in one-stage anaerobic co-digestion

The accumulative methane yield obtained from OFMSW between green waste under mesophilic conditions one-stage anaerobic co-digestion process at different TS contents (10, 20, 30, 40, and 50% TS). In the accumulative methane yield from OFMSW: GW was gradually increased until 55 days of incubation., the methane yields of OFMSW:GW at 10, 20, 30, 40, and 50 %TS with IFA 0.5 For IFA 0.5% was 421.0, 23.0, 13.0, 7.0, and 3.0 mL CH_4 gVS^{-1}. The BMP under by one-stage anaerobic digestion process can improve methane production 5.51% when compared with one-state anaerobic digestion process, the maximum methane yields of one-stage anaerobic co-digestion process was 421 ml gVS^{-1} obtained from 10% of OFMSW: GW and added 0.5% of IFA. And biodegradation of OFMSW: GW can increase to 70% when compared with theoretical methane yield (Figure 40). And total alkalinity after Anaerobic Digestion Process showed that the highest Alkalinity content was 14 grams per liter, reflecting that the system was stable. And Total volatile fatty acids remained the highest at only 2065.5 milligrams per liter. Ash fill 0.5 percent and 50 percent waste and that the highest Alkalinity content was 14.8 grams per liter And Total volatile fatty acids remained the highest at only 275 milligrams per liter. Ash fill 0.5 percent and 50 percent waste.

4.6 Microbial community of one-stage anaerobic co-digestion

Microbial community of biogas production from the co-digestion of MSW with green waste was investigated by PCR-DGGE technique. The bacterial community structure of co-digestion MSW:GW (1:1 and 2:1) dominated by *Clostridium* sp., *Acetomicrobium* sp., *Bacteroides* sp., *Geamella* sp., and *Desulfovibrio* sp. (Figure. 43A). The archaeal community structure of co-digestion MSW:GW (1:1 and 2:1) dominated by *Methanobacterium* sp., *Methanoculleus* sp., and *Methanomicrobium* sp. (Figure. 43B)

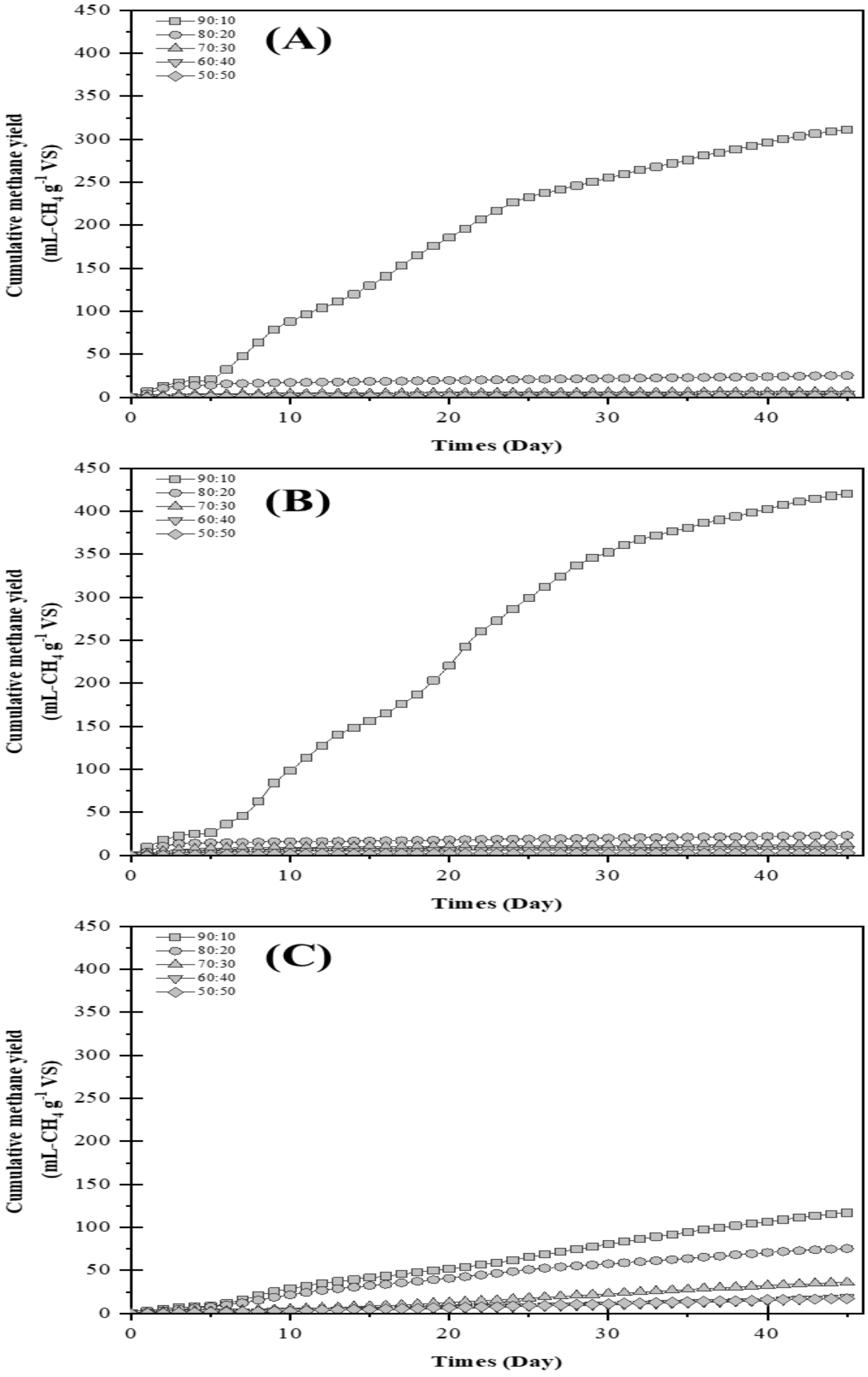


Figure 42 Cumulative methane yield of anaerobic co-digestion of municipal solid waste (MSW) with green waste (GW); MSW: GW ratio 1:1 (A); MSW: GW ratio 2:1 (B); mono-digestion of GW (C).

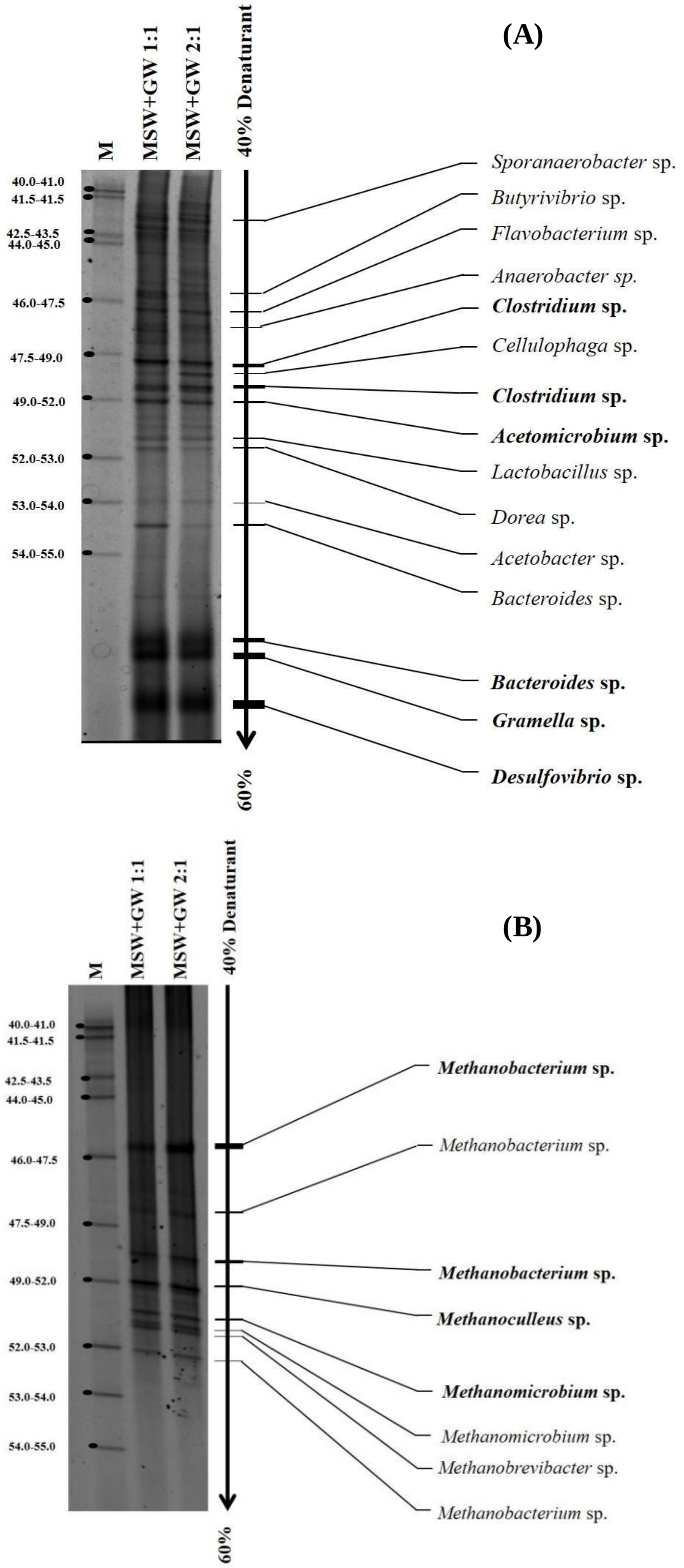


Fig 43 Bacterial (A) and archaeal (B) community of one-stage anaerobic co-digestion.

4.7 Feasibility of using MSW to produce bioenergy by anaerobic digestion process and incineration process.

Energy recovery from municipal solid waste between anaerobic digestion process and incineration process. Fond that the energy recover from low moisture MSW higher than high moisture MSW 4.4 fold. However, this study indicated the anaerobic digestion of MSW can be produced maximum energy 2,502 MJ/ton (Figure 44)

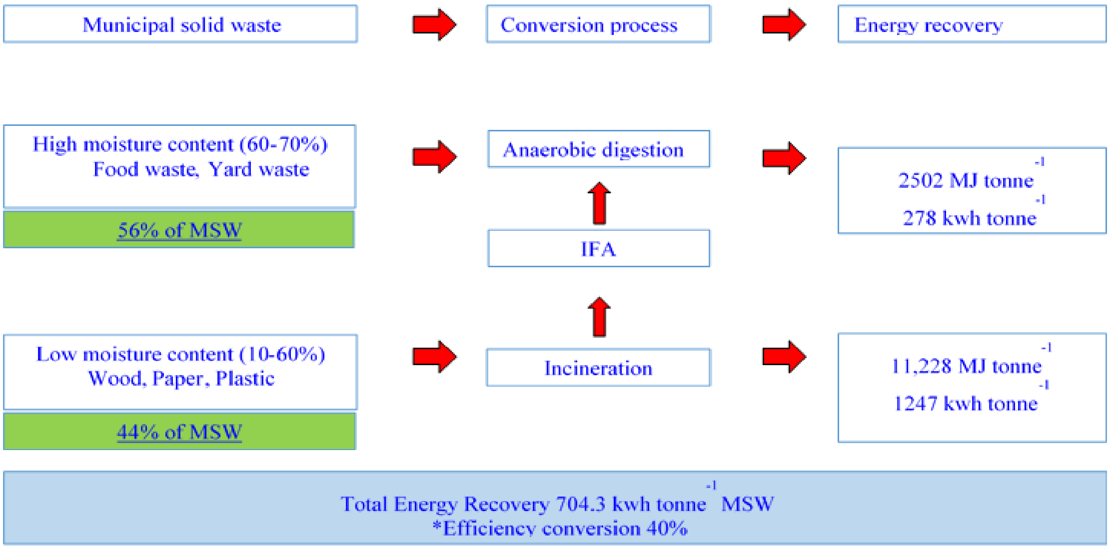


Figure 44 Energy recovery from the municipal solid waste by anaerobic digestion and incineration process.

4.8 Carbon Emissions of Municipal Solid Waste Management

4.8.1 Waste source

By calculating the amount of greenhouse gas emissions from solid waste, it was found that Sichon, Muang and Tha Sala Districts had the highest greenhouse gas emissions. It is equivalent to 275.78, 267.46 and 245.45 KgCO$_2$/Tonne$_{waste}$. The second is Lan Saka, and Phrom Khiri district is equal to 225.13, 212.13 KgCO$_2$/Tonne$_{waste}$, Sichon district, Thasala district and Muang district. The total amount of greenhouse gas emissions from fermentation per year. It is equivalent to 788.69 KgCO$_2$/Tonne$_{waste}$ /year. The second is Lan Saka. This is a good example. KgCO$_2$/Tonne$_{waste}$/ year. Greenhouse gas emissions from fermentation were 1,225.95 KgCO$_2$/Tonne$_{waste}$/Year (table 10)

Table 10 Carbon Emissions of Municipal Solid Waste Management form Waste source

Source (Districts)	Volume of organic waste (Tone/year)		Carbon Emissions ($KgCO_2/Tonne_{waste}$)
	Food Waste	Wood, Green Waste	
Sichon	1,372.32	148.36	275.78
Lan Saka	1,701.14	12.89	212.13
Thasala	2,064.98	0	245.45
Phrom Khiri	1,040.20	225.13	225.13
Muang	5,721.84	3,814.56	267.46
Total	11,900.48	4,200.94	1,225.95

4.8.2 Transport waste to disposal

Waste collection truck used in waste collection system in all 5 districts. There are two types of Municipal waste trucks: Side loading and dumping truck and Compactor truck. The fuel used is diesel. Greenhouse gas emissions from the transportation of solid waste equal to 450. 85 $KgCO_2$/ $Tonne_{waste}$ and 837. 92 $TonneCO_2$/Year (table 11)

Table 11 Carbon Emissions of Municipal Solid Waste Management form Transport waste to disposal

Source (Districts)	Volume of Waste (Tone/year)*	The average transport distance (km)	Fuel (Liter)	Carbon Emissions ($KgCO_2/Tonne_{waste}$)	Carbon Emissions ($TonneCO_2$/Year)
Muang	12,590.66	11	27,532	261.49	679.33
Thasala	1165.75	31	8,400	19.00	23.00
Lan Saka	488.5	27	5760	31.78	15.52
Phrom Khiri	2006.54	26	17264	74.69	47.34
Sichon	2210.29	75	31620	63.47	73.09
Total	18,461.74	170.27	90,576	450.85	837.92

*Total waste was calculated from volume of organic and inorganic waste.

4.8.3 Landfill

Carbon emissions of municipal solid waste management on landfill was calculated from volume of organic and inorganic waste. The results showed that volume of municipal waste was 90,153 tonne/ year. The total municipal waste could produce 376 $KgCO_2$/ $tonne_{waste}$ of greenhouse gas emissions from landfill on landfill. Greenhouse gas emissions from fossil fuels was produced 4.31 $KgCO_2/Tonne_{waste.}$ Total greenhouse gas emissions from solid waste, landfill/dump of 380.56 $KgCO_2/Tonne_{waste}$ (table 12).

Table 12 Carbon Emissions of Municipal Solid Waste Management form Landfill

Parameters	Value	Unit
Volume of municipal waste	90,153.02	Tone/year
Solid waste landfill capacity per year	1,081,836.24	Tone/ Year
Volume of $CH_4/Tonne_{waste}$	17.92	$KgCH_4/tone_{waste}$
Convert methane to carbon dioxide	21.00	$KgCO_2$/ $KgCH_4$
Greenhouse gas emissions from landfill	376.25	$KgCO_2$/ $tone_{waste}$
The amount of diesel fuel used in engines running on landfill.	144,000.00	Liter/Year
Solid waste landfill per year.	90,153.02	Tone/Year
The amount of diesel used per ton of waste	1.60	$Liter/Tone_{waste}$
Greenhouse gas emissions from the use of fossil fuels	4.31	$KgCO_2$/ $Tone_{waste}$
Total amount of diesel fuel used in engines running on landfill.	1,440.00	Liter/Year
The amount of methane emissions from organic waste landfill	17.92	$KgCH_4/Tone_{waste}$
The amount of greenhouse gas emissions directly from solid waste landfills	380.56	$KgCO_2$/ $Tone_{waste}$
Total greenhouse gas emissions from landfills	34,308.94	$ToneCO_2$/Year

* Carbon emissions of municipal solid waste management was calculated from volume of organic and inorganic waste.

Municipal solid waste mainly composed of low moisture content and high moisture content of 60% and 40%, respectively. Low moisture can be raw materials for power plant and high moisture content can be raw materials for biogas. Nakhon Si Thammarat Municipality generate high GHG emission of 2,057.36 $KgCO_2/Tonne_{waste,}$

CHAPTER 5

Conclusion, Discussions and Recommendations

Conclusion

Nakhon Si Thammarat Municipality generate high GHG emission of 2,057.36 $KgCO_2$/tonne-waste, Scenario by applied power plant. This study shows the addition, IFA 0.5% and 1% into OFMSW were effective for control pH of OFMSW digestion at optimal pH 5.5-6.0 and 7.2-7.5 for two-stage anaerobic digestion. The methane productivity was 2 folds greater in the two-stage anaerobic digestion system compared with the one-stage anaerobic digestion system. An energy recovery of 1 tonne mixture of treated MSW would be 2,536 MJ or 704 kW h of electricity.

Discussions

5.1 The Composition of Municipal Solid Waste

The compositions of municipal solid waste (MSW) in Nakhon Si Thammarat landfill were dominated by vegetables 37.04 ±0.31%, paper 11.87±0.46% and plastic, 25.06±0.31%. In generally, the composition of MSW at generation sources and collection points was determined on a wet weight basis and it consists mainly of a large organic fraction (40–60%), ash and fine earth (30–40%), paper (3–6%) and plastic, glass and metals (each less than 1%). The C/N ratio ranges between 20 and 30, and the lower calorific value ranges between 800 and 1000 kcal/kg (Sharholy, Ahmad, Mahmood and Trivedi. 2008; 459) To reduce the amount of wastes destined for landfills, the organics from MSW can be separated and treated through conversion technologies for volume reduction and generation of valuable byproducts, such as biogas energy and compost (Zhu, Gikas, Zhang, Lord, Jenkins and Li. 2009 ; 1123) The composition of waste determine biogas yield and gas quality. The order of biogas volume produced by degradation per unit of organic matter is as follows: lipids > carbohydrates > proteins, the order for methane production is as follows: lipids > proteins > carbohydrates. The composition of the reaction samples was different; thus, biogas and methane production could be predicted according to different compositions.

5.2 Biological Methane Potential of OFMSW via One-Stage Anaerobic Digestion

This study showed the 30% of MSW had maximum methane yields 218 ml per gVS^{-1} with IFA 1%. Most of the digesters had methane contents between 50% and 70% between day 8 and day 30, which is considered steady state. All treatments prolonged the lag phase from 6.66 to 30.6 day. A study by El-Mashad and Zhang (2010 ; 4021) found that inclusion of food waste, at rates of up to 60% of feedstock VS, with dairy manure resulted in higher biogas yields and production rates as compared to the digestion of dairy manure alone. Xu and Li (2012; 219) also showed decreased daily methane yields that approached 0 near day 8 at an F/E ratio of 4 when 100% and 50% dog food was co-digested with corn stover. The FA/MSW 20 g L^{-1} dosed bioreactor appeared to have the experimental highest peak biogas production rate and total biogas production among the four bioreactors. On the other hand, control bioreactor had the lowest peak biogas production rate, however, it produced total biogas production only slightly less than FA/MSW 20 g L^{-1} dosed bioreactor. Biogas production rates in the control bioreactor over the digestion period were comparatively lower compared to those in the ashes dosed bioreactors. However, biogas production rates in the control bioreactor lasted a comparatively longer period over the whole digestion period leading to a comparatively higher total biogas production only slightly less than that of FA/MSW 20 g L^{-1} dosed bioreactor (Lo, Kurniawan, Sillanpää, Pai, Chiang, Chao and Lin. 2010; 6329)

5.3 Biohythane Production in Two-Stage Anaerobic Digestion

The biological hydrogen potential test, the maximum hydrogen yields of MSW was 47.7 ml gVS^{-1} obtained from 0.5% of IFA. Once the process was stable, the average hydrogen concentration in the gas was in the range of 25–27.5%, balanced to CO_2. The maximum methane yields of two-stage anaerobic digestion process was 401 ml gVS^{-1} obtained from 30% of MSW and added 0.5% of IFA. Corresponding to, the hydrogen-producing phase was capable of stable performance under the hydraulic retention times (HRTs) evaluated (3 and 5 days). All treatments of hydrogen production had shortened the lag phase from 0.14 to 1.08 day. Corresponding to All treatments of methane production had shortened the lag phase from 0.85 to 1.91 day. No methane was detected in the first phase at any point during the whole period of the experiment and the hydrogen yield showed no symptoms of declining as time elapsed. The amount of hydrogen obtained from the fermentation process was in the range of 52.5–71.3 N L kg^{-1} VS (Gomez, Moran, Cuetos and Sanchez. 2006; 727) Mamimin, Probst, Gómez-Brandón, Podmirseg, Insam, Reungsang and O-Thong. (2018; 3325) shows the effect of ash supplementation into palm oil mill effluent on biohythane production and responsible microbial communities in thermophilic two-stage anaerobic fermentation was investigated. High biohythane yields were linked to Ni/Co/Fe supplementation (10, 6 and 20 mg L^{-1}, respectively) with maximum H_2 and CH_4 yields of 139 mL H_2 gVS^{-1} and 454 mL CH_4 gVS^{-1}, respectively. The two-stage thermophilic SS-AD process was successfully accomplished for the tests with TS content of 16%. High TS contents of 28% and 40% may even hinder gas-liquid transfer, leading to accumulation of carbon dioxide (CO_2) and hydrogen (H_2) that inhibit methanogens. The high solid content could lead to slow mass transfer between microbes and substrate, resulting in slow methane production and low methane yield (Yang, Xu, Ge, and Li. 2015; 824)

5.4 Microbial Community of Two-Stage Anaerobic Digestion Process

The bacterial communities were dominated by *Clostridium* sp. *Sphingobacterium* sp. *Eubacterium* sp., and *Lactobacillus* sp. in the hydrolysis stage. These genera are very versatile and participate in the degradation of several complex organic residues, such as lipids, carbohydrates and proteins (González, Molinuevo and Garciaet, 2011) Corresponding to, this study indicates the main compositions of OFMSW were 1020 mg/L of carbohydrates, 12.3% of proteins and 20.9% of lipids. (Yuan, Shao, Liang and Bian, 2014) found that *Clostridium* sp. could utilize cellobiose, xylose, glucose and sucrose, and produce acetate, lactate, and hydrogen. Also, the heavy metals of IFA were possibly metabolized as trace nutrients in the first stage of hydrolysis by the three groups of anaerobic microorganisms such as hydrolytic and fermentative microorganisms, obligate proton reducers (Lo. 2005) The prevalence of the Firmicutes and Actinobacteria throughout the AD process reflects their ability to metabolise a variety of substrates including protein, lipids, lignin, cellulose, sugars and amino acids. Actinobacteria (e.g. *Brevibacterium, Streptomyces, Nocardioides*) and Firmicutes (e.g. *Clostridium*) are known to produce cellulases, lipases, proteases and other extracellular enzymes (Leven, Eriksson and Schnurer. 2007) suggesting they are involved in hydrolysis and acidogenesis.

The archaeal community of the methanogenic stage was clearly dominated by members of the genus *Methanobacterium* sp. and *Methanothermus* sp. The *Methanobacterium* sp. can grow with H_2/CO_2 or formate as substrates for methanogenesis (Yang, et al. 2015). In accordance with Luo, Wang, Liu, Wang, Z., Yuan and Yue. (2015) who reported that biochar could enrich hydrogenotrophic *Methanobacterium* sp. when adding biochar, *Methanobacterium* sp. was mainly concentrated in the tight sludge absorbed on biochar. An increase in pH occurred in the methanogenic stage and caused an increase in all methanogens group detected; the populations of *Methanosaeta* sp., *Methanobacteriales, Methanobacterium* sp., *Methanococcales* increased by 208%, 133%, 50% and 144% respectively (Zahedi, 2016)

5.5 Biomethane Production in One-Stage Anaerobic Co-Digestion

The co-digestion of different feedstocks has as main advantages the balance of nutrients, C/N ratio equilibrium and the minerals and metals required for equilibrium, and increased buffering capacity of the system. Therefore, co-digestion enhances process stability and performance of organic matter biodegradation, optimizing the biogas and methane yield (Brown and Li, 2013). The maximum methane yields of one-stage anaerobic co-digestion process was 421 ml gVS^{-1} obtained from 2:1 of OFMSW: GW with inoculum (90%) and substrates (10%). These results indicate synergy between the different substrates, considering that OFMSW has an average cumulative biogas yield much inferior to GW, but the addition of OFMSW does not affect negatively the cumulative biogas yield. Borowski. (2015) found contents of methane in biogas between 55% and 60% for the mono-digestion of OFMSW and between 58% and 66% for the co-digestion of OFMSW and sewage sludge. Regarding the 2:1 OFMSW:GW ratio, the methane yield displayed an increase of 13%. Therefore, it can be assumed that a C/N ratio ranging from 30.5 and 34.7 would be considered an optimum condition for co-digestion of OFMSW and GW. Therefore, the hypothesis of co-digestion of OFMSW and FW was to provide sufficient nutrient balance to enhance the hydrogen production. Indeed, the C/N ratio of co-substrate was 27.7 which is into the optimum range for biological process 20–30 (Khalid, Arshad, Anjum, Mahmood and Dawson. 2011)

5.6 Microbial community of one-stage anaerobic co-digestion

The bacterial community structure of co-digestion MSW:GW (1:1 and 2:1) dominated by *Clostridium* sp., *Acetomicrobium* sp., *Bacteroides* sp., *Geamella* sp., and *Desulfovibrio* sp. Clostridium sp. is able to ferment variouscarbohydrates to acetate, butyrate and hydrogen (Lee, Kim, Lee,H., Chang and Kim, H. 2010) *Clostridium* sp. is an important cellulolytic bacterial group in degradation of lignocellulosic biomass under anaerobic conditions with versatile fermentation capability. Cellulolytic bacteria consisted of *Clostridium* sp. and *Ruminococcus* sp. were found predominantly in thermophilic SS-AD of wheat straw (Heeg, Pohl, Sontag, Mumme, Klocke and Nettmann, 2014) and corn stove (Shi, Wang, Stiverson, Yu and Li. (2013) ; Li, Østensen, Attramadal, Winge, Sparstad and Bones. 2015) These species can produce thermoactive hydrolytic extracellular enzymes (e.g., protease,lipase and cellulase).

The archaeal community structure of co-digestion MSW:GW (1:1 and 2:1) dominated by *Methanobacterium* sp., *Methanoculleus* sp., and *Methanomicrobium* sp. This indicates that Methanosaeta sp. and Methanoculleus sp.are mainly responsible for methane production in AD process. *Methanosaeta* sp. was distinguished from members of the other genera by their exclusive use of acetate as a substrate for producing methane. Methanosaeta sp. always prefers a low acetate concentration for its growth (Narayanan, Krishnakumar, Anupama and Manilal. 2009)

In the AD reactors, the other detected non-acetoclastic methanogens included the genera *Methanospirillum* sp. and *Methanoculleus* sp., which all belong to the class *Methanomicrobia*. *Methanospirillum* sp. is a genus of strictly hydrogenotrophic methanogens. Li, et al. (2015) reported that the genus *Methanothermobacter* sp. *Methanoculleus* sp. was dominated in the thermophilic SS-AD reactors for biogas production from corn stover.

5.7 Feasibility of using MSW to Produce Bioenergy by Anaerobic Digestion Process and Incineration Process.

Based on the latest report published by World Bank. (2012) the annual waste generation in East Asia and the Pacific Region was a proximately 270 million tons per year with an average per capita of 0.95 kg person^{-1} day^{-1}. Almost 70% of the waste generation in this region was contributed by China. Countries in South Asia produced approximately 70 million tons of MSW per year, with an average per capita of 0.45 kg person^{-1} day^{-1}. The annual waste generated in Eastern Europe and Central Asia has been estimated at least 93 million tons with an average per capita of 1.1 kg person^{-1} day^{-1}. In the Middle East and North Africa, the MSW generated per year is 63 million tons with an average per capita of 1.1 kg person^{-1} day^{-1} This study shows municipal waste in the landfill of Nakhon Si Thammarat municipality were collected at 6 points, each with a thermal value of 9,182.9, 14,892.0, 9,204.9, 11,218.4, 11,582.3 and 11,290.9 kJ/Kg with an average heat of 1,122 kJ/Kg of waste (Low moisture content). Energy recovery from municipal solid waste between anaerobic digestion process and incineration process. Fond that the energy recovers from low moisture MSW higher than high moisture MSW 4.4 folds However, this study indicated the anaerobic digestion of MSW can be produced maximum energy 2502 MJ/ton. Municipal solid waste is one of the abundant renewable sources of energy that can be found in Thailand. In terms of economic development, this is valuable for developing the economy in the country as energy can be produced by using MSW generated from the Thailand. This is further supported by (Chaiyapa, Esteban, and Kameyama, 2018; 449) which stated that an abundant supply of energy can influence the growth of the economy in Thailand. More resources are needed in order to support the industrial development with the current economic development to enhance the productivity of labour and capital of energy production. Thailand vision to become a high-income country also can be achieved if there is a supply of new renewable and sustainable energy for the future (Chunark, Limmeechokchai, Fujimori and Masui. 2017; 1296)

5.8 Carbon Emissions of Municipal Solid Waste Management

Nakhon Si Thammarat Municipality generate high GHG emission of 2057.36 KgCO$_2$/tonne-waste, Scenario by applied power plant. The greenhouse gas mitigation from power plant combine with biogas from organic waste can be more effective than electricity generation in a waste to energy plant. Disposal and treatment of MSW can produce significant amount of GHG emissions: carbon dioxide and nitrous oxide are produced by incineration, while methane (which is 21 times more potent than carbon dioxide over 100 years) is produced as a byproduct of the anaerobic decomposition of MSW in landfills. Methane produced at solid waste disposal sites contributes approximately 3–4% of the global anthropogenic GHG emissions (IPCC. 2006) Methane emission from MSW management is estimated to be 1.87–3.37 Mt in China in 2004. Compared to the option of landfilling, WTE can curb the contribution of MSW on GHG emissions through avoiding the release of methane from landfills and offsetting emissions from fossil fuel power plants. Comparative studies of WTE and landfilling have shown that WTE can reduce up to 1.3 tonnes of carbon equivalent per ton of MSW through avoiding the release of methane from landfills and offsetting emissions from fossil fuel power plants.

Recommendations

1. Research and Implication

Community waste (MSW) in this study has the potential to produce high methane gas under an anaerobic decomposition process in which biogas production should be used as a precursor for economic reasons for the industry. Two-stage anaerobic digestion due to higher yield and efficient degradation of methane without additional energy to prevent unwanted products and garbage in some communities. There are differences but in the part of the community waste element, Because the season is an important factor to consider.

2. Future Research

There is still no report on suitable addition of IFA under commercial scale for biogas production by anaerobic digestion process. Therefore, municipal solid waste management and biogas production of MSW should be applied with the large scale to evaluation of economic feasibility. And the ash from other industries should be applied to the anaerobic fermentation system to increase the efficiency of methane.

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