



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ENVIRONMENTAL PROTECTION

Monika Rasinskaitė

**ANALYSIS AND ASSESSMENT OF GAS EMISSIONS FROM DIFFERENT
MUNICIPAL SOLID WASTE LANDFILL MODELS**

**DUJINIŲ TERŠALŲ IŠ SKIRTINGŲ KOMUNALINIŲ ATLIEKŲ
SĄVARTYŲ MODELIŲ TYRIMAI IR VERTINIMAS**
Master Thesis

Study programme of Environmental Technologies and Management, state code
621H17003
Study field of General Engineering

Vilnius, 2016

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ENVIRONMENTAL PROTECTION

ACKNOWLEDGED
Head of the department

(Signature)
Saulius Vasarevičius
(Name, surname)

(Date)

Monika Rasinskaitė
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Supervisor

Assoc.Prof. Rasa Vaiškūnaitė _____
(Degree, name, surname) (Signature) (Date)

Co-supervisor

Assoc. Prof. Elina Dace _____
(Degree, name, surname) (Signature) (Date)

Consultant

(Degree, name, surname) (Signature) (Date)

Consultant

(Degree, name, surname) (Signature) (Date)

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Monika Rasinskaitė, 20103726

(Studento vardas ir pavardė, studento pažymėjimo Nr.)

Aplinkos inžinerijos fakultetas

(Fakultetas)

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(Parašas)

Monika Rasinskaitė

(Vardas ir pavardė)

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ENVIRONMENTAL PROTECTION

Study field of General Engineering

Study programme of Environmental Protection
Technology and Management

code 621H17003

APPROVED BY
Head of the Department

(Signature)
Saulius Vasarevičius
(Name, Surname)

(Date)

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(Name, Surname)

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THE OBJECTIVES:

Objective: The aim of the thesis is to evaluate emitted greenhouse gases from pre-treated municipal solid waste landfill models and, based on the obtained results, suggest the most sustainable municipal solid waste landfill model.

The tasks for achieving the aim are as follows:

- to conduct an analysis of the available scientific literature with respect to waste landfilling, greenhouse gas emissions, emission control systems in landfills, and sustainable waste management concept;
- to elaborate five different landfill models for experimental research;
- to experimentally determine the greenhouse gas and other gas emissions and pH level in each of the landfill models of the collected samples;
- to conduct a mathematical modelling of greenhouse gas emissions for full-scale landfill models to determine their cumulative emissions over the lifetime of a landfill site;
- to conduct an economical evaluation of the landfill model with the least cumulative emissions;
- to discuss the obtained results, and make conclusions on the outcomes of the study.

Academic Supervisor Dr.sc.ing. assoc. prof. Rasa Vaiškūnaitė.....
(Signature) (Title, Name, Surname)

Academic Supervisor Dr.sc.ing. assoc. prof. Elina Duce.....
(Signature) (Title, Name, Surname)

Objectives accepted as a guidance for my Master Thesis

.....
(Student's Signature)
..... Monika Rasinskaitė
(Student's Name, Surname)
..... 22/09/2014.....
(Date)

Vilnius Gediminas Technical University
Faculty of Environmental Engineering
Department of Environmental Protection

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Author: **Monika Rasinskaitė** Supervisors: **Dr.sc.ing., assoc. professor, Elīna Dāce**

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Annotation

Municipal solid waste landfill's surface mainly releases greenhouse gases like CH₄, CO₂, which cause global warming. Huge amounts of biodegradable waste are flowing into the landfill when there is not enough of systematic ways to collect, treat and recycle municipal waste. The lack of waste in situ treatment in landfills have to be revised, otherwise the magnitude of ozone layer will decrease even more and the global warming consequences will get more obviously on the environmental scale. The aim of the research is to evaluate emitted greenhouse gases (GHG) from municipal solid waste landfill models with different parameters and to suggest the most sustainable municipal solid waste landfill model. The object of research is the emissions of methane (CH₄), carbon dioxide (CO₂), hydrogen sulphide (H₂S) and oxygen (O₂) composition amounts from municipal solid waste landfill models. After evaluation of experimental results, LandGEM mathematical modeling and economic evaluation is done. Modelling shows which of the landfill models in real size would emit the lowest amount of gas emissions and after it economical evaluation is done to see main costs benefit. Based on combined results, conclusions and recommendations are submitted. The paper consists of 10 parts: introduction, five chapters, conclusions, recommendations, references, list of publications. Pages – 59 p. text, 57 figures, 12 tables, 59 references.

Appendices separately attached to Master Thesis.

Keywords: municipal solid waste, biodegradable waste, landfill models, sustainability, greenhouse gas emissions.

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Pavadinimas: **Dujinių teršalų iš skirtingų komunalinių atliekų sąvartynų modelių tyrimai ir vertinimas**

Autorė: **Monika Rasinskaitė**

Vadovai: **Dr.sc.ing., assoc. professor, Elina Dāce**
Dr.sc.ing., professor, Rasa Vaiskunaite

Angļu
Latvijas
☐ Lietuviešu

Anotacija:

Didžioji dalis šiltnamio efektą sukeliančių dujų, tokių kaip CH₄, CO₂, išsiskiria iš komunalinių atliekų sąvartynų. Didžiuliai biologiškai skaidžių atliekų kiekiai patenka į sąvartynus dėl nepakankamai sistemingų komunalinių atliekų rinkimo, apdorojimo ir šalinimo sistemos būdų. Privalu įvertinti komunalinių atliekų sąvartynų *insitu* tvarkymo metodus, siekiant išvengti ozono sluoksnio mažėjimo. Šis mažėjimo procesas gali sukelti daug rimtų padarinių, susijusių su globaliniu atšilimu. Šio tyrimo tikslas – įvertinti išsiskiriančių dujų kompoziciją iš komunalinių atliekų sąvartynų modelių su skirtingais parametrais ir pasiūlyti darniausią sąvartyno modelį. Tyrimo objektas – metano (CH₄), anglies dioksido (CO₂), vandenilio sulfido (H₂S) ir deguonies (O₂) kompozicijos kiekis komunalinių atliekų sąvartynų modeliuose. Įvertinus eksperimentinio tyrimo rezultatus buvo atliktas LandGEM matematinis modeliavimas ir ekonominis vertinimas. Matematinis modeliavimas padėjo įvertinti, kuris sąvartyno modelis išskirs mažiausiai dujinių teršalų ir pagal atrinkto sąvartyno parametrus buvo atliktas ekonominis naudingumo vertinimas. Darbą sudaro 10 skyrių: įvadas, 6 skyriai, išvados, rekomendacijos, literatūros sąrašas, publikacijų sąrašas. Darbo apimtis – 59 p. teksto be priedų, 57 iliustracijos, 12 lentelių, 59 literatūros šaltiniai.

Raktiniai žodžiai: komunalinės atliekos, biologiškai skaidžios atliekos, sąvartynų modeliai, darnumas, šiltnamio dujos.

CONTENT

ABBREVIATIONS	11
INTRODUCTION	12
1. ASSESSMENT OF MUNICIPAL SOLID WASTE AND ITS GENERATED AIR POLLUTANTS	14
1.1 Description of municipal solid waste generation and management.....	14
1.2 Municipal solid waste treatment strategies and requirements.....	21
1.3 Towards sustainable municipal solid waste management.....	25
1.4 Description of greenhouse gas emissions from municipal solid waste.....	29
1.5 Sustainable waste management and landfill approach.....	32
1.6. Controlling GHG emissions from landfills	37
1.7 First chapter conclusions.....	40
2. METHODOLOGY	41
2.1 Materials used in the experiment	41
2.2 Experimental equipment	43
2.3 Experimental conditions.....	44
2.4 Parameter calculation	46
2.5 Second Chapter's conclusions	47
3. RESULTS AND DISSCUSSION OF EXPERIMENTAL RESEARCH	48
3.1 Parameters of 5 landfill models.....	48
3.2 Concentration of carbon dioxide and methane in columns.....	53
3.3 Concentration of oxygen and hydrogen sulfide	55
3.4 Third chapter's Conclusions	58
4. MATHEMATICAL MODELLING OF TWO LANDFILL MODELS.....	60
4.1 Mathematical modelling results	60
4.2 Forth chapter's results	63
5. ECONOMIC EVALUATION	64
5.1 4 th landfill model's economic evaluation	64
5.2 Fifth chapter's conclusions	67
CONCLUSIONS	68
RECOMMENDATIONS	69
REFERENCES	70
APPENDICES	75

LIST OF FIGURES

Fig. 1.1. Most common waste fractions and composition found in one of Lithuania's MSW landfill in 2012 (Lithuania's national...2014)	16
Fig. 1.2. Municipal waste landfilling in 32 European countries in 2001-2010 (Managing municipal...2013)	16
Fig. 1.3. Composition of MSW by national income (Modak 2011)	17
Fig. 1.4. Waste management hierarchy (European Commission 2013).....	18
Fig. 1.5. Waste minimization steps (Zorpas & Lasaridi 2013)	18
Fig. 1.6. Waste to energy technologies (Pan et al. 2015).....	19
Fig. 1.7. Landfills in Europe (Eurelco 2015)	20
Fig. 1.8. Percentage of biodegradable municipal waste landfilled in Europe countries with derogation compared with amount generated in 1995 (Managing municipal...2013)	22
Fig. 1.9. Percentage of biodegradable municipal waste landfilled in Europe countries compared with amount generated in 1995 (Managing municipal...2013)	22
Fig. 1.10. Landfill tax for municipal waste landfilling in Europe countries in 2012 (Managing municipal...2013)	23
Fig. 1.11. 7 th EA Programme's action sectors	24
Fig. 1.12. Circles of sustainability (Desai 2013).....	25
Fig. 1.13. Estimated investments (million US dollars) in different regions, according to the World Bank in 2009 (Modak 2011).....	26
Fig. 1.14. Lithuania's MSW treatment in 2009–2011 (Valstybinis atliekų...2013).....	27
Fig. 1.15. Maximum permissible amount of biodegradable waste disposed in Lithuania's landfills, tons per year (Valstybinis atliekų...2013)	28
Fig. 1.16. Greenhouse gas emissions and waste management relationship scheme (Friedrich & Trois 2013).....	29
Fig. 1.17. GHG's path from waste sector (Pipatti, Vieira 2006)	30
Fig. 1.18. Comparison of GHG emissions from solid waste disposal on land (Lithuania's national...2013)	30
Fig. 1.19. Phases in the generation of landfill gases (Tchnobanoglous, Kreith 2002)	31
Fig. 1.20. Gas quality during the "life time" of a landfill (Heyer et al. 2013).....	32
Fig. 1.21. Sustainable waste management model (Memon, 2013)	33
Fig.1.22. The sustainable landfill (based on aeration and leachate injection (Hudgins et al. 2010)).....	34
Fig. 1.23. Development of a sustainable landfill strategy (Team Acumen 2014)	35
Fig. 1.24. Sustainable remediated landfills	36
Fig. 1.25. The benefit of landfill shredded tires cover for stopping gas going to atmosphere (Bentley et al 2007).....	37
Fig. 1.26. Anaerobic laboratory landfill (Zhang, Yue, Liu, et al. 2012).....	38
Fig. 1.27. Scheme of the anaerobic landfill prototype research (Zhang, Yue & Nie 2012)	39
Fig. 2.1. Waste samples	42
Fig.2.2. Maintenance equipment - aerator and thermostat.....	43
Fig.2.3. Gas evaluation equipment "Inca Bio 04" and „Drager“	43
Fig. 2.4. Probiotics "Odor away" (Odor away 2015).....	44
Fig.2.5. Landfill model's research equipment construction.....	44
Fig. 2.6. Landfill models technological inputs and outputs scheme	46
Fig. 3.1. 1 st landfill column's parameters.....	48
Fig. 3.2. 2 nd landfill column's parameters.....	49
Fig. 3.3. 3 rd landfill column's surface parameters.....	50
Fig. 3.4. 3 rd landfill column's bottom parameters.....	50

Fig. 3.5. 4 th landfill column's surface parameters	51
Fig. 3.6. 4 th landfill column's bottom parameters	51
Fig. 3.7. 5 th landfill column's surface parameters	52
Fig. 3.8. 5 th landfill column's bottom parameters	52
Fig. 3.9. CO ₂ composition in landfill columns surface	53
Fig. 3.10. CO ₂ composition in landfill columns bottom.....	54
Fig. 3.11. CH ₄ composition in landfill columns surface	55
Fig. 3.12. CH ₄ composition in landfill columns bottom.....	55
Fig. 3.13. O ₂ composition in landfill columns surface	56
Fig. 3.14. O ₂ composition in landfill columns bottom	56
Fig. 3.15. H ₂ S composition in landfill columns surface	57
Fig. 3.16. H ₂ S composition in landfill columns bottom	57
Fig. 3.17. pH value in five landfill columns.....	58
Fig. 4.1. 1 st landfill model's inputs to LandGEM mathematical modeling program	60
Fig. 4.2. 2 nd landfill model's inputs to LandGEM mathematical modeling program.....	61
Fig. 4.3. CH ₄ results in landfill models LandGEM mathematical modeling results	61
Fig. 4.4. CO ₂ results in landfill models LandGEM mathematical modeling results	62
Fig. 4.5. Cumulative total methane emissions from five landfill models in 157 years	62
Fig. 4.6. Cumulative total carbon dioxide emissions from five landfill models in 157 years..	63
Fig. 5.1. Investment to sustainable landfill.....	65

LIST OF TABLES

Table 1.1. MSW generation as a function of source (Pichtel 2005)	15
Table 1.2. MSW physical composition (Pichtel 2005; Lithuania's national...2014).....	15
Table 1.3. New managed landfills in Lithuania (Lithuania's national...2014)	21
Table 1.4. Chemical and Physical properties (Pichtel 2005)	31
Table 2.1. Composition of used pre-treated organic and inorganic MSW in 19 liters plastic columns (Lithuania's national...2014)	41
Table 2.2. Landfill models conditions	45
Table 2.3. Landfill models conditions for the column testing	45
Table 2.4. Variables data (Fei et. al. 2015;Berge et al. 2009).....	47
Table 5.1. Landfill parameters (Berge et al. 2009; Beaven et al. 2014)	64
Table 5.2. Landfill operation costs (Berge et al. 2009; Beaven et al. 2014).....	64
Table 5.3. Landfill lifetime costs	65
Table 5.4. Suggested rebates for landfill operations (Beaven et al. 2014)	67

ABBREVIATIONS

GDP – Gross domestic product
GHG - Greenhouse gas
LCA - Life Cycle Assessment
LCT - Life Cycle Thinking
MSW – Municipal Solid Waste
NMOCs – Non-methane organic compounds
PM - particulate matter
VOCs – Volatile organic compounds

INTRODUCTION

Problem

In 2010, poor quality of air caused over 400 000 asthma symptoms and early deaths in the European Union. Major greenhouse gas emissions (GHG's) from waste disposal in landfills and particulate matter (PM) is not an exception (Kuenen, Hjelgaard 2013). Organization of Intergovernmental panel on climate change assessment's report of 2006 showed that discordant municipal solid waste management and waste accumulation increased the amount of greenhouse gas emissions released into the atmosphere (IPPC Guidelines 2006). Unsorted or untreated municipal solid waste (MSW) landfills have an influence on forcing air quality rates down to low levels (Watkins *et al.* 2012). Each year 3 billion tonnes of waste are generated in the European Union (EU) and this number is gradually increasing (European Commission 2010).

Municipal solid waste landfill's surface mainly releases greenhouse gases like CH₄, CO₂, which cause global warming (Moreno *et al.* 2014). Also, non-methane organic compounds (NMOCs) like alkanes (C1-C10), alkenes (C1-C4) and halogenated hydrocarbons which effect ozone layer, NO_x, NH₃ and CO are released into the atmosphere but only in small quantities (Schuetz *et al.* 2003; Kuenen, Hjelgaard 2013). Huge amounts of biodegradable waste are flowing into the landfill when there is not enough of systematic ways to collect, treat and recycle municipal waste. The lack of waste in situ treatment in landfills have to be revised, otherwise the magnitude of ozone layer will decrease even more and the global warming consequences will get more obviously on the environmental scale (European Commission 2010). European Union strategy can contribute to the stabilisation of the GHGs, but, even if waste landfilling were to be stopped right now (which is impossible) the problem of methane generated in the already existing landfills would still remain for many years (Lombardi *et al.* 2006).

Actuality

In the past landfills were not considered as a source for energy and/or resource recovery or even as pollution source to the environment. However, The European Union Council started to regulate legislations for landfills of waste, waste statistics and air management in order to control the pollution. According to waste statistics report of 2011, the member states with the highest share of landfilled municipal waste were Romania (99%), Bulgaria (94%), Malta (92%), Latvia and Lithuania (both 88%) (Landfills continue...2013). Other regions of Europe, landfilling is a more important waste treatment option with per capita emergence of up to 421 kg (Bulgaria) (Landfilling 2015).

Company "Eurelco" have summed up that total amount of landfills in Europe is more than 500 000 landfills (year 2015). Comparing the current situation in the landfills and the EU Landfill Directive (1999) approach, about 90 % of these landfills are non-sanitary. This means that at least 450 000 landfills have a lack of environmental protection and require financial and environmental remediation (Eurelco 2015). For this reason, around 40 000 research articles are analyzing waste landfilling approach.

European Commission have announced that EU Member states have committed to reduce the air pollution levels by ratifying the European Council directive for ambient air quality 2008/50/EC. Mentioned policies influence Member States to treat up to waste hierarchy (Watkins *et al.* 2012). They also committed that until 2030, recycling and preparation for waste re-use process will increase by 70%. This subject is ratified by the European Councils' Waste Framework Directive 2008/98/EC and the Landfill Directive 1999/31/EC (European Commission 2010). Despite the environmental protection progress, more positive changes and research have to be achieved by the year 2020.

Aim

The aim of the research is to evaluate emitted GHG's from pre-treated municipal solid waste landfill models and to suggest the most sustainable municipal solid waste landfill model.

Objectives

1. To analyze municipal solid waste management systems and strategies;
2. To assess sustainable waste management and landfill approach;
3. To construct five landfill models with different in situ treatment parameters for municipal solid waste;
4. Evaluate emissions of greenhouse gas emissions from five landfill models;
5. To perform mathematical modelling according to the results of CH₄, CO₂, H₂S emissions from landfill models;
6. To do landfill model's economic evaluation.
7. To suggest a sustainable municipal solid waste landfill model.

Object of Research

The accumulation of methane (CH₄), carbon dioxide (CO₂), hydrogen sulphide (H₂S) and oxygen (O₂) from municipal solid waste landfill models (Kuenen, Hjelgaard 2013).

Novelty

Combination of landfill models in laboratory scale with different inside parameters and analysis of sustainable landfill approach.

Practical Value

After analysis and assessment of emitted GHG's from the municipal solid waste landfill models, the most sustainable waste landfill is suggested that would help to reduce greenhouse gas emissions and shorten landfill aftercare period.

Hypothesis

According to evaluation, landfills with the right operation parameters can reduce greenhouse gas emissions from municipal solid waste landfills and shorten their aftercare.

1. ASSESSMENT OF MUNICIPAL SOLID WASTE AND ITS GENERATED AIR POLLUTANTS

At the time when the first early man started his existence, he composed first type of waste – his manure. As George Perkins Marsh (1874) has said “Man is everywhere a disturbing agent. Wherever he plants his foot, the harmonies of nature are turned to discords”. It is known that even during cave living lifestyle, man piled his waste near entrances. The aim was to avoid unnecessary materials inside the cave. With the growth of the population waste amount gradually exceeded, so its problems started to be associated with diseases, air and water pollution. Ancient people had an opportunity to live in a clean environment, but these days littering people and enterprising industries have completely changed the situation. Dirty streets, full with garbage filled the environment with polluted areas. The open dumps were an improvement (1850s) compared with dumped sidewalks. These dumps were the beginning of a new waste management era. In 1890s concerns were being raised about the health risks of bigger dumps. Incineration or reduction was suggested (Pichtel 2005).

In the late 1900s, the biggest concern related to municipal landfills were fires, which were frequent hazard. Many municipalities used fire as a solution for waste volume reduction. Subsurface liners were rarely used and the waste layers were very thick. Another problem was its location. Most of the landfills were situated near urban areas and its water supplies. The result was public opposition and disposal techniques had to be developed (Pichtel 2005).

United States suggested an alternative – controlled tipping system, which attempted to spread thin waste layers, make them compact size and covering with a layer of soil at the end of each working day. The soil could be replaced with other suitable cover material. Wastes in the landfill were free from odour, vectors and less hazardous to public health. By the year more engineering decisions were developed around the World (Pichtel 2005). Different types of landfills are classified in attempt to reduce hazardous and non-hazardous waste mixing. For this reason The European Council initiated regulations and action programs in order to reduce environmental pollution from waste disposal. The lack of policy could more affect increasing global warming. These regulations encouraged all Member States to implement waste management and to succeed for public and environmental welfare. Although nowadays EU landfills still require renovation because of need for environmental protection.

1.1 Description of municipal solid waste generation and management

In order to identify influencing emissions from non-hazardous municipal solid waste treatment, waste composition has to be analysed. Each waste type can be very specific and contain different quantity of degradable organic carbon (DOC) and fossil carbon. Generated waste composition very depends on countries and regions. Shortly municipal solid waste includes (Sharma *et. al* 2006):

- household waste;
- garden, park waste;
- commercial/institutional waste;

For the diversity of waste sources, solid waste are called municipal waste (Table 1.1). Solid waste are generated by households, offices, shops, markets, restaurants, public institutions, industrial plants, water treatment and sewage facilities, construction and demolition sites, and agricultural activities (Sharma *et. al* 2006). The definition has to be legally strict, because waste has financial implications for business and local authorities. It is also important for national and regional waste management planning and treatment strategy.

Table 1.1. MSW generation as a function of source (Pichtel 2005)

Sources	Typical waste types
Residential (single and multi-family homes)	Food scraps, food packaging, cans, bottles, newspapers, clothing, yard waste.
Commercial (office buildings, retail companies, restaurants)	Office paper, yard wastes, paper napkins, yard waste, wood pallets.
Institutional (schools, hospitals, prisons)	Office paper, restaurant waste, restroom wastes.
Industrial (packaging and administrative; not waste from the process)	Office paper, wood pallets, cafeteria wastes.
Municipal (durable, non-durable goods, containers and packaging, food and yard wastes)	Litter, abandoned automobiles, some construction and demolition debris.

Waste generation covers those activities in which materials are identified as no value material and thrown away or gathered together for disposal. It is very important that every identification step would be noticed and waste would be measured individually. Cleaner production studies are one of the main subjects that can help industries to control waste generation (Pichtel 2005).

When waste source and characteristics data are known, it is easier to collect information for reporting and administrative systems. General composition is classified because of definition that is used for landfilling and incineration taxes (Table 1.2). Classification avoids disagreements between companies and individual consumers. Regulations and policy can be an effective tool for waste classification control in the landfills (Williams 2006). MSW is important issue, because it comes from a responsibility of public and business sector. Mainly waste management help European countries to classify variety of MSW structure. Although problems of different waste data account between countries may appear. When countries include other type of waste to their general MWS composition management, then statistic data of MSW cannot be compared between countries. For this reason countries have to compliance Waste Framework Directive (Managing municipal...2013).

Table 1.2. MSW physical composition (Pichtel 2005; Lithuania's national...2014)

Chemical Class	General Composition	
Organic	Paper products (A.12)*	Office paper, computer printout, newsprint, wrappings.
	Plastics (A.13)	Polyethylene terephthalate, high-density polyethylene, polyvinyl chloride, low – density polypropylene, polypropylene, polystyrene, multi-layer plastics, other plastics including aseptic packaging.
	Food (A.07)	Food (putrescible).
	Yard waste (A.03)	Grass clippings, garden trimmings, leaves, wood, branches.
	Textiles/rubber (A.08)	Cloth, fabric, carpet, rubber, leather.
Inorganic	Glass (A.15)	Clear, amber, green, brown.
	Metals (A.16)	Ferrous, aluminium, other non-ferrous (copper, zinc, chromium).
	Dirt (A.06)	Dirt, stones, ash.
	Bulky wastes (A.18; A.19)	Furniture, refrigerators, stoves.

*- waste code

Organic and inorganic wastes have different chemical composition. According to 2014 survey made in one Lithuanian landfill (Fig. 1.1), the average amount of municipal

biodegradable waste is 58 %. Biodegradable waste is the main environmental threat for its natural production of greenhouse gases like CH₄, CO₂, H₂S (European Commission 2014). By the year 2025 European Union has an aim to reduce food waste generation by 30 % (Waste...2014).

Organic wastes can also be called biodegradable waste, where terms means – waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste, and paper and paperboard (Council Directive 99/31/EC).

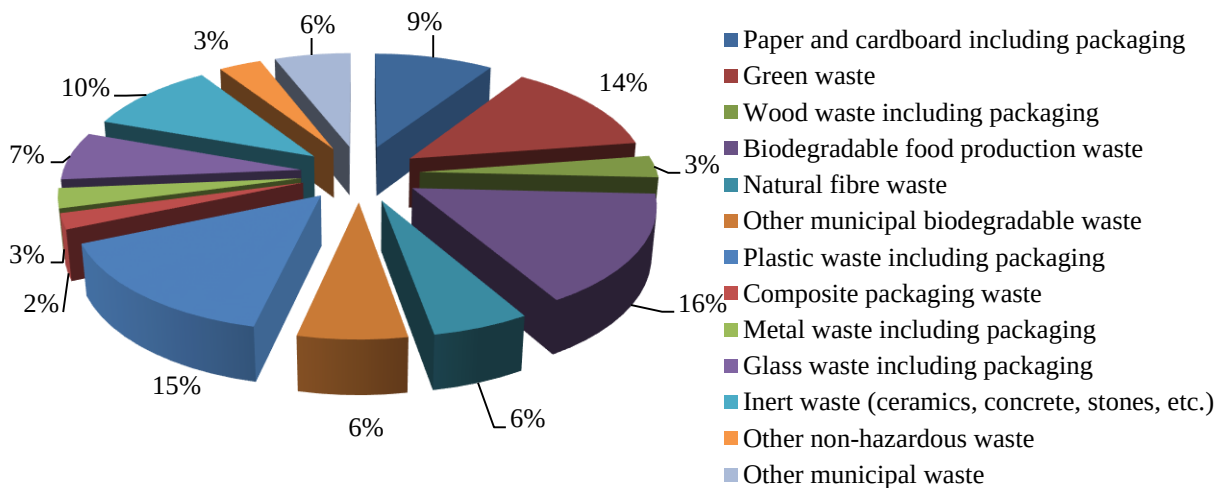


Fig. 1.1. Most common waste fractions and composition found in one of Lithuania's MSW landfill in 2012 (Lithuania's national...2014)

The lack of clear definitions and quality data has made misunderstanding situations in the field of solid waste management. Slow implementation on municipal solid waste strategies is the consequence (Fig. 1.2.).

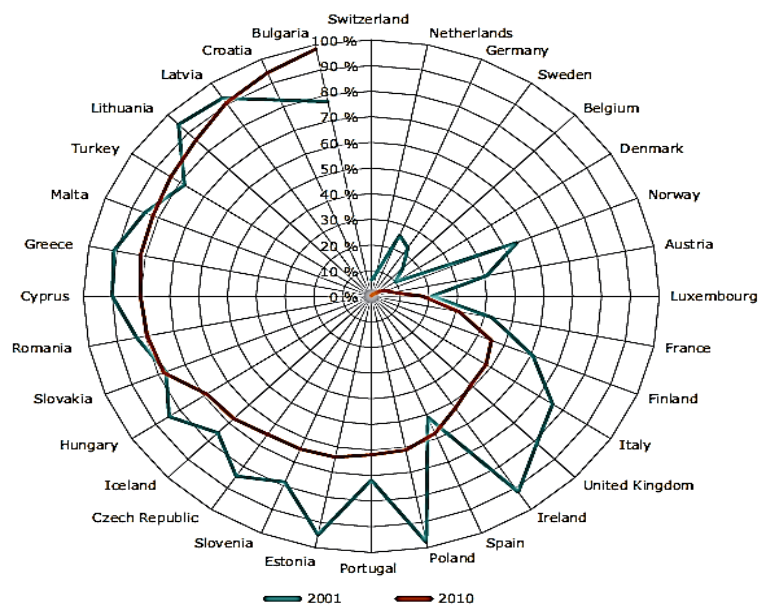


Fig. 1.2. Municipal waste landfilling in 32 European countries in 2001-2010 (Managing municipal...2013)

According to European Environment Agency's review of achievements in managing European municipal solid waste made in 2013, MSW landfilling still has high operational rate in different countries. In a period of 10 years, there are countries that decreased landfilling rate from 10 % to 20 %. However, the major part of European countries landfilled more than a half of MSW in 2010 (Managing municipal...2013).

Clear roles of national and regional government in waste strategy are an important issue. The government has to take the responsibility and take the commitment for environmental, health and safety impacts. Sustainable waste management system has the opportunity to regulate these impacts and can help government and authorities to identify it (Pichtel 2005). On the other hand, landfill taxes can have an important role in reducing landfilling process (Managing municipal...2013).

Size of organic and biomass waste fractions in MSW flow is related to the income rate of a country. Generation of MSW increases evenly with population growth and socio-economic development. The successful waste management have an influence from people living environment, cultural habits and factors, political issues (taxes), urban area development, infrastructure, educational level (Chen & Wu 2015). If it is low (less than 60 GDP/capita), 65 % of biodegradable waste will be generated, if middle (around 110 GDP/capita) then 43 % of biodegradable waste and if the income is high (80-270 GDP/capita), countries will generate around 30 % (Fig. 1.3) (GDP per capita...2015). On average, 136 kg per capita are disposed to the landfill. In central Europe (Germany, Austria, Belgium, Netherlands, Denmark), the levels are comparably low with 2-16 kg / capita. Norway (6), France (141) and Poland (186) constitute the middle range.

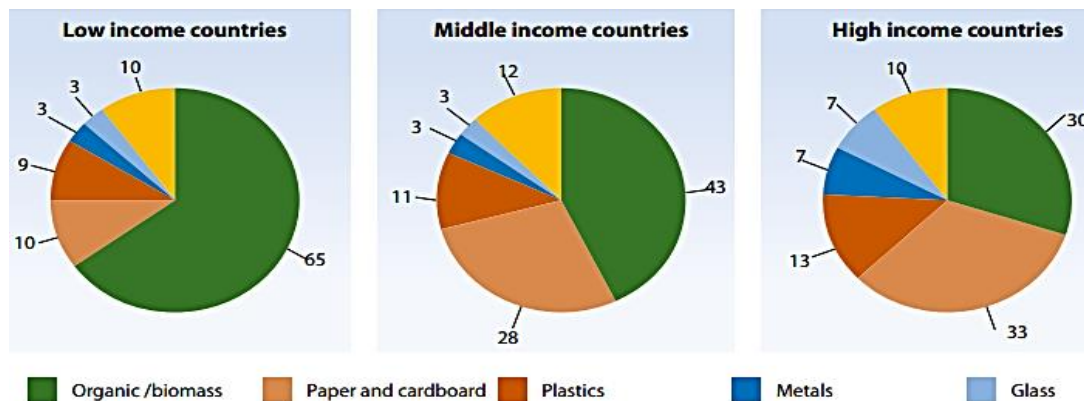


Fig. 1.3. Composition of MSW by national income (Modak 2011)

Organic waste generation in the middle income countries is 22 % less than in low income countries, but 13% smaller than in high income countries. The aim of solid waste management (SWM) strategies is to address the health, environmental, aesthetic, land-use, resource, and economic concerns associated with the improper disposal of waste. These issues are topical concern for nations, municipalities, corporations, and individuals around the world, and the global community at large. In developing countries, the waste produced by growing cities is overwhelming local authorities and national governments alike (Marshall & Farahbakhsh 2013).

Prevention and minimization

Sustainable waste management has five steps that describe the preferable order of waste treatment options (Fig. 1.4). In general, waste prevention have to ensure goals for waste quantity control, waste impacts if human health and environment and reduce harmful substances from materials in generating products (Wilts et al. 2013).



Fig. 1.4. Waste management hierarchy (European Commission 2013)

For these reasons, life cycle of a product and material flow ecological innovation consideration can be the most effective. Consumer's knowledge of rational consumption can lead to waste prevention as well. Authors Dehaoust et al. in 2012 have introduced the concept of product service system which would optimize material resources and offer a high waste prevention potential (Wilts et al. 2013).

For example, an international organization named "Zero waste" have a target to control disposal to landfill, minimize waste (Fig. 1.5.), increase recycling, re-use rate and improves environmental assessment (Gentil et al. 2011). It is the most common way for succeeding obvious waste quantity reduction.

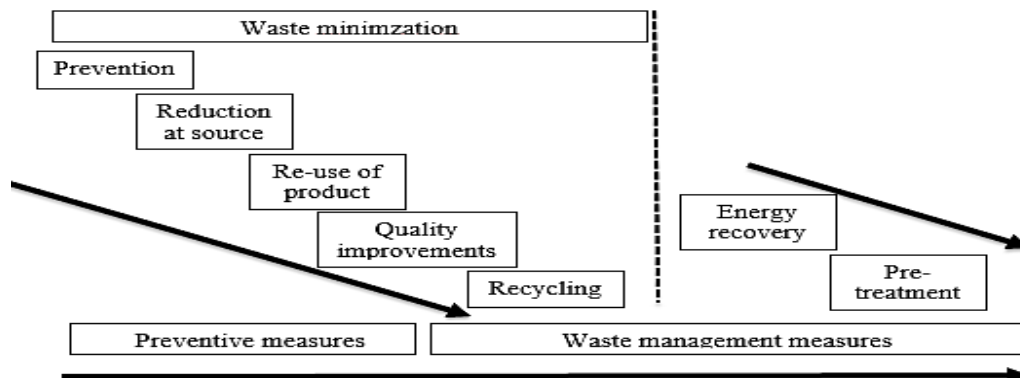


Fig. 1.5. Waste minimization steps (Zorpas & Lasaridi 2013)

Evaluation and waste generating monitoring can have an influence for waste minimization. Governmental institutions have to inspect industries, but individual person's waste generation evaluation is more complicated. In this case, interview or survey method could be use in large scale.

Re-use and recycling

Reuse process means using an item for its original purpose without large resources consumption. Earlier, waste recycling was listed near the top of the waste management hierarchy. At the moment, recycling stays in the middle because of energy consumption and its likely environmental pollution. By the year 2030 European Union has an aim to (Waste...2014):

- increase MSW recycling and re-use to 70 %;
- increase packaging waste recycling and re-use to 80 %;
- achieve reduction level for plastics (60%), wood (80 %), ferrous metal and glass (90%).

Materials recovery belongs to MSW management and was developed because of landfill fees that are not economically attractive to municipalities and waste industry. The material

recovery can come up with processes like screening, magnetic separation. Other type of waste recovery is also being a concern, because the recovery requires resources for process maintenance. The process is designed to (Pichtel 2005):

- alter physical waste characteristics;
- remove useful components from waste stream;
- remove contaminants from waste stream;
- prepare separated material for further processes.

Technological equipment has been developed for waste recovery processes – vibrating and disk screens, balers, shredders, hammer–mills, magnetic separators and air classifiers. The equipment is basically designed for environmental control like dust collection, odours control and noise suppression (Pichtel 2005).

Other recovery

Generally, physical, chemical, biological and thermal technologies are suitable for waste-to-energy (WTE) approach. Combustion process is a thermal MSW treatment technology, which reduce the volume of MSW and possible hazardous materials. The by-products of this treatment is flue gas, fly and bottom ash. Emissions like N₂, CO, CO₂, NO_x, SO, methane, ammonia are strictly controlled. Final products are bio-gas, heat and refuse derived fuel (Fig. 1.6.) (Pan et al. 2015).



Fig. 1.6. Waste to energy technologies (Pan et al. 2015)

Anaerobic digestion (bio-gasification) is a renewable energy process that produces energy by decomposition of biodegradable waste. This process reduce waste treatment costs and GHG's emissions. The most important operating process is fertilization, because microbiological process requires nutrients.

In order to implement WTE, planning is done. It consists long-term objectives and policy aims, which leads to waste stream identification, energy demand and technology identification. The efficiency of waste collection has to be evaluated as well. Second step is implementation as itself. WTE models have to be designed through regulations and policy measures.

Third step is evaluation/assessment. Here performance indicators have to be identified and analysed. Environmental assessment is needed for monitoring program evaluation and public reception assessment. The last one step is mobilization, which leads to integrated professionals, stakeholders, successful solving of waste management problems (Pan et al. 2015).

Disposal

Disposal is being investigated, because it causes environmental pollution and it is the least favourable way to treat waste (Fig. 1.7). Unfortunately, this kind of treatment still is the most widely used, so the process has to be strictly regulated. The research raises issue how to manage waste disposal and to assign it to sustainable waste management. By the year 2025 European Union has an aim to phase out landfilling of recyclable (glass, paper, plastics,

metals and biodegradable waste) waste in municipal landfills to a maximum of 25% landfilling rate (Review of waste 2014).

In current situation, Baltic states have this landfill rate order – Estonia (74 %), Lithuanian (58 %) and Latvia (40 %) is the leader. The highest rate in Europe belongs to Turkey (82 %), Bulgaria (88 %), Serbia (88 %). Leaders of low landfill rate are Netherlands (3 %) and Luxembourg (1 %). If were compare the size of country, then Scandinavians and Germany have the strongest position in controlling waste streams going to the landfill.

The European Commission sets guidelines for Life Cycle Assessment and Life Cycle Thinking to plan the management of bio-waste. For example, Lithuania generates 5 million tonnes of waste per year. About half of all generated waste in Lithuania is disposed of in landfills – 58 % according to Eurostat data.

Back in the early 1990s there were about 1000 non sanitary dumps (more of them were small and unmanaged) in the country which had an impact for human health and environment. After European Union requirements for waste management infrastructure 666 landfills and dumps were closed by 2012 and 142 landfills are foreseen to close by the end of 2013 in Lithuania.

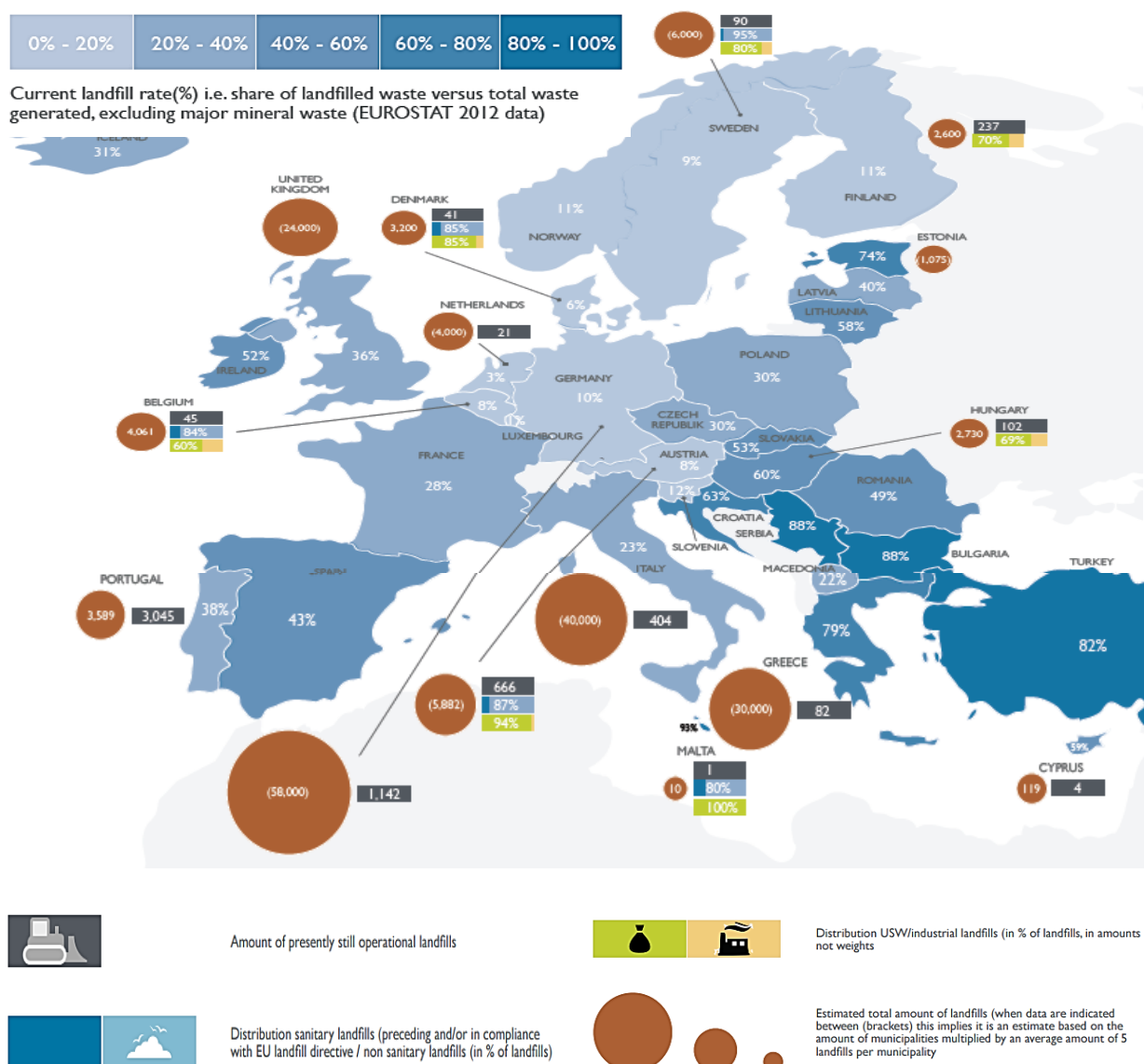


Fig. 1.7. Landfills in Europe (Eurelco 2015)

The disposal of waste in the old landfills was stopped in July of 2009 and since then all waste is disposed of in 11 regional non-hazardous waste landfills (Table 1.3). Through the waste management strategies and country's development 11 regional municipal waste sanitary landfills were built. New regional landfills were reorganized by EU requirements with the supply of EU structural funds (Lithuania's national...2014).

Table 1.3. New managed landfills in Lithuania (Lithuania's national...2014)

Region	Start of disposal
Alytus	January 2008
Marijampolė	April 2009
Tauragė	April 2009
Šiauliai	July 2007
Vilnius	January 2008
Telšiai	January 2008
Klaipėda	July 2008
Kaunas	July 2009
Utena	April 2008
Panevėžys	October 2009

The reconstructions were made, but there is still a lack of waste management. Huge amounts of biodegradable waste are flowing into the landfill, because there is not enough of systematic ways to collect and recycle waste in Lithuania. Landfill managers are more interested in collecting as much waste as possible, without applying evaluation methods of greenhouse gas emissions. The lowest fraction of biodegradable waste was found in rural waste collected area in Panevėžys region. Biodegradable waste fraction in waste collected from rural areas is lower than in urban areas which is explained by population distribution.

Europe's waste amounts generated are increasing, and not all regional landfills are able to stop biodegradable solid waste disposal in them. When the biodegradable solid waste are landfill, the pollution is unpredictable. Moreover, according to waste hierarchy, waste disposal is at the pyramids bottom and has to be avoided and strictly controlled (European Commission 2013).

1.2 Municipal solid waste treatment strategies and requirements

The European Commission initiates all regulation and its implementation in all Member States. It has one president and nineteen commissioners who have an important responsibility of administration of EU budget. The commission advises Council of Ministers that develops EU Legislation, Regulations, Directives and Decisions. Since 1973 there have been seven Environmental Action Programmes that had in common with waste, pollution control, prevention and sustainable development approach.

EC Waste Landfill Directive

The key of the directive 99/31/EC is that waste must be treated before it is landfilled in Europe. In this thesis, the focus is on municipal solid waste, therefore landfill of non-hazardous waste is relevant, where (Landfill Directive 99/31/EC):

- measures of methane gas from landfills are required in order to reduce global warming through reduction of landfilling biodegradable waste;
- the measures should encourage separate waste fraction collection, general sorting, recovery and recycling;
- requirements or limitations for biodegradability for organic waste components are recommended;

- landfill gas should be collected and must be treated. If energy production technology cannot be applied, the gas must be flared.

Nowadays, biodegradable wastes are separated from general waste flow. The reason is serious environmental and safety risks related to landfill gas, leachate and landfill settlement (European Commission 2008). Countries are divided according if there were any derogation (Fig. 1.8).

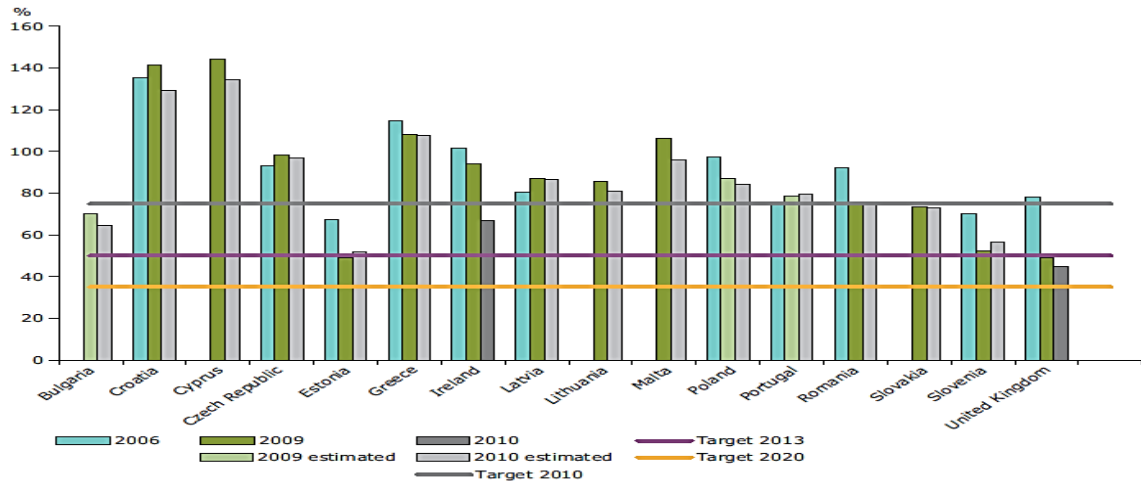


Fig. 1.8. Percentage of biodegradable municipal waste landfilled in Europe countries with derogation compared with amount generated in 1995 (Managing municipal...2013)

The Landfill Directive (1999/31/EC) obliges Member States to reduce the amount of biodegradable municipal waste that they landfill to 35% of 1995 levels by 2016 (for some countries by 2020) which will significantly reduce this problem.

The European Union has developed strict requirements for landfills to prevent and reduce the negative effects on the environment. Landfill Directive requires that waste must be treated before being landfilled and that the biodegradable waste going to municipal landfills must be reduced gradually to 45% of the levels of the total amount of biodegradable municipal waste produced in 1995 (European Commission 2008).

Figure 1.9 shows that biodegradable waste amount in the municipal landfills is decreasing in Europe countries that had no derogation, compared with amount generated in 1995.

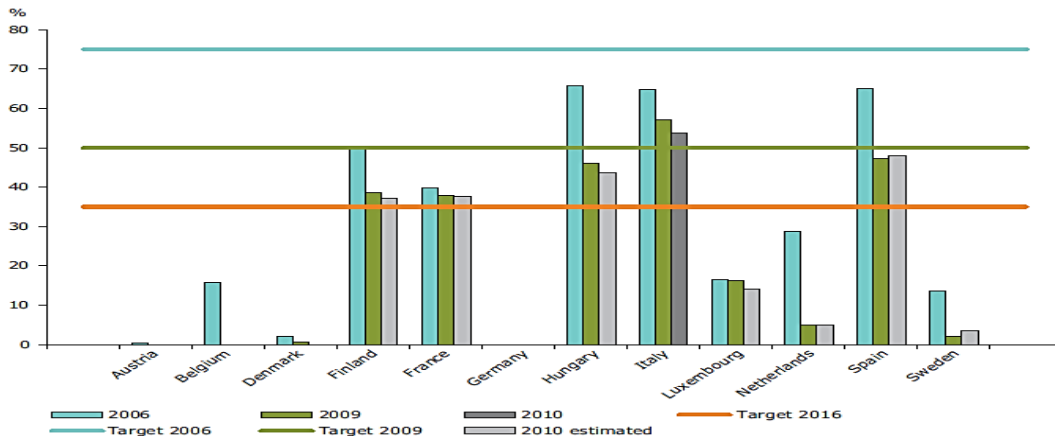


Fig. 1.9. Percentage of biodegradable municipal waste landfilled in Europe countries compared with amount generated in 1995 (Managing municipal...2013)

This trend came up when landfills permitted to take only certain categories of waste, namely and with the regulatory authority. Biodegradable municipal waste means any waste that is capable of undergoing anaerobic or aerobic decomposition. Currently the main environmental threat from biodegradable waste is leaching and production of methane from waste decomposing in landfills (Managing municipal...2013).

All Member States must contain a description of waste types and quantity that is going to be disposed. The acceptance procedure has documentation that includes register of quantities and characteristics. Origin, date of delivery and identification of collector documents are being used for municipal solid waste. In a case of waste leaving the landfill, regulatory authority has to be informed (Williams 2006).

Each EU Member State has to have regulatory authority that controls and operates country's landfill sites. It is very important to ensure landfill monitoring programs, that would help to indicate the most sensitive landfill operating issues.

The responsible authority has to collect the information about site (hydrogeological and geological characteristics), methods of controlled environmental pollution and monitoring program it sets taxes (Fig. 1.10) (Williams 2006). Landfill taxes are flexible and can be increased or reduced in order to succeed environmental goals.

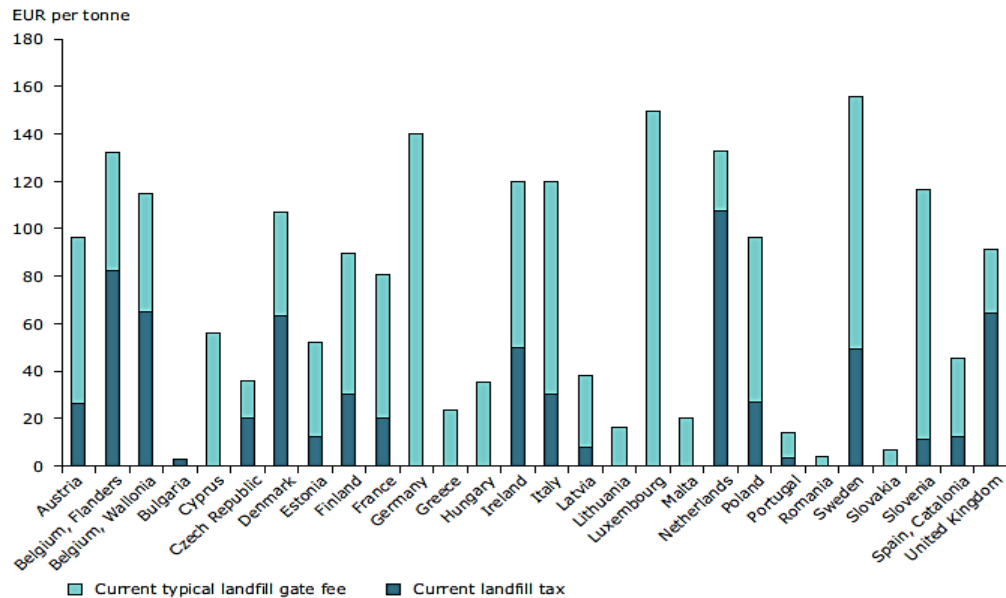


Fig. 1.10. Landfill tax for municipal waste landfilling in Europe countries in 2012 (Managing municipal...2013)

The largest taxes for landfill are in Sweden, Luxembourg and Germany (more than 140 Eur/tonne) while Bulgaria, Romania and Slovakia have the lowest (less than 15 Eur/t).

Waste Framework Directive

Waste prevention and recycling strategy adopted by the European Commission proposed to clarify when waste can be considered as recovered material. Shortly, if a Member State has the needed landfill capacity but has not enough recovery capacity, it is allowed to export waste to another country for waste recovery (Scharff 2014).

Waste Framework Directive contains a vision that waste can be regarded as material and sold in the open market. The purpose of end of waste criteria is to promote recycling by reducing waste fraction sent for disposal, ensuring environmental protection and reducing the consumption of natural resources. The directive concerns about the greenhouse gas emissions from biodegradable waste disposal in landfills. Proper separation for compost production

from these wastes would let avoiding environmental pollution from landfills. The scope is to help all Member States to comply with waste management plans, where biodegradable waste are not going to be disposed to landfills. It was estimated, that full implementation of EU waste legislation would save €72 billion a year (Council Directive 2008/98/EC).

End of waste criteria is included into Waste Framework Directive and can help to protect human's health and the environment management. End of waste criteria divides waste into specific streams and Member States are able to improve their individual frameworks for regulating the recovery and re-using of secondary materials. The criteria is able to improve certain production quality from recycled wastes within better environmental protection. Final products demand leading to increase after usage of suitable legislations (European Commission 2008).

The 7th Environmental Action Programme

The programme “Living well, within the limits of our planet” was established to promote ‘the shift towards an economy that is efficient in the way it uses all resources, absolutely decouples economic growth from resource and energy use and its environmental impacts, reduces greenhouse gas emissions, enhances competitiveness through efficiency and innovation and promotes greater energy and resource security’ (Fig. 1.11) (7th EAP 2012).



Fig. 1.11. 7th EA Programme's action sectors

Two additional horizontal priority objectives complement the programme (EC 2012):

- to make the Union's cities more sustainable
- to help the Union address international environmental and climate challenges more effectively.

In waste sector, main goals are to focus on turning waste into a resource, with more prevention, re-use and recycling, and phasing out wasteful and damaging practices like landfilling because of climate change. Air quality is an important sector for human health which would be controlled by full achievement of set targets. A priority for waste sector is non-toxic environment which would be implemented with efficient use of resources.

Sustainable city is a city which does not have poor air quality or emit greenhouse gas emissions, does not make high levels of noise, takes care of water security, and generates zero waste. Waste management have huge influence in connecting 7th EAP Programme's action goals into successful implementation of a better – more sustainable living environment.

1.3 Towards sustainable municipal solid waste management

Sustainable development strategy

The term of sustainability means environmental, economic and social equity and progress which is operating the consumption of natural resources and production industries (Fig. 1.12). It is recommended for the governments to integrate economic and environmental strategies into one section, because it is important to control the finance equally for both approaches. It is important to understand that natural environment is important to the economic strategies. Recent attention is concentrated into ecology section towards sustainable development. Main interests are competing between developed and developing countries, present and future generations (Desai 2013).

According to figure 1.12, ecology sector is the weakest section in the circle of sustainability. Inside this sustainable development quarter, constructions and settlements have achieved the satisfactory with a plus ratio. Although it still concerns about materials and energy consumption, which is in a bad condition and requires higher attention for development strategies. However, emissions and waste are in a critical position. This section stays in the lowest fraction comparing with all sustainability aspects. In this case, municipal solid waste disposal in landfills has to be avoided. Although, all sectors – economics, ecology, politics and culture have influence on waste sector's development. It is important to find a balance which would reduce the critical levels of sustainability and to succeed new levels which would be stable for future generations.

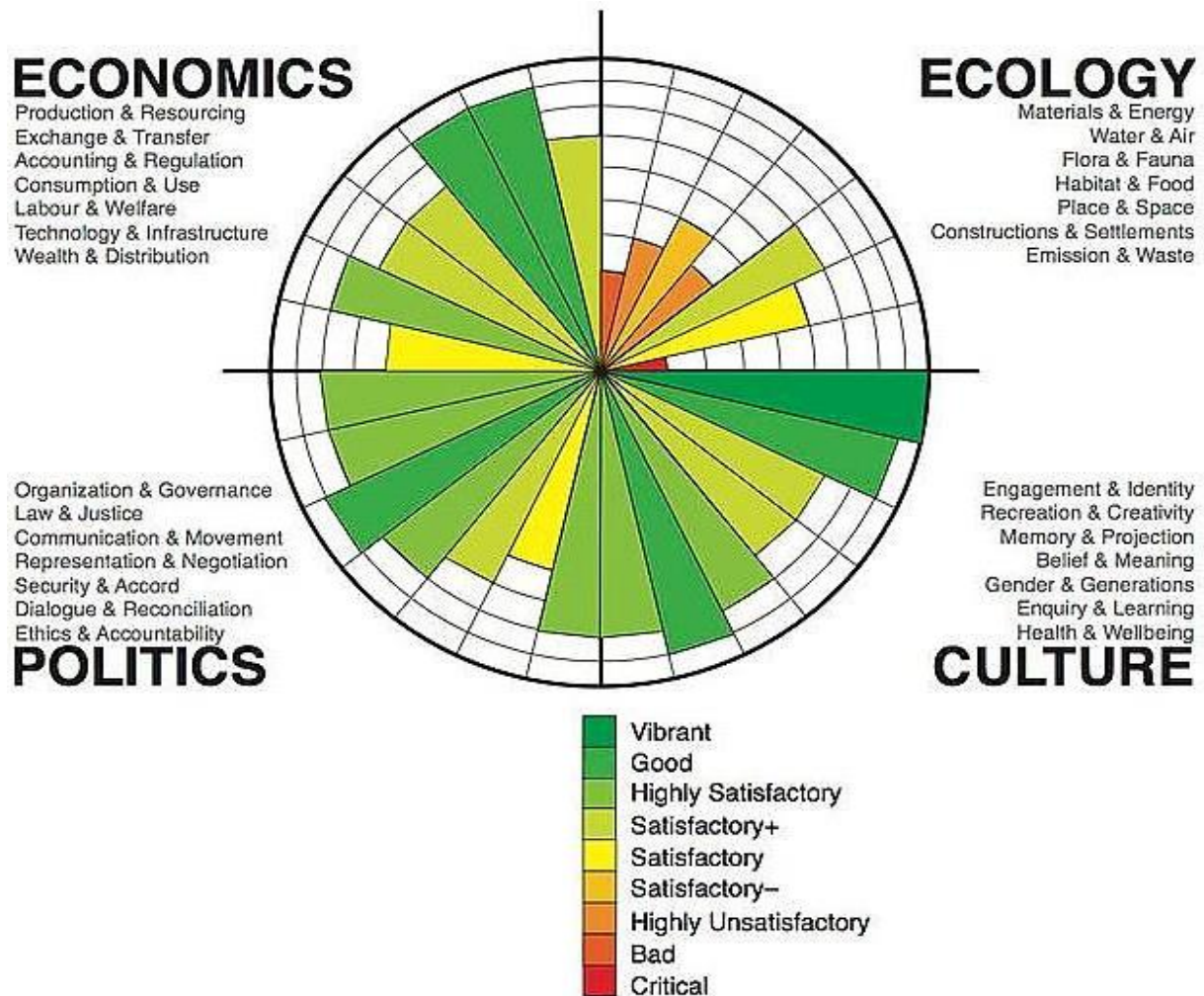


Fig. 1.12. Circles of sustainability (Desai 2013)

That is why countries with high income uses selective collection, incineration and recycling >20 % for waste treatment. Countries are also able to dispose only 20–40 % of biodegradable waste into the municipal landfills. Middle-income countries use landfill sites >90 %, start for selective collection, organized recycling and recycling. They dispose around 20–65 % of biodegradable waste into the municipal landfills. Unfortunately, low-income countries have uncontrolled landfills >50 % and informal recycling 15 %. Such countries dispose 50–80 % of biodegradable waste, which emits greenhouse gases to the atmosphere (Desai 2013; Modak 2011). Finally, sustainable MSW management depends on investments (Fig. 1.13).

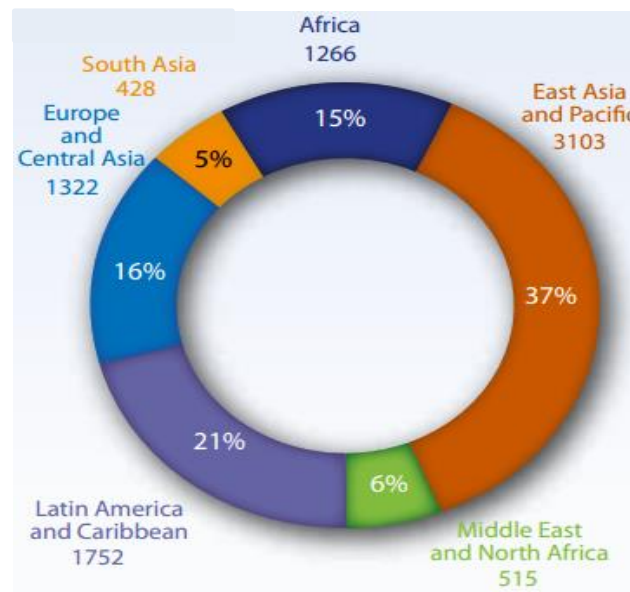


Fig. 1.13. Estimated investments (million US dollars) in different regions, according to the World Bank in 2009 (Modak 2011)

According to figure 1.9, sustainable MSW management gets the biggest investments from East Asia and Pacific, Latin America and Caribbean regions. This data shows the weakest regions from waste management and income points. Even though it is hard to say the real situation, because Europe in this case still has to invest into MSW management, because there is a big difference between each country's GDP.

Sustainable waste management (SWM)

SWM contains strategies for reuse, recycling and WTE processes, which are applied for waste stream usage as a material resource and environmental protection. All these areas have to be assessed and integrated into MSW management system which have the aim towards environmental and economic sustainability. Tools such as Life Cycle Assessment (LCA) and Life Cycle Thinking (LCT) can quantify environmental impacts (Rigamonti et al. 2016).

For best-performing scenarios development LCA is a suggestion. It helps to evaluate the performance relationships and to minimize particular environmental impacts by providing an optimum management solution. Requirements for LCA and sustainable waste management is that it would be developed through useful decision-making and policy support in urban areas and districts or regions (Tascione et al. 2016).

Cost have to be compared with saved material resources and energy consumption in waste management. Environmental and economic performance indicators can help to monitor the performance of waste management towards sustainability (Rigamonti et al. 2016):

- Material recovery indicator have to sum tons of materials from packaging, combustion residues, materials from mechanical-biological treatment,

composting. It shows a ratio between amount of recycled materials and the amount of collected MSW;

- Energy recovery indicator takes into account direct energy recovery in MSW and residues sorting and pretreatment. Electricity or heat recovered from biogas combustion in landfills are also included;
- Pollution indicator (air, soil, water);
- Cost indicator sums three types – waste collection cost (transport to treatment plant), waste treatment cost (operational costs) and final disposal costs (disposal to the landfill).

Sustainable waste management system can be applied not only for cities but it can be integrated into companies, which are easier to control in making decisions and analysis. New plants should involve their authority in order to reduce environmental impact and to activate sustainable performance (Tascione et al. 2016).

Lithuania's waste treatment action plan for 2014–2020

Recent waste treatment situation in Lithuania was glanced over and compacted into a strategy, which could help to identify and solve environmental problems caused by waste sector (Fig. 1.14). Main problems are (Valstybinis atliekų... 2013):

- large part of MSW is disposed into the landfills, because of financial approach. Prevention, recycling or recovery processes are not being taken into account;
- not all municipalities give for waste holders a condition to use public municipal waste management service;
- unsecured regional security in waste management departments, lack of control in waste management tasks or the European Union funded projects. As a result, the lack of the initiative to create a separate waste collection systems have come. Failure in implementation of the National Strategic waste Management Plan for the period 2007-2013 came up with the lack of biodegradable waste management infrastructure.
- at the state level, there is no uniformed methodology for municipal solid waste management systems data collection and provision, there are no clear, transparent and fair municipal tasks plan, that could implement and evaluate the mechanism.

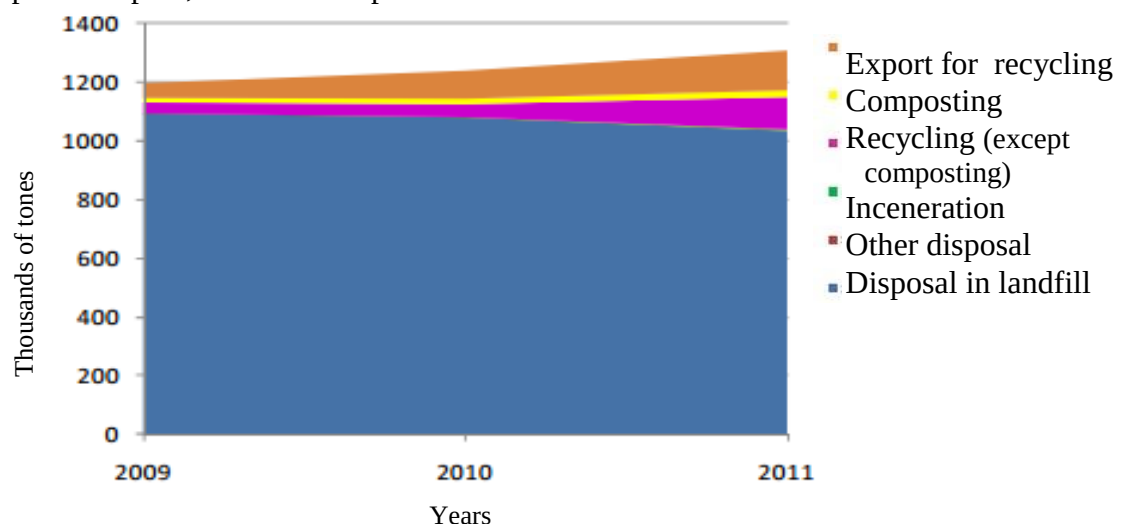


Fig. 1.14. Lithuania's MSW treatment in 2009–2011 (Valstybinis atliekų...2013)

The priority for disposal in landfills has to change. About 58 % of MSW was disposed in Lithuania's landfills in 2014. Only 42 % were reused or recycled, according to Environmental Agency of Lithuania. Economic instruments are not adapted in the country and because of that landfilling is the least expensive method of waste management. In other

words, waste sorting, recycling and other usage is not cost-effective. The country also has insufficiently developed waste sorting and separate collection systems. Waste prevention indicators were achieved by the economic recessions, but not because of states used measures. Waste prevention has to help to form Lithuania's policy. Landfill taxes also would be effective economic tool. Waste treatment action plan aims are to recycle or reuse (Valstybinis atliekų...2013):

- at least 45 % of MSW flow by 2016;
- make sure that MSW and its biodegradable waste fraction will have enough capacity for its treatment by 2016;
- at least 65 % of MSW flow by 2020;
- at least 50 % of MSW flow materials like paper, cardboard, metals, plastics and glass by 2020. Biodegradable waste fraction in landfills makes a huge impact for climate change. Waste management aims are (Valstybinis atliekų...2013):

- from 2013 – not more than 50 % of biodegradable waste according to its amount in 2000. According to Lithuanian Ministry of environment, the task is completed because in 2010 the allowed amount was 544 500,0 tonnes and results show that in 2012 were disposed 401 842 tonnes, which shows that the task was accomplished (Regioninių atliekų...2013);

- until 2020 – not more than 35 % of biodegradable waste according to its amount in 2000.

Lithuania's waste treatment action plan sets the maximum permissible fraction of biodegradable waste which can be disposed in the country's landfills (Fig.1.15).

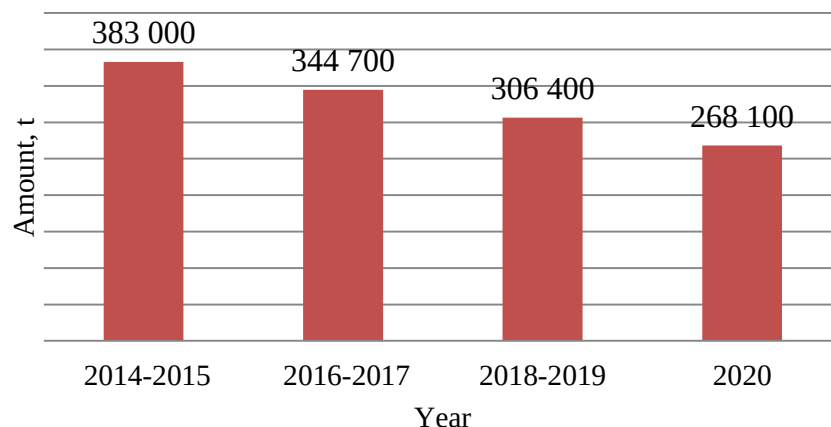


Fig. 1.15. Maximum permissible amount of biodegradable waste disposed in Lithuania's landfills, tons per year (Valstybinis atliekų...2013)

On purpose to reduce the municipal biodegradable waste disposal in landfills it is planned to encourage waste collection and treatment, to tax waste disposal in the landfills. Another plan is to encourage compost market, make requirements for its production and storage. Also, public would be informed about the importance of biodegradable waste treatment, compost boxes would be given to municipalities. The centralised collection and its infrastructure would be organized as well. Environmental protection departments must control biodegradable waste reduction in landfills. Comparing with 2011 landfill taxes grown up 3 times in 2016 and it will gradually increase (Valstybinis atliekų...2013).

1.4 Description of greenhouse gas emissions from municipal solid waste

Municipal solid waste moisture and composition have the main influence on GHG emissions from MSW landfills. Waste sector is being identified as one of the main sources for GHG emissions and it is responsible for about 5% of global emissions.

Large usage of material resources instead of waste is also associated with emissions potential. IPCC have developed a global application for GHG emission estimation, by using different methods. It shows, that food waste have the highest (60 %) moisture, while paper contains only 10 %. This means that food waste biodegradability determined by waste composition in the landfill increase methane generation potential (Kumar & Sharma 2014).

Quantification of MSW can be framed into a general scheme (Fig.1.16). It shows the path of data, technique and system that is related with GHG reporting system.

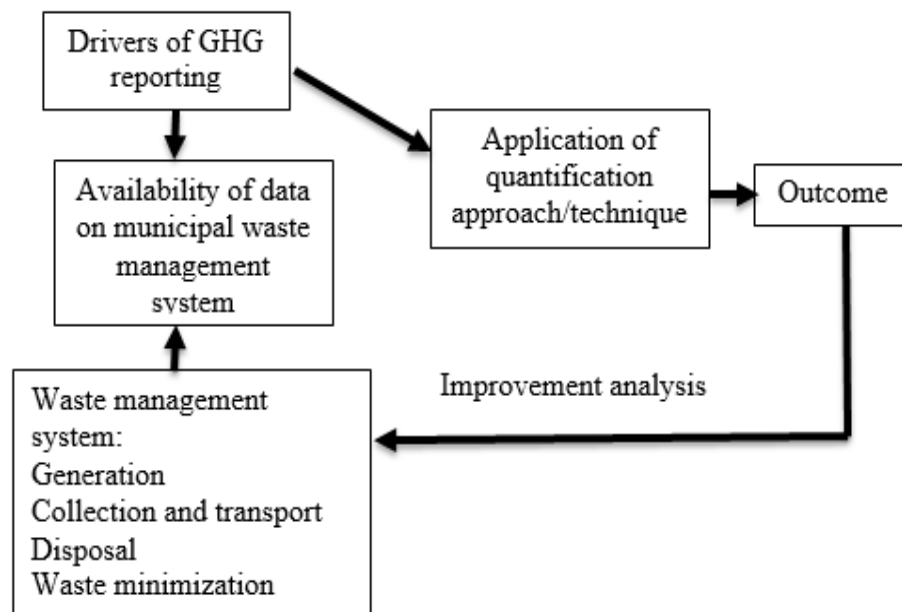


Fig. 1.16. Greenhouse gas emissions and waste management relationship scheme (Friedrich & Trois 2013)

Decision making for GHG emissions reduction can help to reduce climate change and to ensure sustainable development with a reduction of global warming. These emissions factors in waste sector (Fig. 1.17) are collection, transport and landfilling, composting (Rolph et al. 2012). For this reason any of waste management process which will save or replace this fossil fuel intensive energy will have positive effects in terms of overall GHG emission reductions (Friedrich & Trois 2013).

Majority of municipal solid waste sector's emissions are carbon dioxide (CO₂), methane (CH₄) and hydrogen sulfide (H₂S) which evaporate from (Pipatti, Vieira 2006):

- solid waste disposal;
- biological solid waste treatment;
- waste incineration;
- wastewater treatment.

GHG emissions assessment is concentrated on solid waste disposal, which is divided into three sections. First section is managed waste disposal sites. The amounts of generated waste, the composition of the waste as well as the technologies used for handling and

disposing this waste will determine the final amount of greenhouse gases emitted from a waste management sector.

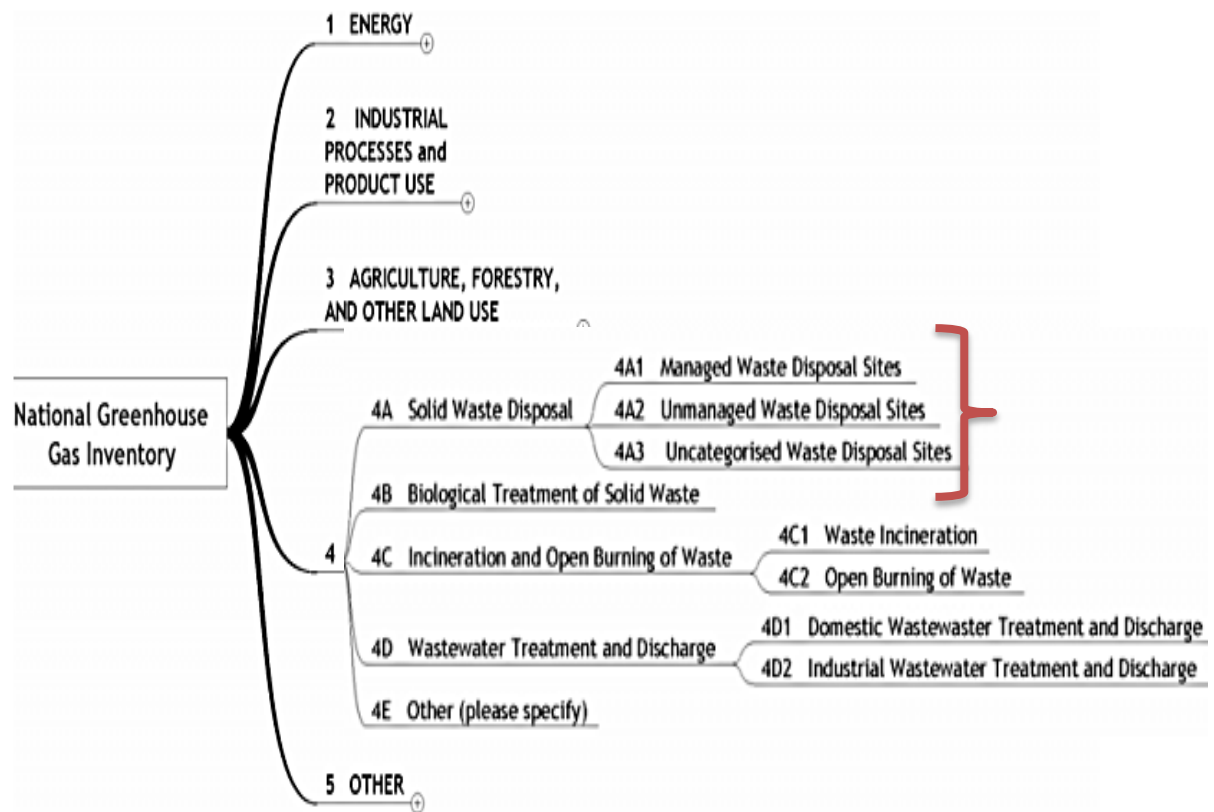


Fig. 1.17. GHG's path from waste sector (Pipatti, Vieira 2006)

The generated landfill gas (LFG) is mainly composed of methane (45–60%) and carbon dioxide (40–55%) with trace amounts of other gases such as sulphur dioxide or volatile organic compounds (Feng & Zheng 2015). In a sustainable landfill, greenhouse gas emissions (CH_4 , CO_2) are evaluated through methods like tracer techniques, emission modelling and open path method.

For example, biodegradable fraction in landfills produces a liquid leachate and landfill gas, composed of methane and carbon dioxide. As compared to other countries, in Lithuania, in 2012 there was the highest amount of GHG emissions from waste disposal per capita (see Fig. 1.18).

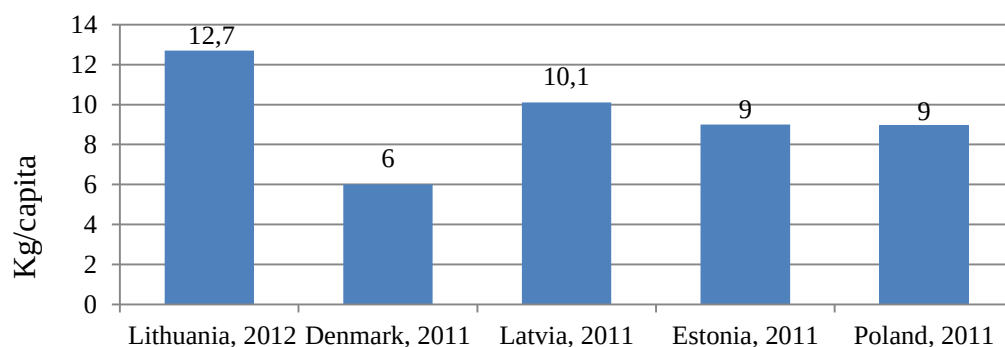
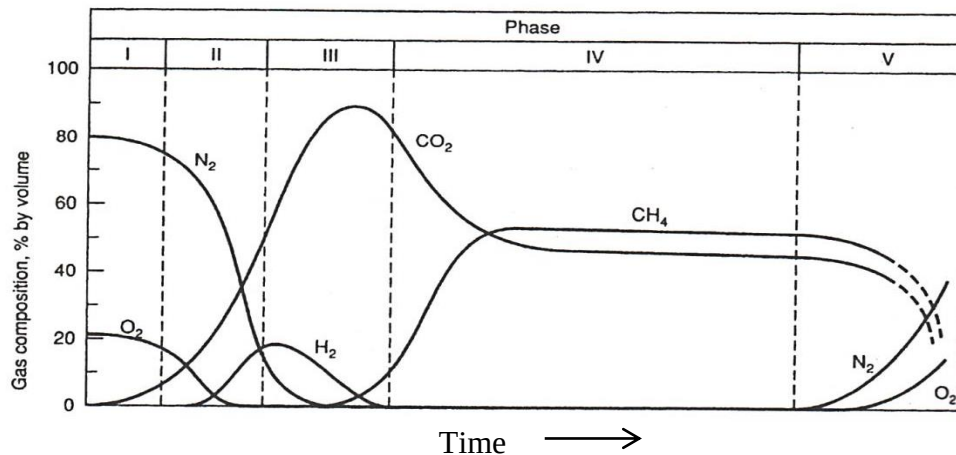


Fig. 1.18. Comparison of GHG emissions from solid waste disposal on land (Lithuania's national...2013)

Organic waste degradation process have five phases that generate in a landfill (Fig. 1.19). These processes forms landfill gas. The first phase of landfill gas generation is Initial Adjustment Phase that includes CO₂, H₂O, NO₃ and other oxygen compounds. In transition Phase (II phase) – extent and anaerobic conditions can be monitored by measurements of oxidation and reduction potential of municipal solid waste. Acid Phase (III phase) is acids with high concentrations of CO₂. Small amounts of H₂ is also being produced. The fourth phase is methane formation phase, where group of microorganisms converts the acetic acid and hydrogen gas to methane and carbon dioxide. The last one is maturation phase (V phase) where reduction of CH₄ and CO₂ obvious contrary to N₂ and oxygen which emissions are increasing. Biodegradable organic materials are being converted into biomass, H₂O, CH₄ and CO₂. If landfills waste contains less biodegradable waste, it will have less gaseous emissions (Tchnobanoglous, Kreith 2002).



I - Initial Adjustment, II – Transition Phase, III –Acid Phase, IV – Methane Fermentation, V – Maturation Phase.

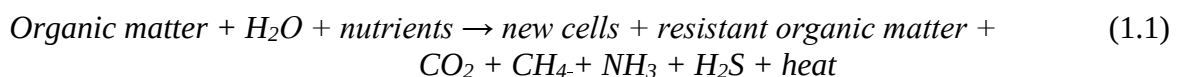
Fig. 1.19. Phases in the generation of landfill gases (Tchnobanoglous, Kreith 2002)

Greenhouse gases are identified by chemical and physical properties. Parameters in Table 1.4 show the gas physical and chemical parameters in the municipal solid waste.

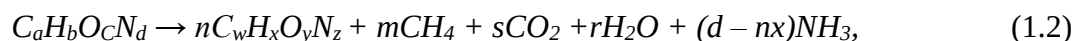
Table 1.4. Chemical and Physical properties (Pichtel 2005)

Gas	Formula	Molecular Weight, g/mol	Density, g/L
Carbon dioxide	CO ₂	44,00	1,9768
Hydrogen sulfide	H ₂ S	34,08	1,5392
Methane	CH ₄	16,03	0,7167

Anaerobic transformation of organic matter is described by the following equation:



Methane, carbon dioxide and ammonia is expressed by the following equation:



where $s = a - nw - m$ and $r = c - ny - 2s$. $C_aH_bO_cN_d$ and $nC_wH_xO_yN_z$ represent organic material composition at the beginning and at the end of the decomposition process. If it is assumed that biodegradable organic waste is stabilized completely, expression is as follows:

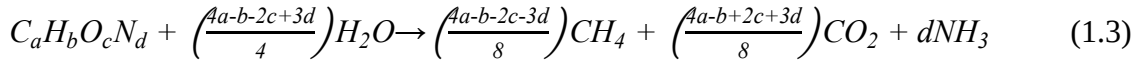


Figure 1.20 shows how air intrusion phase decreases the amount of CH_4 from 70 % of gas composition and quality till 20 % up to methane oxidation phase. In medium and long-term time frame at most landfills the gas quality corresponds to the average values that are characteristic for the landfill phase IV and V. VI phase shows the most dramatic changes in the gas decreasing measures (Heyer et al. 2013).

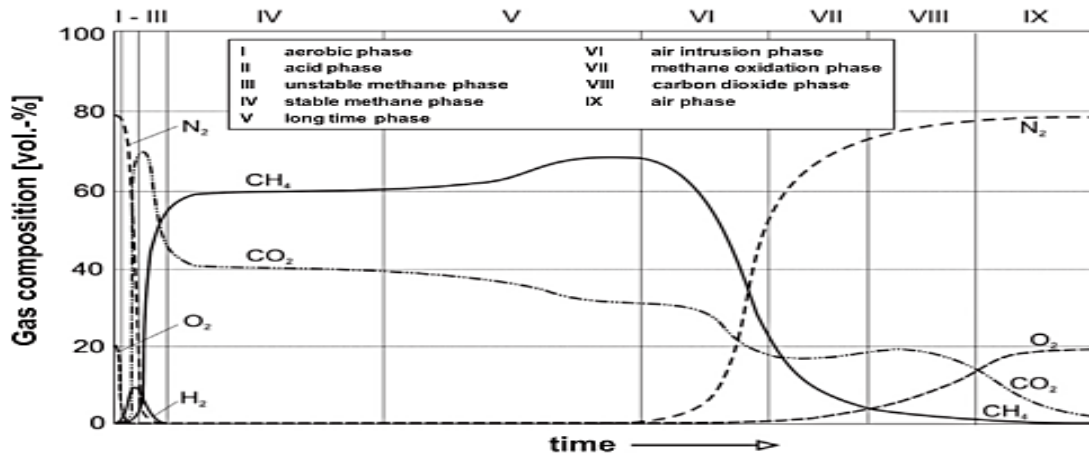


Fig. 1.20. Gas quality during the “life time” of a landfill (Heyer et al. 2013)

CO_2 in aeration phase decreases by about 15 %. N_2 is the only one gas that increased during the aeration (VI) phase by dramatic 50 %. Oxygen stays stable till methane oxidation phase (Heyer et al. 2013). Organic waste biochemical anaerobic degradation is as follows: with organic waste $\rightarrow$ fatty acids, aldehydes, alcohols $\rightarrow CH_4 + CO_2 + H_2 + NH_3 + H_2S +$ mercaptans (smelly gaseous materials) $\rightarrow N_2 + N_2O$ (loss of nitrogen because of descendent denitrification). During this process multiply anaerobic microorganisms mesophyll bacteria (temperature of 20-40 °C) (Zuokaitė 2011).

Methane (CH_4) is the second largest driver of climate change behind carbon dioxide and one of the six greenhouse gases (GHGs) listed in the Kyoto Protocol, with global warming potential of 25 over 100 years. CH_4 is also a short-lived climate pollutant with an average life-time around 12 years in the atmosphere (Bo-feng et al. 2014).

1.5 Sustainable waste management and landfill approach

Sustainable waste management model

Waste management developed in mid-1980s and is further developing. It acknowledges the importance of three dimensions when analyzing, developing or changing a waste management system. The dimensions are: the stakeholders that have an interest in solid waste management, the elements or stages of the movement or flow of materials from the generation points towards treatment and final disposal, and the aspects or issues through which the system is analyzed (Fig.1.21) (Guerrero et al. 2013). The most effective management of MSW has to relate to local environmental, economic and social priorities (Morrissey & Browne 2004).

The existing elements of the waste management systems are described in terms of waste generation and separation, collection, transfer and transport, treatment, recycling and final disposal.

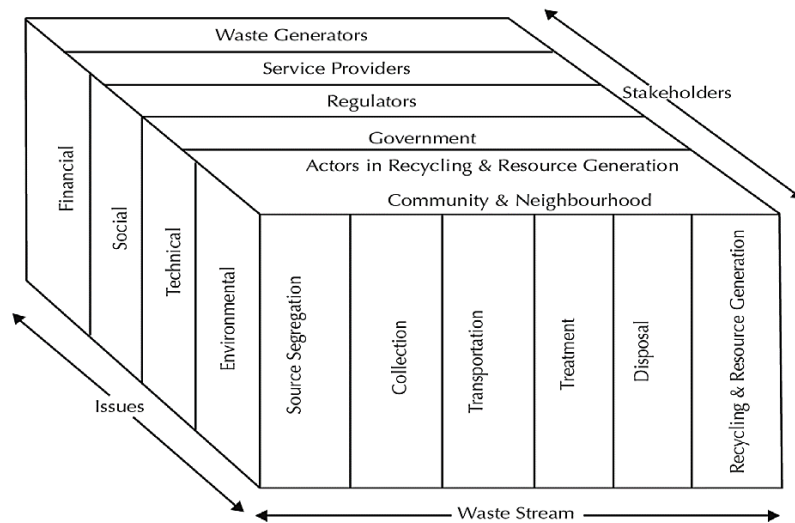


Fig. 1.21. Sustainable waste management model (Memon, 2013)

In this thesis, the focus is on the final disposal in a landfill with analysis of its sustainability.

Sustainability via different landfill management principles

In general, a landfill is being called sustainable, when waste inside are in a stable phase, do not cause any emissions and leachate to the environment. In addition, it has to comply with requirements and local limiting values for landfill emissions to the environment.

MSW landfills can be divided into two management and safety types. First type is unmanaged or non-sanitary open dumps or landfills which do not have leachate collection system, LFG monitoring system, LFG collection system, base liner, compaction, leveling and covering of wastes. By management lack increase problems of ground water contamination by leachate, increase GHG emissions, risk of fire and explosion, human health hazard and sanitary problems (Kumar & Sharma 2014). Typical landfills in European Union meets the lowest environmental and social, economic requirements.

Landfill can be called sustainable if it has benefits of resource generation through clean development mechanism (CDM). For this reason the easiest way is to design new landfill but there is also an opportunity to remediate landfill in such way is the country has strong economy and high income (Kumar & Sharma 2014).

Alternative landfill models

The aerobic landfill bioreactor can be applied as remediation tool to a waste treatment method which is a part of landfill management strategy. Sustainable landfill (Fig.1.22) – the aerobic bioreactor should consist of the following steps (Hudgins et al. 2010):

1. The incoming MSW composition has to be analysed to determine the percentages of household waste, organic matter, glass, metal, plastic and other inorganic solids present. This helps the operator decide where to place the waste, and the designer in the layout and operation of the bioreactor cell.

2. By using traditional waste placement methods and conventional equipment, the first cell is being filled with MSW on the top of a leachate drainage collection and a bottom line system (gravel). After filling and reaching landfills designed height with MSW, the waste is covered with an intermediate soil cover.

3. The aerobic bioreactor system is installed into the landfill cell with air and liquid injection systems. Over a period of about 2 years, the waste degrades aerobically, is monitored closely and is treated to the point where it is safe to excavate, also where the waste mass is stable.

4. Using traditional waste treatment equipment, the waste is being excavated from landfill cells and separated (using rotating trammels) into at least four waste streams for recycling or energy use (incineration):

- a) high calorific value materials;
- b) recyclable materials like metals and glass;
- c) compost (soil and degraded organics);
- d) construction and demolition waste (inerts).

5. The high calorific materials are tested for use as refuse-derived fuel (RDF). The metals and glass are characterized.

6. There are two ways to use composted materials – to use as every day landfill cover material or marketable agricultural products.

For these possibilities, specific quality measurements have to be evaluated. The waste with high calorific potential can be sent to energy-to-waste plants. The metals and glass can be sent to recycling plants. Construction and demolition waste that are landfilled and cannot be recycled can be shredded and used for quarry filling or for road site construction if the pollution measurements satisfy the limiting values of heavy metal concentration. The waste cell floor becomes empty and the cell can be refilled with incoming MSW. Alternatively, the mined cell can be closed and the land redeveloped.

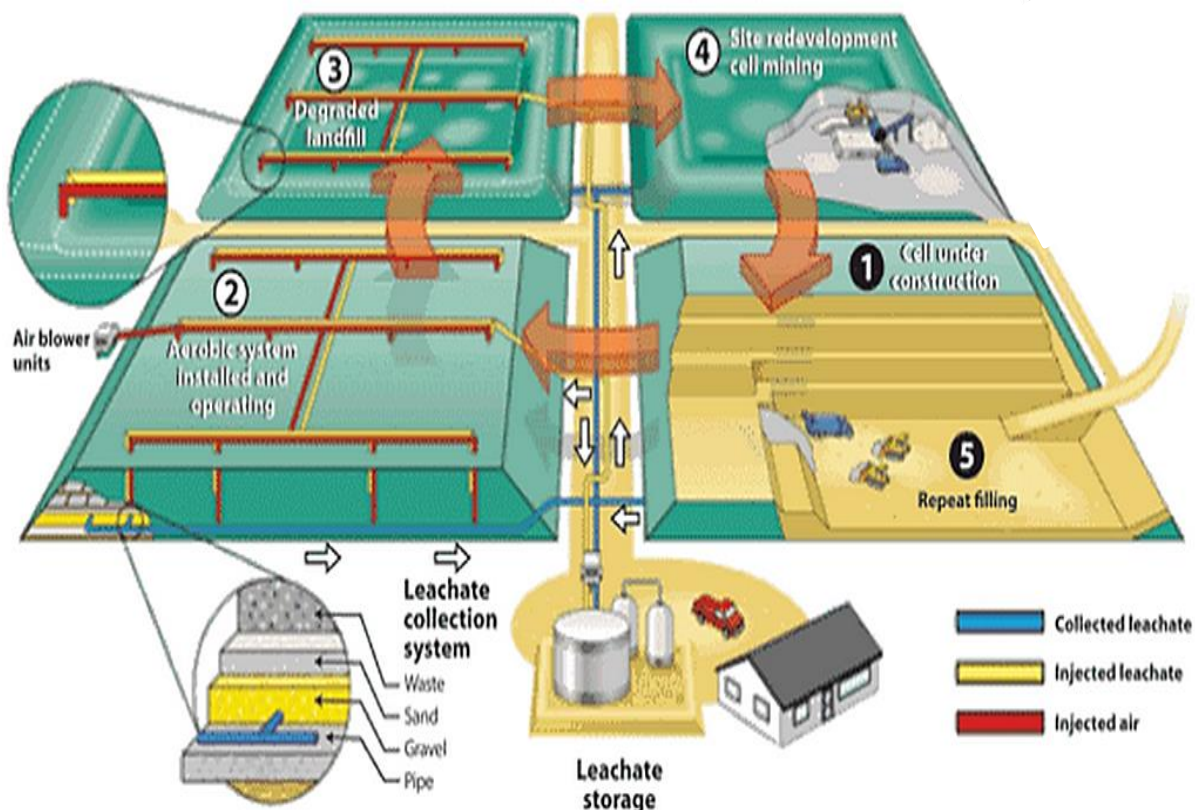


Fig.1.22. The sustainable landfill (based on aeration and leachate injection (Hudgins et al. 2010))

- 1) Construction cells; 2) Installed aerobic system; 3) Stabilized waste; 4) Redeveloped cell; 5) Cycle can be repeated in less than two years.

The main aspects inside sustainable landfill are (Fig. 1.22):

1. Cell construction (waste storage cells have to be isolated from causing groundwater pollution and covered with biosoil to hold GHG emissions from the atmosphere pollution);
2. Air injection and leachate collection and injection system installation and operation (insulation, rainwater filtration, a surface (rain) wastewater collection system, respectively reconstruction of leachate and surface (rain) runoff drainage systems, air blower units, leachate storage tank);
3. Rapid stabilization of waste (waste are degrading and becoming stable with a help of aeration and leachate injection processes);
4. Redeveloped cell or landfill mining;
5. Filling cycle repeat every two years.

The sustainable landfill strategy scheme is shown in Figure 1.23.

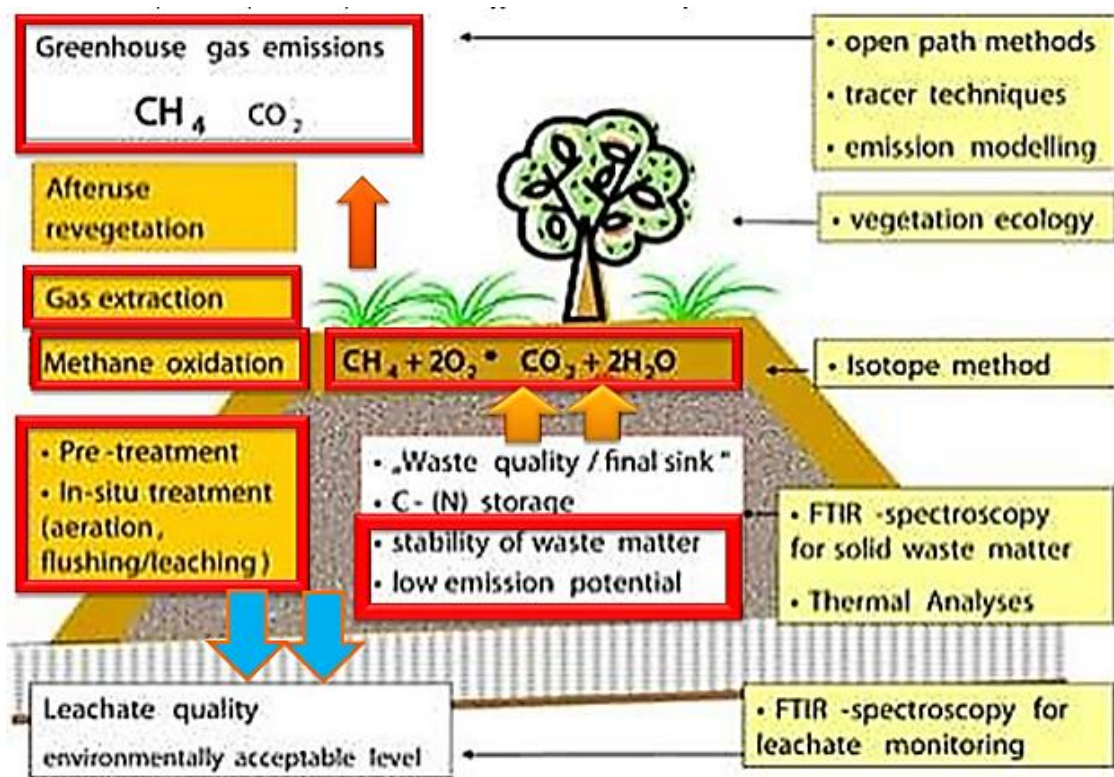


Fig. 1.23. Development of a sustainable landfill strategy (Team Acumen 2014)

Bioreactor landfills operate the processes by adding moisture to the waste in a suitably designed and operated landfill. These processes should increase the rate of waste degradation, leading to less risk and a move towards sustainability. Aerobic conditions can lead to lower leachate treatment costs, reduced methane gas and less odour. In general, landfill bioreactor systems can be anaerobic, aerobic or semi-aerobic (Hudgins et al. 2010). The main options that are being evaluated for reduction of landfill emissions in order to meet sustainability requirements are pre-treatment of waste (mechanical-biological processes or thermal treatment) and in-situ aeration of the waste mass, by natural air inflow (semi-aerobic landfill) or by forced aeration.

Aeration, moisture addition and gas extraction are needed to control the conditions required for aerobic processes to achieve the maximum efficiency. Air is injected through vertical wells installed through the landfill cover to maximize air delivery and to help control

the heat generated. Because over two-thirds of the original water content in the waste mass may be lost during decomposition, water or other liquids are added to maintain the aerobic activity. Waste mass should contain dry density $0,32 \text{ t/m}^3$ and a wet density of $0,67 \text{ t/m}^3$.

The nature of every landfill can make development of a sustainable landfill strategy a challenge. Successful strategies also require a multi-discipline approach that addresses the many environmental, political and social issues surrounding landfills. If these aspects are adopted to an old landfill then it is called sustainable remediated landfill (Fig. 1.24).

Remediation was done in the Netherlands for limiting the impact of the landfill Hooge Maey site on the environment to the minimum. The rainwater that had permeated into the landfill over the course of time was actively extracted to treat it in a biological water treatment plant. The landfill provides electricity for 5000 families, its place is open for cultural events. In general, the remediated landfill provides nutrients (present in the leachate that is to be treated), CO_2 (from the gas engines), heat (residual heat from the engines) and space. (Hooge Maey 2012).



Fig. 1.24. Sustainable remediated landfills

- 1) The Netherlands (Hooge Maey 2012);
- 2) Georgia, USA (Hickory Ridge 2012); 3) New York, USA (New Yorks...2013)

Hickory Ridge Landfill was transformed into the largest solar energy generating facility in Georgia, USA. It is the world's largest solar energy cap and the first use of the technology as a fully permitted landfill final closure system. The remediated landfill got three awards for engineering excellence (Hickory Ridge 2012).

Freshkills is a 890 hectares area, one of the largest trash landfills in the world. At the edge of New York City, specifically on Staten Island, the mega-landfill was created more than half a century ago. In 2015, it have to become the photovoltaic park of more than 47 hectares with a 10 MW capacity. It will become the city's largest energy production plant and will

represent sustainable landfill approach. It will be three times larger than the Central Park in New York city and will count as the largest remediated landfill (New York's...2013).

Air and leachate injection into MSW landfill of Columbia County, Georgia (USA) for 18 months increased biodegradability by 50 %, leachate BOD fell by 65 %, methane production decreased by 90 % and non-methane organic compounds declined by 75 %. In Atlanta, Georgia MSW landfill same research showed, that waste degrades faster under aerobic than anaerobic conditions (Hudgins et al. 2010). From a life-cycle perspective, the bioreactor landfill could be the basis for a cost-effective sustainable solution to solid waste.

1.6. Controlling GHG emissions from landfills

Landfill covering

Methane oxidation in landfill cover soils (LCS) is a cost-effective technology in controlling CH_4 emission from landfill. The available laboratory experimental construction is showed in figure 1.25. It is known that 6–96% of emitted CH_4 from landfills is oxidized by methanotrophs in LCS. In addition to oxidizing CH_4 from landfills, LCS also can function as a sink for atmospheric CH_4 . This process can lead to lower level of greenhouse gas emissions in landfills surrounding. CH_4 oxidation capacity in landfill cover soils lead to environmental factors, including cover soil texture, temperature, soil water content, CH_4 and O_2 availability, NH_4 and NO_3 contents (He et al. 2012).

Biocover soils such as compost material, waste biocover soil (WBS), shredded tires, sewage sludge and yard waste are rich in organic matter and have high CH_4 oxidation capacity. Biocover is one of the aspects of innovative technologies for reducing CH_4 emission from landfills and achieving landfill's sustainability through remediation. The oxidation activity of methanotrophs in the WBS cover could quickly adapt to the variation of CH_4 loading during landfill stabilization. Compared to the LCS cover, lower CH_4 emissions in the WBS covers were found (near 0). This study of author He in 2012 demonstrated that the WBS had a higher CH_4 oxidation activity than the LCS and worked well for the fluctuant influent CH_4 flux during landfill stabilization (He et al. 2012). Gas have to be regulated by landfill's cover soil in order to protect the atmosphere (Fig. 1.25).

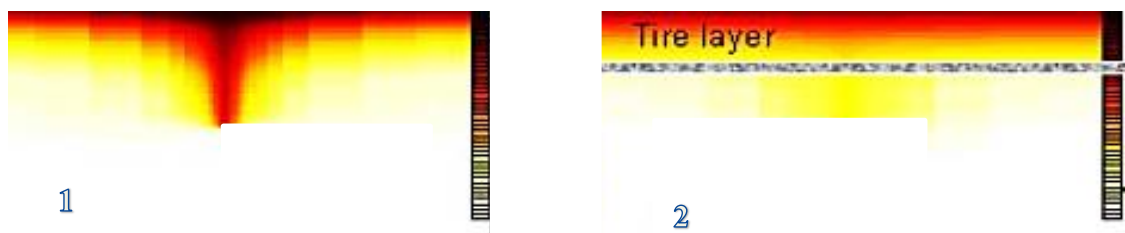


Fig. 1.25. The benefit of landfill shredded tires cover for stopping gas going to atmosphere (Bentley et al 2007)

1) Not prevented landfill from oxygen evaporation; 2) Prevented landfill from oxygen evaporation.

For example, when shredded tires are used as sustainable landfill's cover, that the gas are being stopped inside the landfill. (Bentley & a 2007).

Gas extraction

Landfill gas (LFG) extraction in a landfill with cover soil can visually help to concentrate landfill gas to intake tube, which directly provides collected gas to heat or electricity generator. By this type of LFG extraction, efficiency of recovery increases (Bentley & a 2007).

The sustainable landfill provides the idea of efficient gas extraction for improving energy recovery needs for surrounding living areas, which could get economic benefits from

landfill for citizens. Besides that, the atmosphere gas concentration is below limited values, which provide human and environment safety and it depends on the efficiency of the collection system.

Landfills that generate too little biogas for economic energy recovery can potentially offset methane (CH_4) emissions through biological oxidation by methanotrophic bacteria in cover soils (Pratt et al. 2013). CH_4 is a powerful greenhouse gas, recovery of landfill gas through technological systems can provide environmental and energy benefits by reducing gas emissions and can be used as an alternative energy source. The efficiency of landfill gas recovery largely depends on operating conditions (Zhang, Yue & Nie 2012). Recovery and utilization of landfill gas (LFG) CH_4 can not only reduce the greenhouse effect but also permit the generation of electricity (Feng & Zheng 2015).

Aerobic pre-treatment

Aerobic pre-treatment of municipal solid waste reduces waste mass and improves landfill processes. The meaning of aeration is to achieve increase of oxygen in the waste mass, thus achieving aerobic decomposition. When the MSW that is disposed of in a landfill has been aerobically pretreated, leachate pollution load and biogas production potential obviously decreases (Zhang, Yue & Nie 2012). Aerobic pretreatment of MSW can reduce mass of waste and visually improve landfill in-situ behavior.

Interest on GHG emission reduction effect of semi-aerobic landfill has been increased with concerns on global warming. The CH_4/CO_2 ratio values are reported for semi-aerobic (0,3–1,0) landfill sites and close to (1,0–2,0) for anaerobic landfill sites. Air is introduced to waste layer to accelerate stabilization of landfill sites, improve leachate quality (especially with respect to ammonia), and avoid GHG emissions by reducing anaerobic decomposition. As the remainder is considered as atmospheric air, $\text{CH}_4 + \text{CO}_2$ (% in landfill gas) implies the intensity of air intrusion to landfill gas. If semi-aerobic structure works well, the $\text{CH}_4 + \text{CO}_2\%$ and the velocity of landfill gas may have positive correlation (Jeong et al. 2015).

Aeration of the waste mass produces a rapid oxidation of organics and nitrogen when compared to the anaerobic bioreactor landfill. Under aerobic conditions some of the organic carbon in the waste mass is emitted as carbon dioxide and some would be stabilized as carbonates. The intensity of the carbon conversion depends greatly on ambient conditions around the microorganisms (e.g. oxygen concentration, pH, temperature, water content) and the availability of biologically degradable organic substances in the landfilled waste. The waste settlement in the aerobic reactors occurred faster than the waste settlement in the anaerobic reactors. Aeration at the bottom layer was the most effective for contaminants decomposition (Wu et al. 2014).

Anaerobic pre-treatment

Sources of Non-methane organic compounds (NMOCs) in landfill gas include the anaerobic biodegradation intermediates and the volatilization of hazardous organic compounds present in MSW. Figure 1.26 show a typical in-situ experiment equipment for anaerobic process gas evaluation.

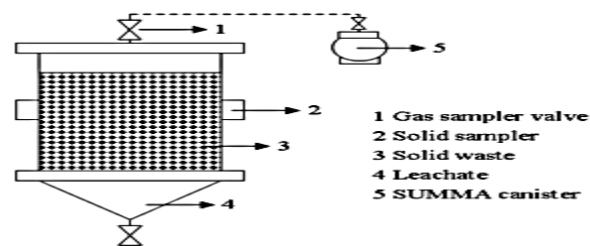


Fig. 1.26. Anaerobic laboratory landfill (Zhang, Yue, Liu, et al. 2012)

When aerobically pretreated MSW (APMSW) is buried in a landfill, the leachate pollution load and the biogas production potential will be diminished, the stabilization process will be enhanced and the intensity of the NMOC emissions will be reduced. The equipment in Figures 1.26 and 1.27 is applied not for sustainable landfill concept. In Figure 1.27, one tube was for air sampling, and the other was for measuring cumulative biogas, performed by discharging saturated salt water (Zhang, Yue, Liu, et al. 2012).

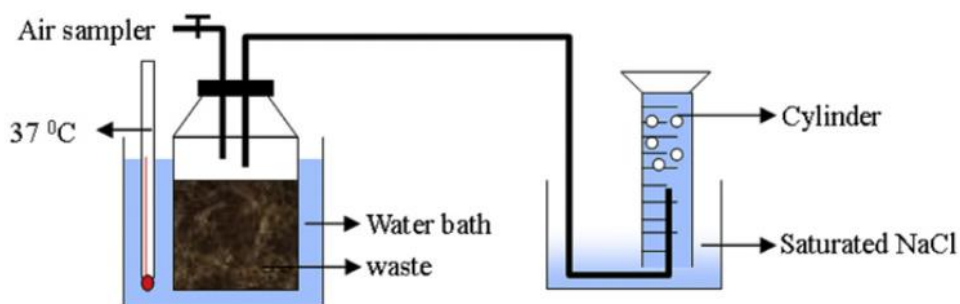


Fig. 1.27. Scheme of the anaerobic landfill prototype research (Zhang, Yue & Nie 2012)

The method shown in Figure 1.27 can be applied in laboratory scale for investigation about greenhouse gas emissions in landfills without oxygen.

Leachate recirculation

In recent years, it has been analyzed and evaluated that landfill technology promotes the decomposition and stabilization of biodegradable organic waste, through water addition, leachate recirculation or air injection. Leachate recirculation is used to ensure better nutrient distribution and appropriate moisture content (Cossu et al. 2015).

The organic carbon concentration in leachate is also considered as a contributor for greenhouse effect, assuming that biogas was generated as 50% CO₂ and 50% CH₄, according to the default values of IPCC 2006. Reduction in CO₂ is positive for contribution of leachate (Zhang, Yue & Nie 2012). After bioreactor procedure and stable solid waste matter reducing organic content of leachate is no longer needed. By the method of flushing, the leachate is pumped back into the cell to transport more of the releasable carbon. Additional carbon could be removed from the landfill cell by aerobic biodegradation if air is injected into landfill (Batarseh et al. 2010).

Waste biological stability

Waste stabilization can be identified when all biological parameters do not change and keep in a stable position. Municipal solid waste stability have a correlation with leachate quality (heavy metals, ammonia and chemical oxygen demand (COD)). Aeration can result in increased biological waste stability as well (Raga et al. 2015).

Biostabilization can remove considerable amount of moisture and degradable organic materials from municipal solid waste (MSW), and can therefore be an effective form of in-situ pretreatment prior to landfill (Zhang et al. 2011).

Stabilization parameters like gas emissions, heavy metals, COD are approved and used successfully in reducing emissions, but several interests still need to be solved:

- residual emissions, that remain after pre-treated municipal solid waste are being disposed to the landfill;
- aerobic landfill's drainage can clog;
- probiotics usage in the landfills could be evaluated.

1.7 First chapter conclusions

1. Municipal solid waste amounts are growing up all around the world. For this reason, Europe has set Waste Landfill Directive, Waste Framework Directive and European Seventh Action Programme. The aim is to reduce organic waste disposal in landfills which emit greenhouse gases and causes global warming;
2. Developing country such as Lithuania disposes 53,2 % municipal biodegradable waste into landfills. Lithuania has to be more strictly on its municipal solid waste treatment strategy.
3. Main GHG emissions from municipal solid waste sector are carbon dioxide (CO₂) and methane (CH₄) generated in solid waste disposal;
4. Sustainable landfill is considered as the best alternative for developed countries firstly. Developing countries should overview an opportunity for old landfill remediation, in order to control the landfilling process;
5. European countries have already overviewed and planed the sustainable landfill and waste minimization concept but the implementation of it is still weak. Afterwards it would help to succeed environmental, social and economic benefits;
6. European Union needs to increase research interests into sustainable landfill development and research on greenhouse gas emissions from municipal solid waste landfills evaluation on laboratory scale.

2. METHODOLOGY

The main challenge in municipal solid waste (MSW) research is to predict the rate and total production of methane from landfills and thus the long-term stability of the waste. After landfilling, waste go through degradation with bacterial action. In general it works under aerobic conditions, but as more waste is added, overlying layers hold the airflow and the dominant biochemical reactions become anaerobic.

Methane (CH₄) and carbon dioxide (CO₂) are the main components of the biogas that is produced during anaerobic MSW decomposition (Meima et al. 2008).

2.1 Materials used in the experiment

The research study is investigating the behaviour of different models available for sustainable landfill. The in-situ treatment processes include anaerobic, aerobic, semi-aerobic and flushing bioreactor technology. For the experiment, MSW that is mechanically-biologically pre-treated (MBP) is taken from JSC “Biodegra” which is placed in Lithuania, Medziuku village. JSC “Biodegra” does the mechanical-biological pre-treatment for biodegradable waste. The company separates, mills and sieves organic MSW (paper, cardboard, wood, textile, food and green wastes) and packages.

Laboratory research contained five hard plastic columns (Capacity – 19 liters). Each of them were filled with Table 2.1 total composition. Nowadays European Union Landfill Directive requires that all MSW disposed to the landfill would be pre-treated. The evaluation mass is being composed of pre-treated waste from JSC “Biodegra”.

Table 2.1. Composition of used pre-treated organic and inorganic MSW in 19 liters plastic columns (Lithuania’s national...2014)

Measure	Paper/ Cardboard	Wood waste	Textile waste	Food waste	Green waste	Plastic packaging	Metal packaging	Glass packaging	Inert waste	Other non- hazardous MSW	Composite packaging	Total
%	9,00	3,00	6,00	21,00	19,00	12,00	2,80	6,80	10,2	8,00	2,2	100,0
kg	0,45	0,15	0,30	1,05	0,95	0,6	0,14	0,34	0,51	0,4	0,11	5,00

All columns were filled with materials shown in figure 2.1. Materials were mechanically and biologically treated (MBT) as it must be before being accepted into the landfill. It helps to ensure lower volume and higher waste mass stability.

In the European Union (EU), only waste that has a low organic content may be landfilled. The emission potential of landfills shall be significantly reduced. This is due to the fact that the main emissions (gas, leachate) are associated with the biological degradable waste. In order to reduce this waste fraction significantly MSW has to be treated in order to meet the target values set by the different EU member states (Heyer et al. 2013). In this thesis, organic MSW treated in MBP are used for the experiment, as in Lithuania 54 % of landfill waste still is biodegradable waste.

All columns bottoms were filled with gravel layer that is suitable for drainage. The cover of gravel contains geotextile layer which is suitable material for waste cell combination. The biocover of municipal solid waste contains geotextile layer and year old high quality stable compost layer. These layers describes the construction of sanitary landfill.



Fig. 2.1. Waste samples

- 1) Gravel; 2) Wood waste; 3) Glass waste; 4) Plastic waste; 5) Inert waste; 6) Metal waste; 7) Other non-hazardous MSW; 8) Green waste; 9) Food waste; 10) Cardboard waste; 11) Textile waste; 12) Composite waste (shredded bottle closure); 13) Paper waste; 14) one year old compost for biocover.

2.2 Experimental equipment

These columns were closed and installed into a container, which was filled with water and had a thermostat (Fig. 2.2). Water have a constant temperature of 35 °C. The columns were kept in 35 °C temperature to establish a favourable growth environment for the microorganisms in columns (Erses et al 2008). Additional aeration was added for columns with aerator “Oxyboost” (Fig. 2.2.)



Fig.2.2. Maintenance equipment - aerator and thermostat

All of the gases that were generated inside five landfill models were collected into gas sampler bag (Fig. 2.3) and transported to gas monitoring equipment “Inca” (Fig. 2.3) every week. This research experiments were done in Vilnius Gediminas technical university’s Environment Protection Institute with the help of equipment named “Inca” and “Dräger” which showed gasses like CO₂ (%), CH₄ (%), O₂ (%) and H₂S (ppm) concentration. Columns had different conditions (Table 2.2).



Fig.2.3. Gas evaluation equipment “Inca Bio 04” and „Dräger“

Benefits of probiotic „Odor Away“ (Fig. 2.4) injection (Odor away 2015):

- Increase productivity of waste stabilization in the treatment process;
- Improve air quality by increasing the biodegradability and fermentation of the waste and gas emissions inside the columns (Biodegra TIPK...2015);
- Achieve targeted reductions in odor control quality parameters;
- safe for human and environment;
- Concentrated formula for cost-effective application (dilution is available).



Fig. 2.4. Probiotics “Odor away” (Odor away 2015)

The probiotic is produced through a natural fermentation process, and is not chemically synthesized or genetically engineered or modified. Probiotics „Odor Away“ are in liquid phase and produced through a natural fermentation process using beneficial and effective microorganisms. These effective microorganisms are fed on high levels of ammonia, hydrogen sulfide and methane causing bad odors found in biodegradable waste. Applying SCD Odor Away changes microbial ecology to one that is balanced and healthy for the environment. This research will show if the usage of probiotics in a landfill could change greenhouse gas emissions into the atmosphere and make the landfill more sustainable.



Fig.2.5. Landfill model’s research equipment construction

The research equipment was situated in Medziuku village of Lithuania, JSC „Biodegra“. All gas sample bags were being transported around 30 kilometers every week in order to measure them in laboratory.

2.3 Experimental conditions

Each column was fed with distilled water (0,563 L). Each week collected air emissions were evaluated and collected leachate was reused for column’s watering process. Columns number 1 and 2 were anaerobic. Column number 2 was filled with 1,5 ml of probiotics “Odor Away”. Columns number 3, 4, 5 were aerobic. Column number 5 was also filled with 1,5 ml of probiotics “Odor Away”. Columns number 3, 4 were maintained with 50 l of O₂ per day, 4 hours per day and 5 days per week. Column number 5 was maintained with 100 l of O₂ constantly.

Table 2.2. Landfill models conditions

Column	Material	Operating conditions	Landfill models
1	Waste after MBP	Anaerobic with single input of water and leachate recirculation	Anaerobic with low flushing waste landfill
2	Waste after MBP	Anaerobic with single input of water, leachate recirculation and doze of probiotics	Anaerobic with high flushing landfill
3	Waste after MBP	Aerobic with high air inflow, single input of water and leachate recirculation	Aerated bioreactor landfill
4	Waste after MBP	Aerobic with low air inflow, single input of water and leachate recirculation	Semi-aerobic bioreactor landfill
5	Waste after MBP	Aerobic with low air and single input of water, leachate recirculation and doze of probiotics	Semi-aerobic and flushing bioreactor landfill

Leachate recirculation was done once in a week in order to feed the columns. The amount (Table 2.3) of clean distilled water was added once to all columns for increasing the field capacity of the waste to generate the leachate (Sri Shalini et al. 2010). The amount is used to simulate long-term landfill behaviour of the liquid/solid (L/S) ratio. All columns were fed by amount of 0,563 l of distilled water, to reach $L/S = 7,5$ (Erses *et al* 2008). Leaching was being used as closed recirculation system in the columns in order to replace water consumption and to increase waste biodegradability during the research. This process is being called flushing/leaching.

Table 2.3. Landfill models conditions for the column testing

Column	Waste (kg)	Air inflow	First added water flow (L)	Leachate input (L/week)	Probiotics (liquid) (L)
1	±5,0	-	0,563	0,188	-
2	±5,0	-	0,563	0,563	One doze of 1,5 ml
3	±5,0	100 l/h, continuously	0,563	0,188	-
4	±5,0	50 l/h, 4h/d, 5 d/week	0,563	0,188	-
5	±5,0	50 l/h, 4h/d, 5 d/week	0,563	0,563	One doze of 1,5 ml

The columns were equipped with four ports. One port was used for drainage. Other two ports were used to collect gas samples and inject liquid, air. Columns 3, 4 and 5 were equipped with an air compressor “Oxyboost 100”. Aerated landfill model (3 column) was fed with air continuously and columns 4 and 5 were fed 4 hours per day and 5 days per week. All testing parameters are given in Table 2.3. In 3rd, 4th and 5th landfill columns, CO₂ concentrations were measured in two points – column’s surface and bottom, in order to evaluate air and biogas evaporation through municipal solid waste with compulsory aeration. Waste were held in columns for 120 days. The technological scheme of landfill model is shown in Figure 2.6. The biocover for waste in columns were composed from the yard waste, such as wood branches, grass that were kept more than a year.

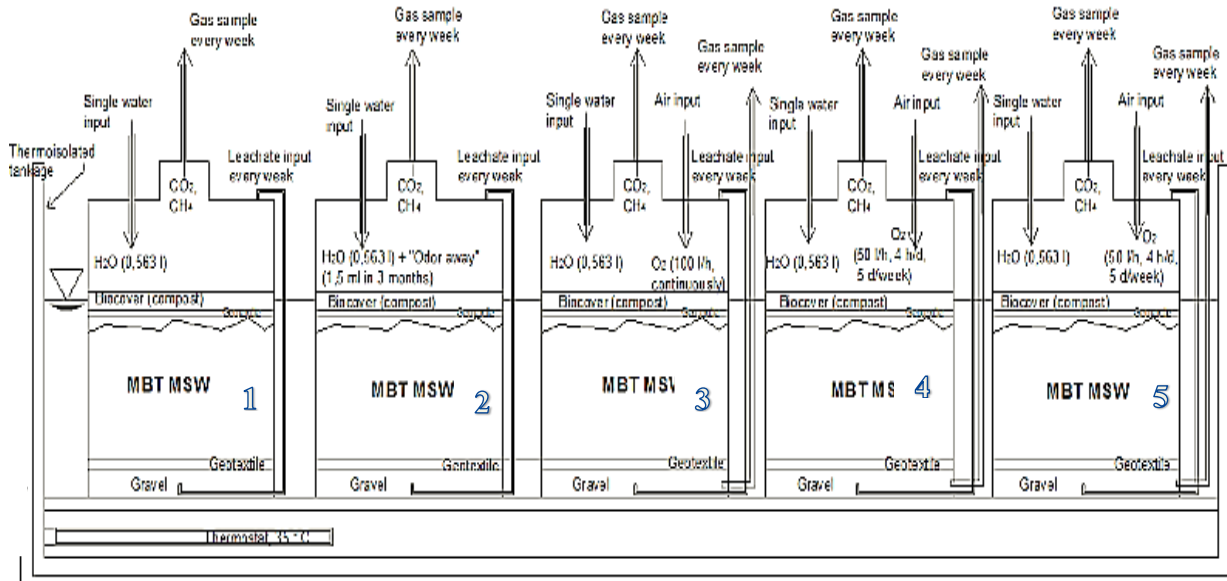


Fig. 2.6. Landfill models technological inputs and outputs scheme

After this time period, the columns conditions were used for mathematical modeling, which is able to model gas emissions from real size landfill with different inside parameters.

2.4 Parameter calculation

The percentage of biodegradable waste (B_0 (%)) is defined as the proportion by mass of food, yard, and paper waste of the entire waste mass (W) including all landfilled waste and daily cover soils:

$$B_0 = \frac{\text{mass of biodegradable waste}}{\text{total mass of waste}} \quad (2.1)$$

According to experimental data, the percentage of biodegradable waste is 58 %.

The proportion by mass of food and yard waste by weight of all biodegradable waste is defined as the percentage of readily biodegradable waste (B_{r0} (%)):

$$B_{r0} = \frac{\text{mass of food and yard waste}}{\text{mass of biodegradable waste}} \quad (2.2)$$

According to experimental data, the percentage of readily biodegradable waste is 40 %.

The values of B_0 (%) and B_{r0} (%) were calculated since their waste composition was known in all five landfill models. The mean values for the laboratory experiments are (Fei et. al., 2015): $k = 5,66 \text{ yr}^{-1}$, $L_0 = 98 \text{ L/kg}$, $t = 1 \text{ year}$, mass value is accepted as 550 t/day. For landfill methane amount calculation the following equation was used:

$$Q_{CH_4i} = \sum k \cdot L_0 \cdot m_i \cdot e^{-kt}; \quad (2.3)$$

where

k – methane generation rate constant, yr^{-1} ;

L_0 – methane generation potential, $\text{m}^3 \text{ CH}_4/\text{t waste}$;

m_i – waste mass disposed in year, t ;

t – time estimated, years;

e – mathematical constant.

These very low composition amounts showed in table 2.4. do not insure proper calculations of program LandGEM, because this program was created for traditional landfills modeling, where main evaporating gas is methane. As it so it can be said, that 3rd and 5th landfill models should have showed similar results to 4th landfill modeling results. For this reason, it is recommended to create new modeling program for sustainable landfills, which would indicate results with low methane amounts or would have user inputs for compositions of more possible gas types. Figure above indicated only carbon dioxide emissions, which could be summed up with methane emissions in order to see total landfill emissions amount.

Table 2.4. Variables data (Fei et. al. 2015;Berge et al. 2009)

No.	Model type	CH ₄ generation variables			Calculated methane amount	Measured composition of methane
		k, (yr ⁻¹)	L ₀ (m ³ /t)	t (yr)	Q _{CH₄} , m ³ /yr	%
1	Anaerobic with low recirculation landfill	0,063	120	1	1 421 102,00	36,61
2	Anaerobic with higher recirculation landfill	0,04	110	1	846 340,00	39,23
3	Aerated landfill with low recirculation	0,15	100	1	2 584 706,00	0,33
4	Semi-aerobic landfill with low recirculation	0,08	100	1	2 584 706,00	4,14
5	Semi-aerobic and higher recirculation landfill	0,10	100	1	2 584 706,00	0,18

Overall, the mean L₀ value is similar for the laboratory and the field data. The recommended ranges of k and L₀ in LandGEM are 0,04–0,20 yr⁻¹ and 100– 170 L/kg, respectively, although the upper-bound values of k and L₀ are often considered unrealistic for conventional landfills.

Methane and carbon dioxide gas generation in all 5 landfill models was calculated using the EPA (Environmental Protection Agency) LandGem equation. It was assumed that landfill will accept 200200 t of waste every year for 10 year period.

2.5 Second Chapter's conclusions

1. Five landfill models were constructed. The tests lasted for 120 days. The columns were kept in mesophilic temperature 35° C;
2. Columns were filled with waste composition of which is typical for Lithuanian landfills;
3. Conditions in all columns were differed by changing the inlet and outlet flows of air, water/leachate, and probiotics;
4. It is expected that results will show difference between gas measurement values in columns and will be compared at once.
5. The column with the lowest greenhouse gas emissions, the most stable waste mass and the lowest costs will be considered the most sustainable landfill model.

3. RESULTS AND DISCUSSION OF EXPERIMENTAL RESEARCH

This chapter contains experimental results of biogas quantity and quality. Carbon dioxide, methane, hydrogen sulphide, oxygen and pH measures of five landfill columns were evaluated. The most important parameters are composition of biogas which were measured and the amount which was determined theoretically.

3.1 Parameters of 5 landfill models

Chemical decomposition of organic waste under anaerobic conditions (putrefaction) is as follows: organic waste $\rightarrow$ fatty acids, aldehydes, alcohols $\rightarrow$ $\text{CH}_4 + \text{CO}_2 + \text{H}_2 + \text{NH}_3 + \text{H}_2\text{S}$ + mercaptan (smelly gas) $\rightarrow$ $\text{N}_2 + \text{N}_2\text{O}$ (nitrogen is lost due to the ongoing denitrification). The process of anaerobic microorganisms multiply – mesophilic bacteria.

Biomass decomposition is slow and during its time nitrogen is lost and form a global greenhouse gas like methane, various unpleasant-smelling volatile compounds. Biodegradable fresh waste is dominated by fungi, especially particular mold fungi, as well as various organic acid-producing bacteria and other mesophilic bacteria. They are primarily absorbed liquid form sugars and amino acids, mainly located in various parts of the plant, as well as starches and carbohydrates (polysaccharides and cellulose). Methane and carbon dioxide produces during the decomposition of organic fraction of waste under anaerobic conditions.

1st landfill model

CH_4 emissions increased at 42nd day of the experiment and at 77 days reached 60% because of mesophilic bacteria digestion of organic waste (Fig. 3.1). From day 77 it is noticeable a mesophilic mineralization and maturation process in which organic nitrogen is rapidly transformed into inorganic - under intense mineralization (an inorganic nitrogen rollover) - ammonification and nitrification process. In this stage mesophilic bacteria and fungi also destroys (oxidizes) fermentation products from earlier (anaerobic micro-environments) phases - methane and other noxious (harmful) gases (hydrogen sulphide, sulfur mercaptan, light aromatics) - reducing bad odors and other toxic intermediate risk - the end of the experiment the methane gas emissions decreased to 49%. This was influenced by oxygen reduction.

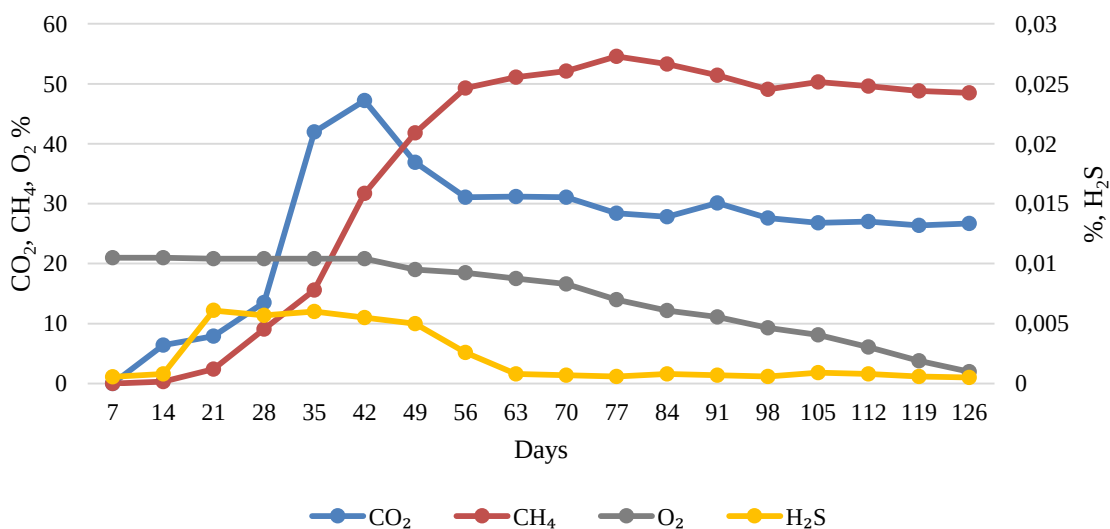


Fig. 3.1. 1st landfill column's parameters

When CO₂ gas evaporation started, the largest release value (50%) was achieved at day 49 because of the intensification of mesophilic bacteria. Gas evaporation instability was influenced by leachate injection is carried out each week.

It was observed that the oxygen content a steadily decrease throughout the experiment, and at the end of the experiment decreased to minimum.

H₂S release was very minimal, the maximum value was only 0,006% due to the lack of experimental waste containing protein. In landfills it is prohibited to dispose animal waste because of strict veterinary standards and directives.

2nd landfill model

The second anaerobic landfill is different with these parameters - probiotics injection and double amount of injected leachate.

CH₄ emissions increased at 84th day (Fig. 3.2) of the experiment and reached 60% because of mesophilic bacteria digestion of organic waste. The lowest value s recorded at the end of the experiment - 49%. It can be said that larger leachate injection determined more equal distribution of methane gas emissions, although emissions reduction did not reach the value of the first model end results (57%). Larger emissions at the end of experiment were influenced by the excessive amount of leachate recirculation, which apparently consisted of too much moisture and proceed the unfavorable development of microorganisms. When the humidity is above 60% there is a risk that the oxygen do not enter composted mixture.

Second landfill has released less carbon dioxide comparing with released methane. The maximum of emitted value was 39%, which is 10% less compared with the first landfill model. The amount after day 98 slowly reached 22 %, which left stable until the end of experiment.

It was observed that the oxygen amount steadily decreased throughout all experimental time, and the end of the experiment decreased to minimum. With increasing population of microorganisms, oxygen concentration in the mixture decreases and CO₂ begins to grow.

Probiotics insertion into the second landfill model affected the release of hydrogen sulfide and reduced it to a minimum. Larger filtrate injection determined a little bit bigger amount 0,009% of H₂S gases at the beginning than in the first landfill. After probiotic injection levels reduced its emissions to a minimum.

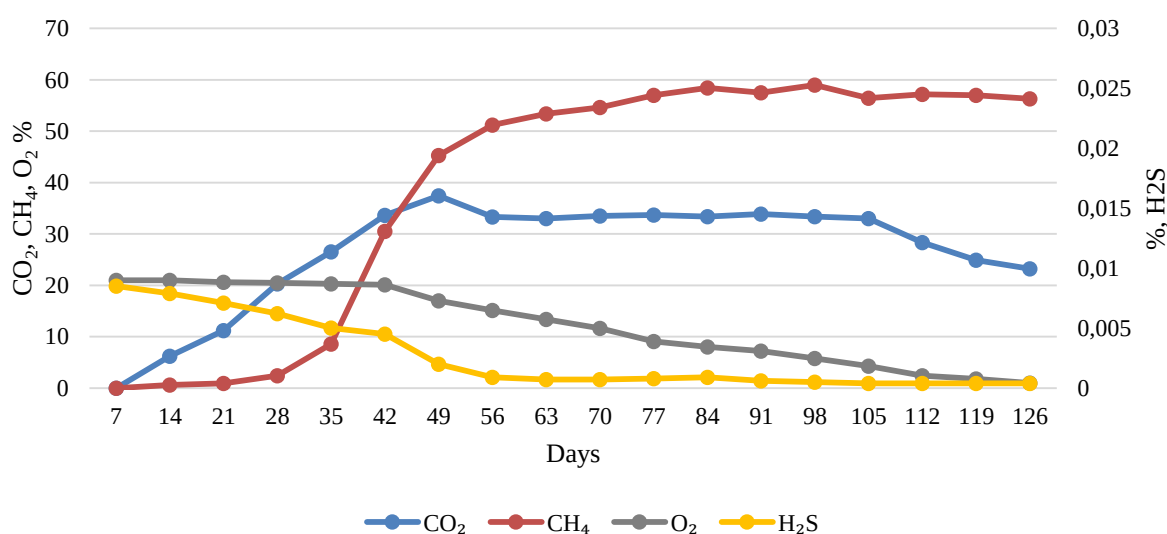


Fig. 3.2. 2nd landfill column's parameters

Both anaerobic landfills models can be applied for gas extraction process, but not for a sustainable landfill conception because anaerobic process increases, not reduces GHG emissions.

3rd landfill model

Biochemical decomposition of organic waste under aerobic conditions (in the presence of atmospheric oxygen and enzymes) is as follows:

- fat, polysaccharides, carbohydrates --> $\text{CO}_2 + \text{H}_2\text{O} + \text{Q}$;

- cellulose (green waste mass consists of 20-40%), lignin, pectin, tannins --> $\text{CO}_2 + \text{H}_2\text{O} + \text{heat}$.

3rd landfill column's surface qualitative parameters are showed in figure 3.3, and column's bottom parameters showed in figure 3.4.

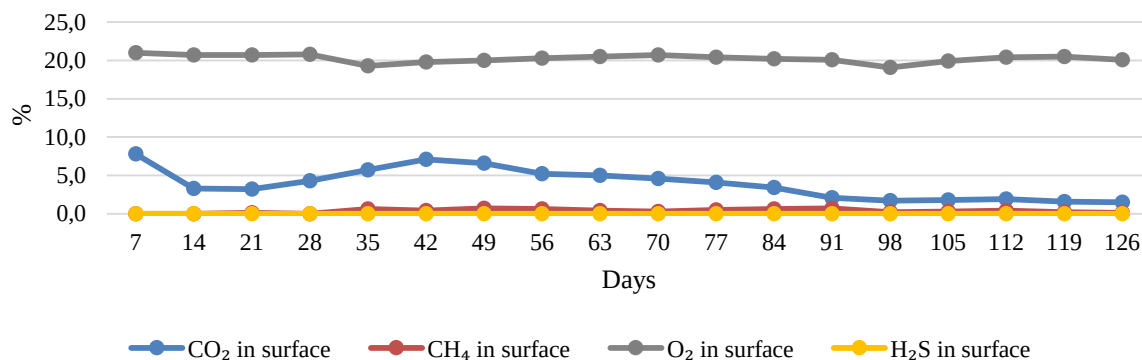


Fig. 3.3. 3rd landfill column's surface parameters

CH₄ emissions increased at 49th day (Fig. 3.3) of the experiment and reached 0,7% because of mesophilic bacteria digestion of organic waste, while the lowest value recorded at the end of the experiment 0,1%. Release curve changes during the experiment places was 0,6%. It was found that this model is practically do not emit methane.

The maximum of carbon dioxide emissions achieved amount of 10% in day 14. After it steady declined until it reached the minimum 3% at day 84. Permanent aeration and (as in all landfill models) mechanical – biological waste treatment helped to reduce carbon dioxide emissions in the third landfill. Aerated landfill models gas quantity was measured at the bottom, because aeration was applied of the surface of landfill, not directly to the waste mass.

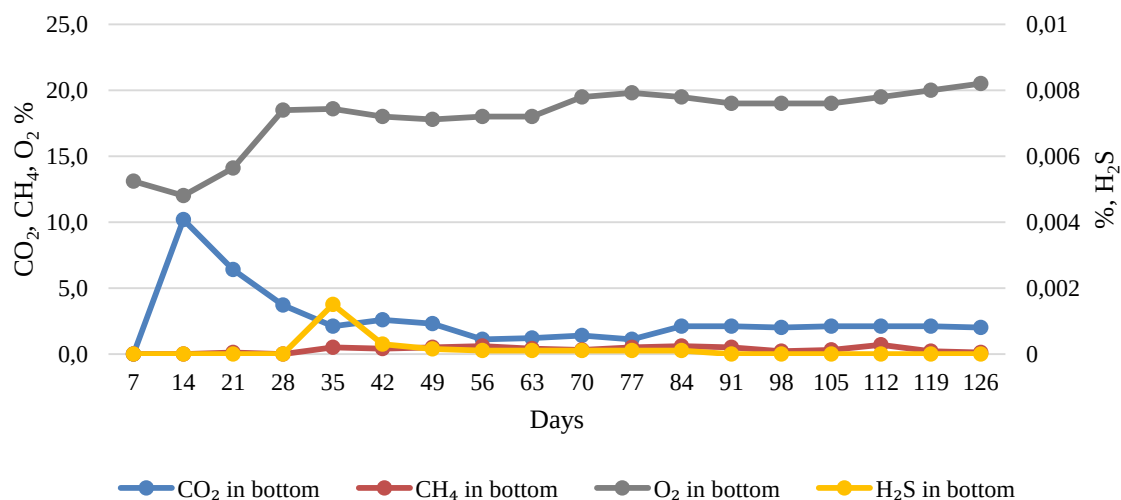


Fig. 3.4. 3rd landfill column's bottom parameters

The oxygen amount in the whole experimental period remained constant due to the continuous aeration (about 20%). The bottom of the landfill model in the beginning got less oxygen (13%) because of difference waste density. After oxygen penetration to the bottom, methane gases increased since the microorganisms have been supplied with oxygen. H₂S amount was close to 0 %.

4th landfill model

CH₄ emissions increased at day 70 (Fig. 3.5) of the experiment and reached 25 % because of mesophilic bacteria digestion of organic waste, while the lowest value recorded at the end of the experiment 1%. The bottom of the landfill gas parameters (Fig.3.6) differed slightly - the highest concentration of CH₄ observed in the experiment day 49 (23%) and the lowest (4%) value reached 126 days, which is higher than the upper part because of trapped methane gas.

It is important to note that higher CO₂ concentrations were found in the lower part of the landfill. Maximum amount was 24%, which at the end of the experiment decreased to 6%. The upper measuring point parameters showed smaller gas amount, which was the highest at day 28th (20%). This difference showed that a further decrease was due to the penetration of gas in the lower part of the landfill.

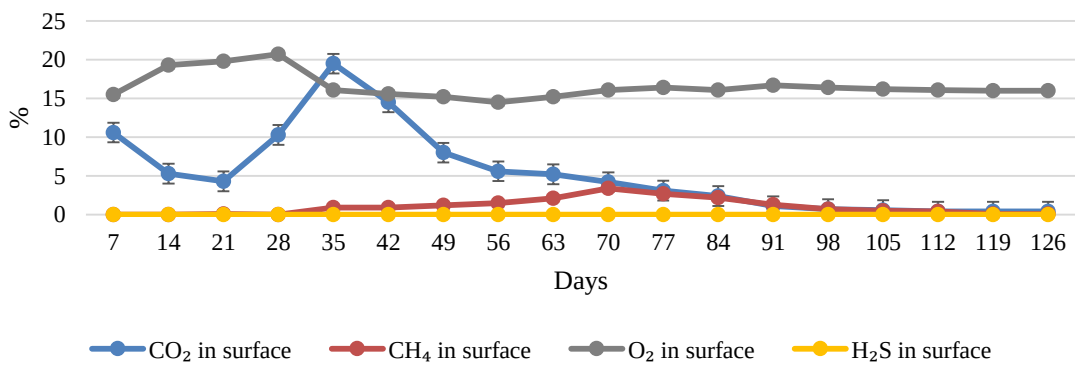


Fig. 3.5. 4th landfill column's surface parameters

The amount of oxygen during the experiment ranged up to 5%, most time it was constant - 16%. The bottom of the landfill remained minimal amount of oxygen because of non-permanent aeration (Fig. 3.6). H₂S amount was close to 0 %.

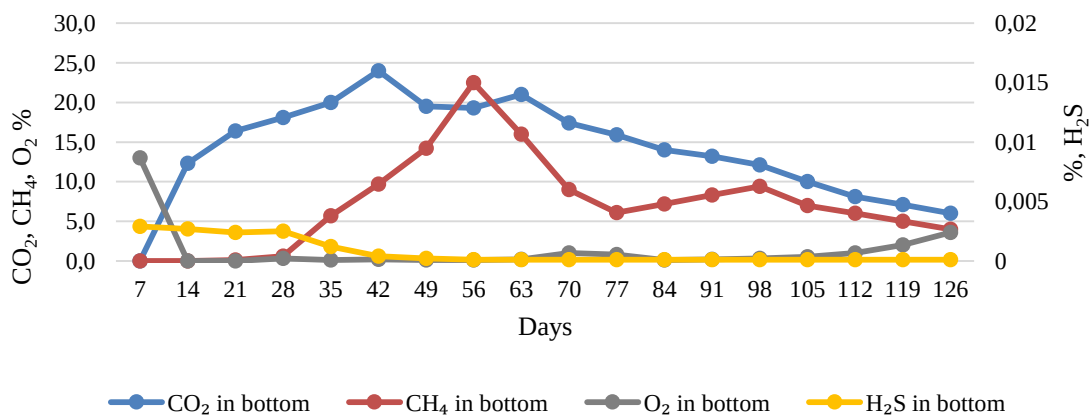


Fig. 3.6. 4th landfill column's bottom parameters

5th landfill model

Maximum amount of released methane was 0,4% (Fig.3.7) and by the end of the experiment it decreased to 0%. The lowest methane evaporation amount was achieved comparing all five landfill models.

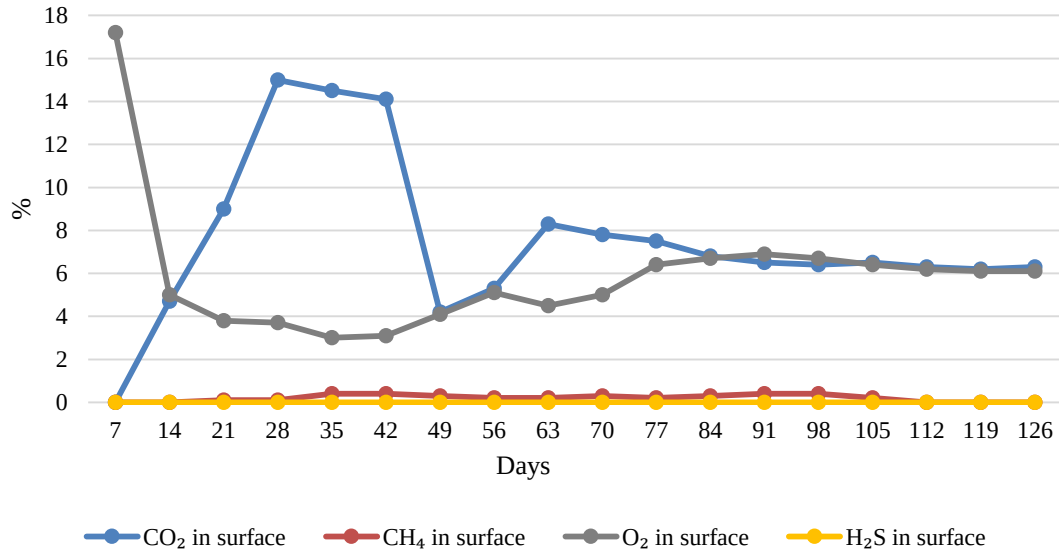


Fig. 3.7. 5th landfill column's surface parameters

Carbon dioxide emissions amount was 18%, which is more than from 3rd landfill, but less than from 4th landfill. The lowest amount was emitted at the end of the experiment 6-8% at the from the top and bottom (Fig. 3.8) measuring points of 5th landfill. Oxygen emissions decreased after the first week of insertion of the filtrate. During the experiment the oxygen changed in the range of 4-6%. H₂S amount was close to 0 %.

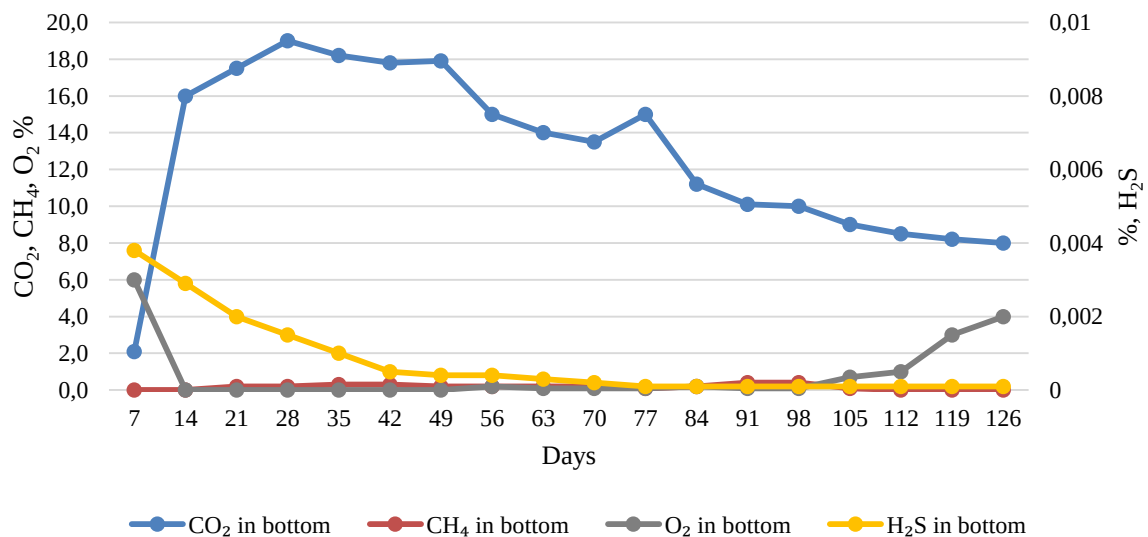


Fig. 3.8. 5th landfill column's bottom parameters

Results showed that first and second landfill models can be used for biogas production, not for sustainable landfill approach. The third and the fifth landfills results showed the lowest quantitative parameters of greenhouse gas emissions.

3.2 Concentration of carbon dioxide and methane in columns

The results show that in column 1 (Fig.3.9), the highest carbon dioxide point (49,2 %) was reached on 42nd day. In the beginning, organic matter in landfill model are hydrolyzed and the produced organic acids cease gas production. During the intermediate anaerobic degradation stage, methanogenic bacteria slowly start to appear and gas production rate increases (Erses et al. 2008). After that CO₂ concentrations gradually decreased and after day 105 it became stable (27 %). 2nd column was filled with one doze (1,5 ml) of probiotics and larger amount of leachate. For this reason, CO₂ concentrations gradually increased until day 49 (38,4 %), and after that it reached stable CO₂ evaporation (33,5 %). At day 105 the concentration decreased to 23,2 %. The reason was larger amount of leachate injection.

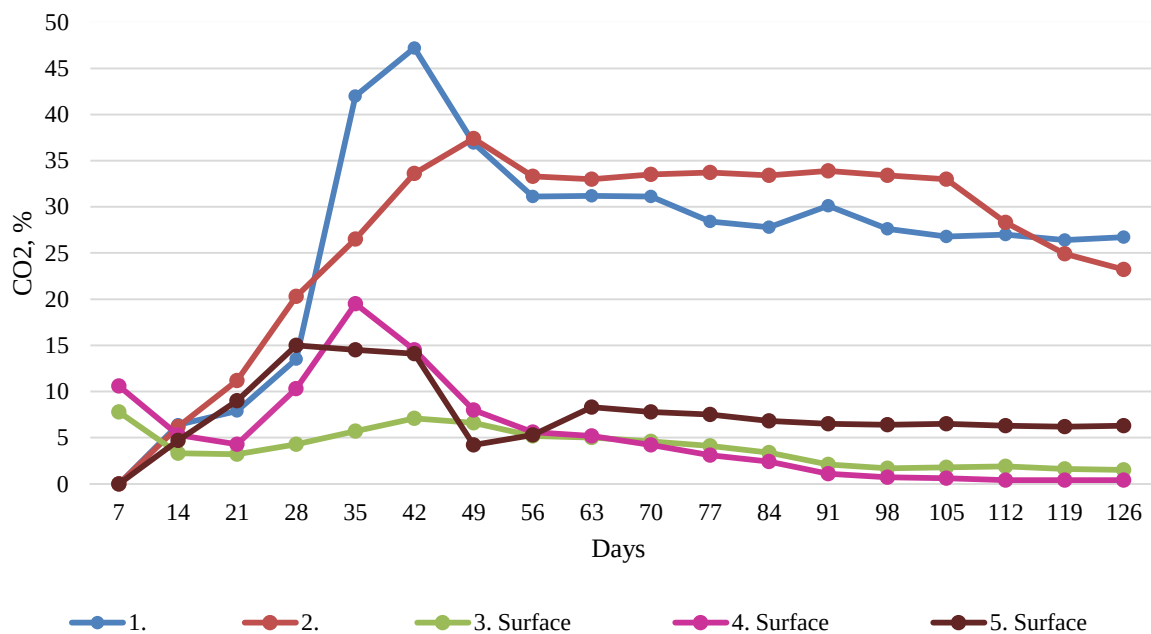


Fig. 3.9. CO₂ composition in landfill columns surface

- 1) Pre-treated waste anaerobic landfill; 2) Pre-treated anaerobic waste landfill with flushing; Pre-treated waste aerobic landfill 100 l/h; 4) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week; 5) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week and high flushing

By comparing 1st and 2nd landfill column's CO₂ concentrations, it can be seen, that 2nd had more stable parameters because of probiotics and larger leachate recirculation. Both columns had a similar evolution over observation time and evaporated highest percentage of CO₂ comparing with all five landfill columns. After seven days it had decreased to 3,3 %. After this period, CO₂ concentration slightly increased (7,1 %) and stabilised on day 91 (1,8 %). Landfill column's bottom measurements showed different concentrations of CO₂. It started from 0 % of volume and in 14 days reached the highest (10,2 %) point. Although, surface and bottom CO₂ concentrations stabilized until day 91. Surface concentrations can be higher because of biocover (one year old compost) layer, which reduce biogas evaporation to the atmosphere.

Surface CO₂ concentrations started from (10,6 %) and increased only after one month (19,5 %) to the highest point of the experimental period. However, 4th landfill column concentrations of CO₂ were the only one that decreased until 0,4 % and kept it stable from day 112 until the end of experiment.

Bottom concentrations were much higher probably because of difficult air infiltration through municipal solid waste layers. This may indicate that the biodegradation process can be affected by the changes in hydro-dynamic conditions when moisture, nutrients and bacteria are well-distributed in the waste. The result shows that the gas generation rate and perviousness can lead to a quite different distribution of gas pressure. The maximum gas pressure for cases occurs at the bottom of the landfill. However, the maximum gas pressure appears at the upper layer of the landfill. This is because the landfill gas can flow to the bottom and then be collected by bottom wells due to the low-permeability cover and large difference between the gas generation rates of the upper and lower layer (Feng & Zheng 2015)

Measures started from 0 % and until day 49 it reached 25 %. Although there are some fluctuations, the overall CO₂ dynamics has a decreasing tendency from day 42. Aeration was discontinuous in all 3 cases. Under aerobic conditions some of the organic carbon in the waste mass is emitted as carbon dioxide and some would be stabilized.

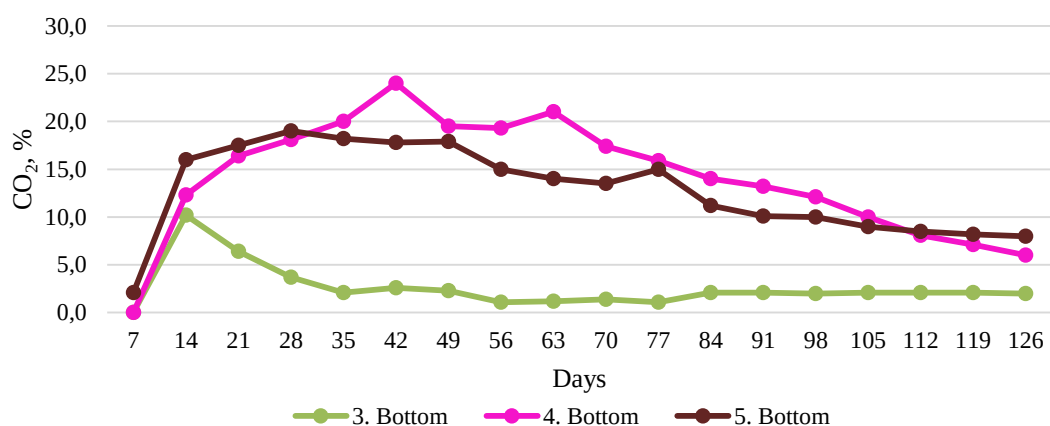


Fig. 3.10. CO₂ composition in landfill columns bottom

This column's concentrations started from 0 % and reached their highest point at the same observation time (21st day) – surface 15 %, and bottom 19 % of volume. Comparing with other experimental landfills, surface concentrations became stable fastest – day 70. Bottom measures reached stabilization a bit later – on day 112. The intensity of the carbon emissions depends on ambient conditions around the microorganisms (e.g. oxygen concentration, pH, temperature, water and leachate content) and the availability of biologically degradable organic substances in the landfilled waste inside landfill models.

Methane in 1st and 2nd anaerobic landfills (Fig. 3.11) reached the highest points of concentration (60 %), comparing with all five landfill columns and all of them evaporated methane from the lowest 0 % amount. In comparing of 1st and 2nd columns graphical results it can be seen that there is no significant difference between the graphics. Although it can be mentioned that higher amount of leachate and a dose of probiotics might kept methane concentrations more stable, but relentless. Methane oxidation in landfill model top cover layers has been proposed as a means of treating the low rates of gas generation, possibly following in situ aeration.

The aerobic conditions throughout the waste mass reduced methane level rapidly and kept it at a minimum. Third landfill column's measures were similar, comparing bottom and surface values. High concentration of air inlet might spread methane concentration evenly. The highest concentrations of methane were 0,7 % in 49th, 91st and 112th days. Even the concentration was really low, it did not reached stable value.

Forth landfill column's surface measures showed its highest concentration on day 70 (3,4 %). During the other time of experiment the measures were quite stable. Although, bottom showed different concentration values. It took 56 days to reach its highest 22,5 % volume and the lowest value 4,0 was reached on the last experimental week.

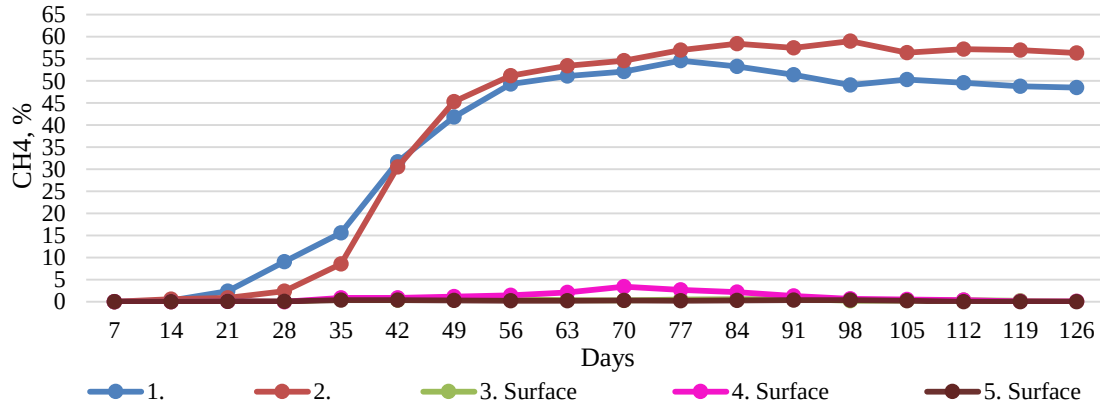


Fig. 3.11. CH₄ composition in landfill columns surface

1) Pre-treated waste anaerobic landfill; 2) Pre-treated anaerobic waste landfill with flushing; 3) Pre-treated waste aerobic landfill 100 l/h; 4) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week; 5) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week and high flushing

Fifth landfill had lower concentration of methane than fourth landfill, because of anaerobic condition in certain time periods. Highest amount that was reached in bottom measures is 11 % of volume. It is important to mention, that 4th and 5th landfill columns reached their highest methane evaporation value at the same operational time (day 56). Although at day 98 bottom and (Fig. 3.12) surface concentrations became finally stable – 0 % and left zero impact to the environment.

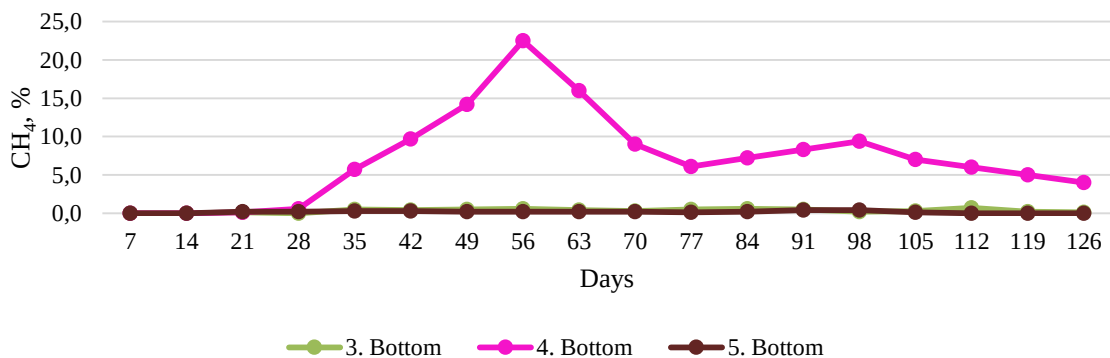


Fig. 3.12. CH₄ composition in landfill columns bottom

The aerated landfill models probably were producing less gas because the total volume of leachate recirculated at the time of this analysis was different.

3.3 Concentration of oxygen and hydrogen sulfide

Oxygen concentrations were measured in all landfill models surface, but in 3rd, 4th and 5th bottom measures were included. Oxygen injection in the landfills speeds up biodegradation process (Fig. 3.13).

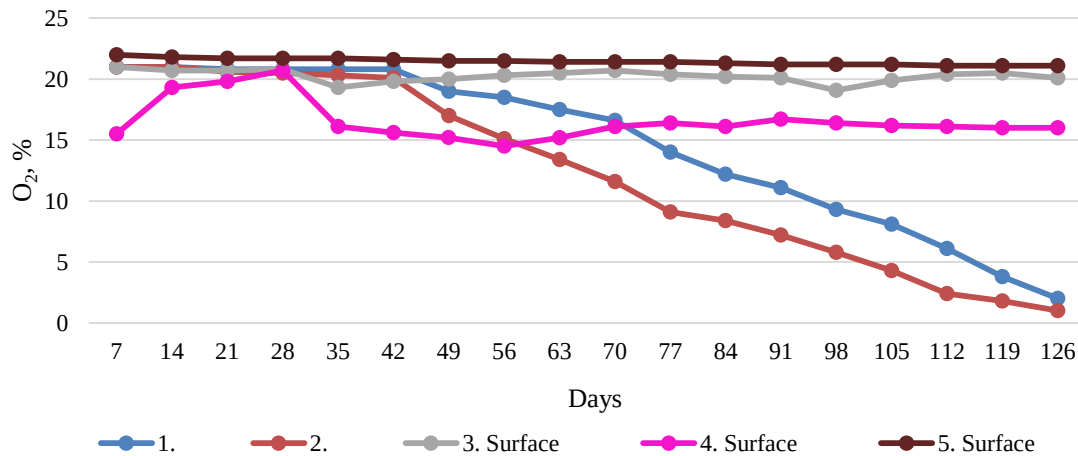


Fig. 3.13. O₂ composition in landfill columns surface

1) Pre-treated waste anaerobic landfill; 2) Pre-treated anaerobic waste landfill with flushing; Pre-treated waste aerobic landfill 100 l/h; 4) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week; 5) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week and high flushing

Third landfill column's surface measures showed that here was around 20 % of oxygen, during all experimental period. High concentration might be found because of constant air input near the surface. In this case, bottom measurements shows really amount of oxygen inside municipal solid waste layers. In general, it started from 0 % of concentration, which means that until day 28 oxygen was used by column's waste microorganisms and later it became stable (around 21 %).

Forth landfill column's surface oxygen on day 42 was low (9 %) because of higher methane concentrations. After this decrease oxygen amount was stable – around 16 % of volume. Oxygen and methane concentrations were stable together in 4th landfill column's surface. Although, only first week showed oxygen parameters in column's bottom (Fig. 3.14).

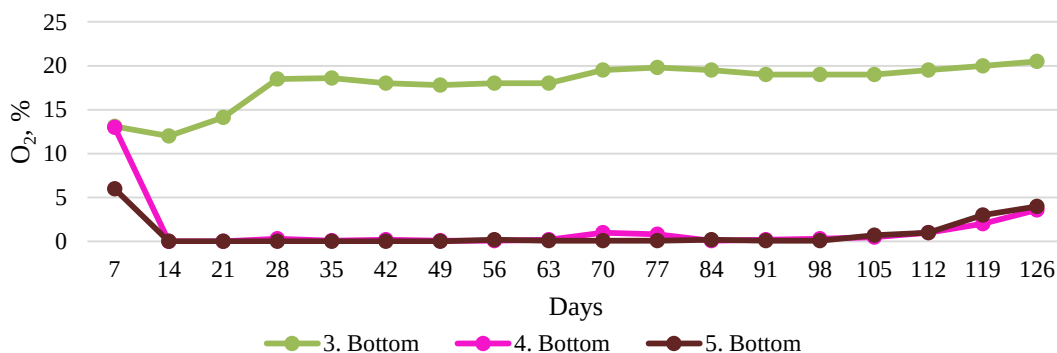


Fig. 3.14. O₂ composition in landfill columns bottom

Later it stayed close to zero and increased only at the end of the experiment. Reproducibility of these measurements are seen in 5th column's bottom values. However, surface oxygen was much lower. It may be effected by methane and carbon dioxide evaporation.

Hydrogen sulphide is one of the main odour contaminants, known for evaporation from the landfills. Figure 3.15 shows the results of anaerobic 1st and 2nd landfills H₂S contamination to the atmosphere. Sulfur is a component in waste that indicates odour

pollution. It is important to mention that biocover has an important value for stopping odour particles from evaporation to the environment.

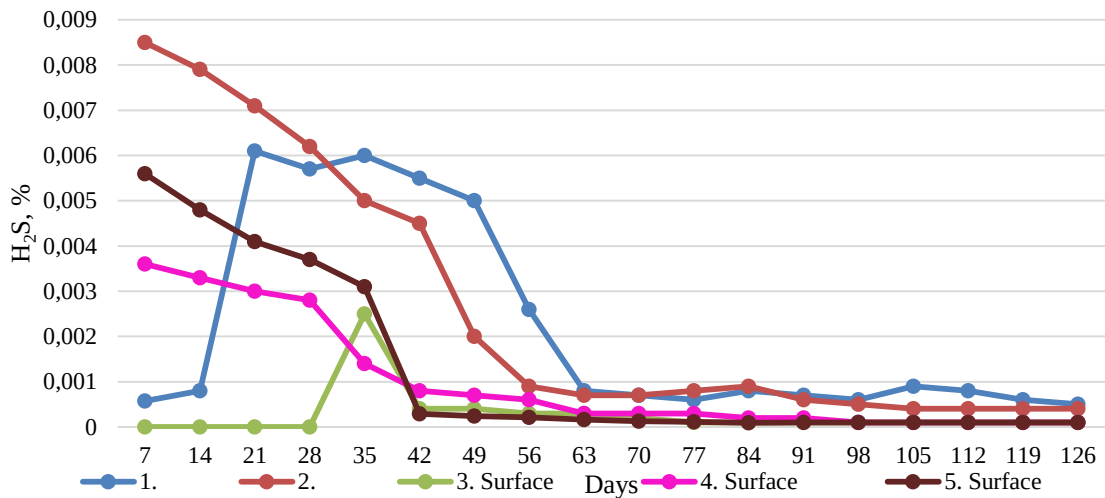


Fig. 3.15. H₂S composition in landfill columns surface

1) Pre-treated waste anaerobic landfill; 2) Pre-treated anaerobic waste landfill with flushing; 3) Pre-treated waste aerobic landfill 100 l/h; 4) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week; 5) Pre-treated waste aerobic landfill with low air inflow 50 l/ 4h/day/5 days per week and high flushing

Over time, in all experimental landfill's hydrogen sulphide concentration decreased during the time. At 1st landfill odour began to evaporate only after two weeks and the volume increased to 0,006 % from 0,00057 %. The reason of this change is smaller amount of recirculated leachate. H₂S measurements became stable at day 63. Second landfill showed similar results, but the biggest difference is seen at the beginning of experimental time – larger amount of leachate increased hydrogen sulphide concentration suddenly.

Figure 3.16 shows H₂S concentration in landfill columns bottom. The moment, when concentration reached the highest value is at day 35 (0,0025 % in surface and 0,0015 % in bottom). Besides this growth, the average of concentration would be close to 0 %. However, 3rd landfill is stable from this point of view and has the lowest level to the odour pollution from all.

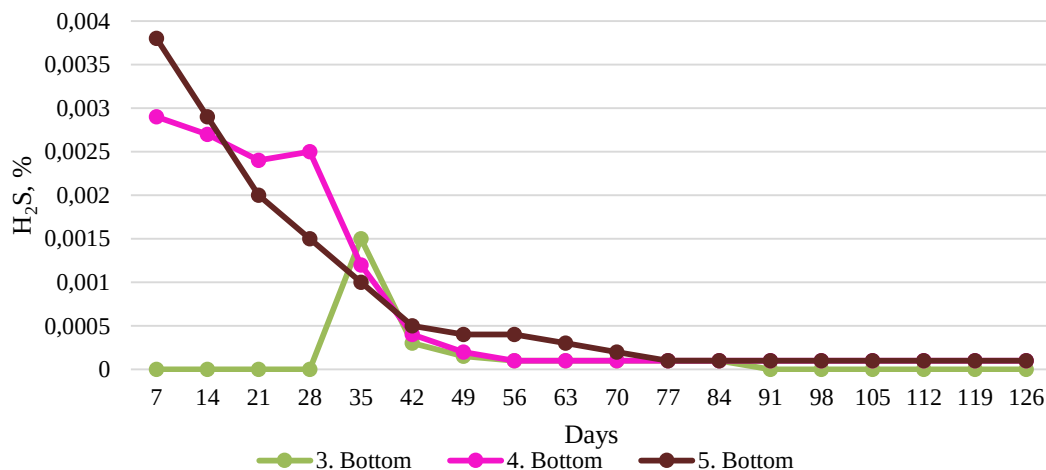


Fig. 3.16. H₂S composition in landfill columns bottom

4th landfill column evaporated odor to day 63 and until then its highest value was 0,0035 % on the surface. After that H₂S concentration became stable and was close to 0 %.

5th landfill evaporated 0,0056% and 0,0038 % of hydrogen sulphide and it became stable and lower at day 42 (0,00029 %). The total decrease was lower because of larger amount of leachate and probiotics. In general, N₂ emissions were not measured, but according to the literature it might consist large quantitative part in aerated landfill models (in some cases up to 80 %).

pH measurements

First landfill column's pH value had changes almost every week. The lowest pH was measured in day 28 and 35 (Fig. 3.10). It decreased to 6,4 pH value. Highest known value was 6,9, which is optimal for anaerobic conditions.

Second landfill column's pH had the largest decrease comparing with other four landfills – it had 5,9. It is close to a critical zone, where microorganisms can die because of not suitable medium. Leachate amount might effected the value. The highest pH value in 2nd landfill was 6,7. It is the lowest value comparing with other landfills highest values.

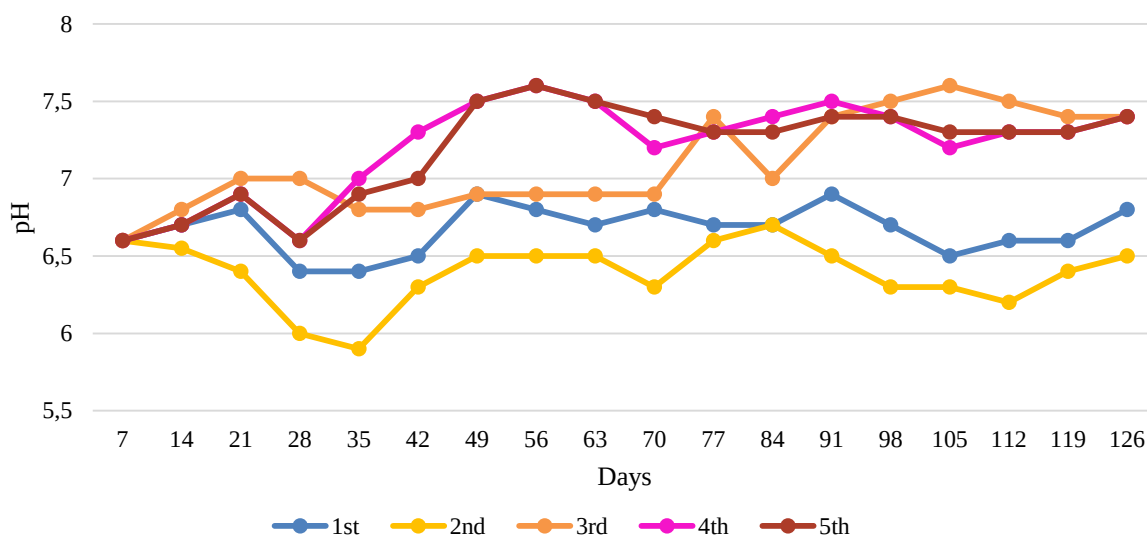


Fig. 3.17. pH value in five landfill columns

Third landfill reached 7,6 pH value, which was close for not suitable medium for microorganisms. The lowest value was at the beginning – it was 6,6 pH.

4th landfill column reached highest value at day 56 (7,6). Its value during all the experimental time was appropriate for microorganisms to develop. 5th landfill during 63 days reached 7,6 pH value and then decreased to 7,3 and left more or less stable.

3.4 Third chapter's Conclusions

1. First and second landfill models can be used for biogas production, not for sustainable landfill approach;
2. The anaerobic process strongly depends on the pH. Hydrolysis of the fermentation takes place in an acid environment at pH 5 ÷ 7,1 and 2 landfill models complies with the required values because it is ranging 5,8 and 6,7 pH;

3. Aerobic process needs to stay between 6 -8 pH values. During the experiment, three anaerobic landfill models stayed in a pH range between – 6,6 to 7,6 pH. For pH modification no additional changes was necessary;
4. First landfill model reached the highest amount of carbon dioxide (39%). Third landfill model had the lowest level (10%), because of instant aeration. After day 91, all amount values decreased;
5. First and second anaerobic landfill models emitted the large amount of methane (60 %). The lowest amount of methane was emitted from 5th (0,4 %) and 3rd (0,6 %);
6. Oxygen amount in anaerobic landfill models was decreasing, in 3rd stable;
7. H₂S emission amount was low during all experimental time (0-0,0085 %);
8. 3 model with intensive aeration and 5th model with normal aeration and leachate flushing have reduced impact for the environment;
9. 3rd and 5th landfill models are selected for further economical evaluation towards a sustainable model suggestion and recommendations.

4. MATHEMATICAL MODELLING OF TWO LANDFILL MODELS

4.1 Mathematical modelling results

Greenhouse gas emissions from 1st and 2nd anaerobic landfill models were mathematically modeled with basic landfill modeling program -the LandGEM. In general it helps to get results of methane and carbon dioxide evaporation from municipal solid waste landfills, but it did not help to indicate other three aerated landfill models. Non methane organic compositions were not evaluated in this thesis as well. Used user inputs for 1st landfill model is showed in Fig. 4.1.

INPUT REVIEW

Landfill Name or Identifier: 1st landfill model

LANDFILL CHARACTERISTICS

Landfill Open Year: 2017

Landfill Closure Year (with 80-year limit): 2037

Actual Closure Year (without limit): 2037

Have Model Calculate Closure Year?: No

Waste Design Capacity: megagrams

MODEL PARAMETERS

Methane Generation Rate, k: 0,063 year⁻¹

Potential Methane Generation Capacity, L₀: 120 m³/Mg

NMOC Concentration: 600 ppmv as hexane

Methane Content: 37 % by volume

GASES / POLLUTANTS SELECTED

Gas / Pollutant #1: Methane

Gas / Pollutant #2: Carbon dioxide

METHANE

Landfill Name or Identifier: 1st landfill model

First-Order Decomposition Rate Equation: $Q_{CH_4} = \sum_{i=1}^n \sum_{j=0.1}^1 k L_0 \left(\frac{M_i}{10} \right) e^{-k t_{ij}}$

Where,

Q_{CH₄} = annual methane generation in the year of the calculation (m³/year)

i = 1-year time increment

n = (year of the calculation) - (initial year of waste acceptance)

j = 0.1-year time increment

k = methane generation rate (year⁻¹)

L₀ = potential methane generation capacity (m³/Mg)

When Model Calculates Closure Year...

Final Non-Zero Acceptance Entered = 200 200 megagrams in 2037

Waste Design Capacity = megagrams

Closure Year (with 80-year limit) = 2037

Actual Closure Year (without limit) = 2037

Model Waste Acceptance Limit = 80 years

4: ENTER WASTE ACCEPTANCE RATES

Input Units: Mg/year

Year	Input Units (Mg/year)	Calculated Unit (tonn/year)
2017	200 200	220 220
2018	200 200	220 220
2019	200 200	220 220
2020	200 200	220 220
2021	200 200	220 220
2022	200 200	220 220
2023	200 200	220 220
2024	200 200	220 220
2025	200 200	220 220
2026	200 200	220 220
2027	200 200	220 220
2028	200 200	220 220
2029	200 200	220 220
2030	200 200	220 220
2031	200 200	220 220
2032	200 200	220 220
2033	200 200	220 220
2034	200 200	220 220
2035	200 200	220 220
2036	200 200	220 220
2037	200 200	220 220

Model Parameters from User Inputs:

k = 0,063 year⁻¹

L₀ = 120 m³/Mg

Fig. 4.1. 1st landfill model's inputs to LandGEM mathematical modeling program

Got results were put to Excel sheet in order to get higher graph quality and to be able to compare 1st and 2nd landfill modeling results. After, 2nd landfill model parameters were entered to LandGEM program (Fig. 4.2.)

INPUT REVIEW

Landfill Name or Identifier: 2nd landfill model

LANDFILL CHARACTERISTICS

Landfill Open Year

2017

Landfill Closure Year (with 80-year limit)

2037

Actual Closure Year (without limit)

2037

Have Model Calculate Closure Year?

No

Waste Design Capacity

megagrams

MODEL PARAMETERS

Methane Generation Rate, k

0,040

year⁻¹

Potential Methane Generation Capacity, L_o

110

m³/Mg

NMOC Concentration

600

ppmv as hexane

Methane Content

39

% by volume

GASES / POLLUTANTS SELECTED

Gas / Pollutant #1: Methane

Gas / Pollutant #2: Carbon dioxide

4: ENTER WASTE ACCEPTANCE RATES

Input Units: Mg/year

Year	Input Units (Mg/year)	Calculated Units (short tons/year)
2017	200 200	220 220
2018	200 200	220 220
2019	200 200	220 220
2020	200 200	220 220
2021	200 200	220 220
2022	200 200	220 220
2023	200 200	220 220
2024	200 200	220 220
2025	200 200	220 220
2026	200 200	220 220
2027	200 200	220 220
2028	200 200	220 220
2029	200 200	220 220
2030	200 200	220 220
2031	200 200	220 220
2032	200 200	220 220
2033	200 200	220 220
2034	200 200	220 220
2035	200 200	220 220
2036	200 200	220 220
2037	200 200	220 220

METHANE

Landfill Name or Identifier: 2nd landfill model

First-Order Decomposition Rate Equation:

$$Q_{CH_4} = \sum_{i=1}^n \sum_{j=0.1}^1 k L_o \left(\frac{M_i}{10} \right) e^{-k t_{i,j}}$$

Where,

Q_{CH₄} = annual methane generation in the year of the calculation (m³/year)

i = 1-year time increment

n = (year of the calculation) - (initial year of waste acceptance)

j = 0.1-year time increment

k = methane generation rate (year⁻¹)

L_o = potential methane generation capacity (m³/Mg)

M_i = mass of waste accepted in the ith year (Mg)

t_{i,j} = age of the jth section of waste mass M_i accepted in the ith year (decimal years, e.g., 3.2 years)

Model Parameters from User Inputs:

k = 0,040 year⁻¹

L_o = 110 m³/Mg

When Model Calculates Closure Year...

Final Non-Zero Acceptance Entered = 200 200 megagrams in 2037

Waste Design Capacity = megagrams

Closure Year (with 80-year limit) = 2037

Actual Closure Year (without limit) = 2037

Model Waste Acceptance Limit = 80 years

Fig. 4.2. 2nd landfill model's inputs to LandGEM mathematical modeling program

Firstly, landfill models methane emissions were modeled in the Excel sheet (Fig. 4.3).

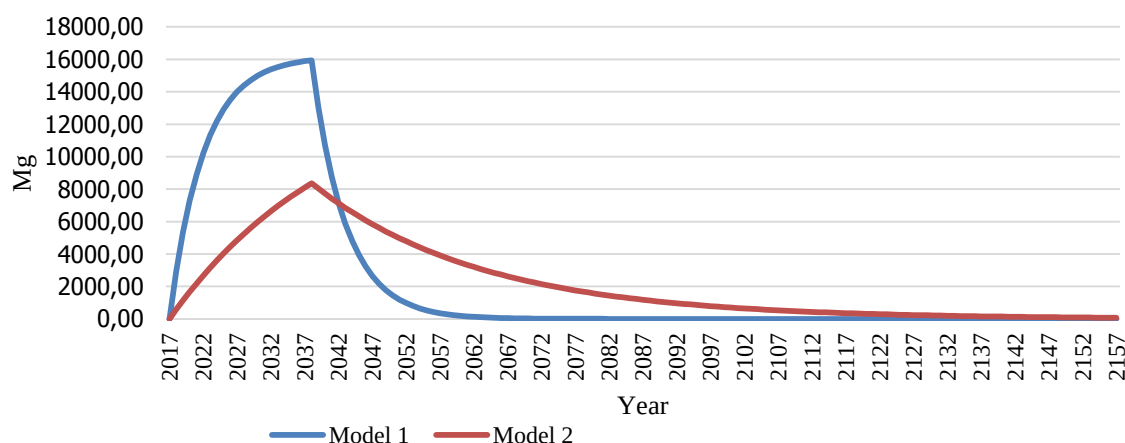


Fig. 4.3. CH₄ results in landfill models LandGEM mathematical modeling results

Mathematical calculations showed that it would take twenty five years for each of landfill model to reach the highest amount of methane. 1st landfill model's highest methane emissions amount (peak) is more than 16000,00 t/year. 2nd landfill model's mathematical calculations showed that the highest methane amount in all period in one year is about 8000,00 t/year. Figure 4.3. shows that methane emissions will have different trend. Although 1st landfill model would reach higher yearly amounts of methane, it would still have a benefit of reducing emissions amount to minimum in a quicker period of time – in 45 years, when 2nd landfill would reach minimum only after 110 years.

1st and 2nd landfill model's mathematical calculations shows that the carbon dioxide amounts will have evaporation trend in almost all landfill lifetime period (Fig. 4.4).

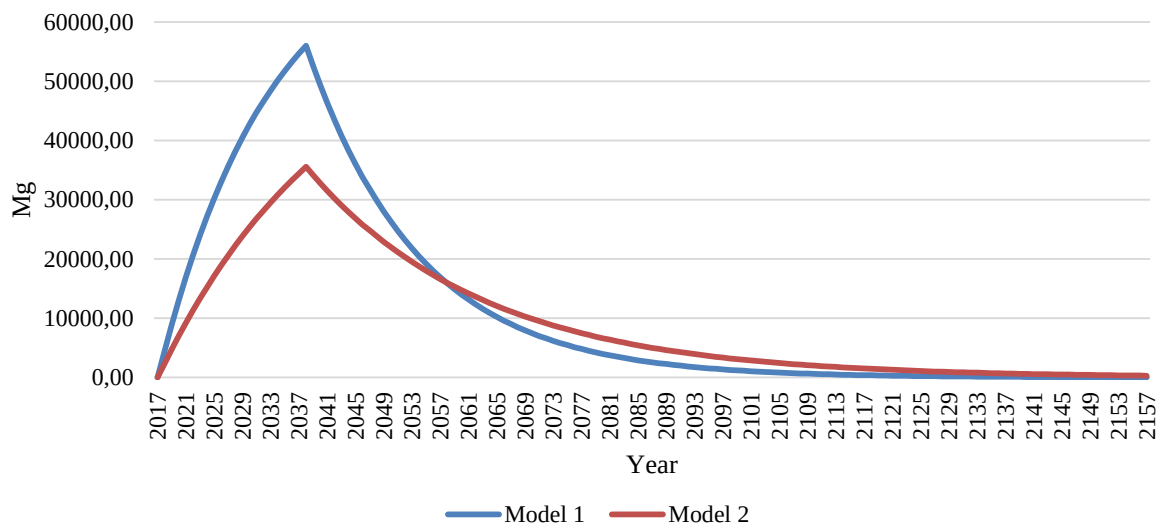


Fig. 4.4. CO₂ results in landfill models LandGEM mathematical modeling results

Although, both landfills will reach its highest peak at year 2040. 1st landfill model's carbon dioxide emissions will reach 56040,35 Mg/year and 2nd landfill model 35557,81 Mg/year (37 % less than 1st landfill model). Graphic shows that after 40 years of 1st landfill life time CO₂ emissions would equalize and gradually decrease.

Total cumulative amount of methane and carbon dioxide emissions in 157 years from traditional anaerobic 1st and 2nd landfill models are showed in figure 4.5 and figure 4.6. According to LandGEM calculations, first with second anaerobic landfill model would emit between $30 \cdot 10^4$ - $34 \cdot 10^4$ t of methane.

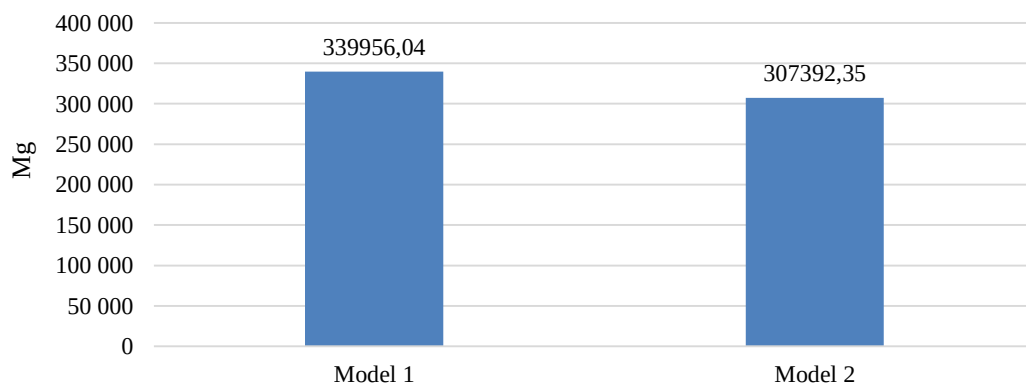


Fig. 4.5. Cumulative total methane emissions from five landfill models in 157 years

1st landfill model, according to LandGEM program, would emit 9,6 % less methane than 2nd landfill model during 157 years of landfill lifetime.

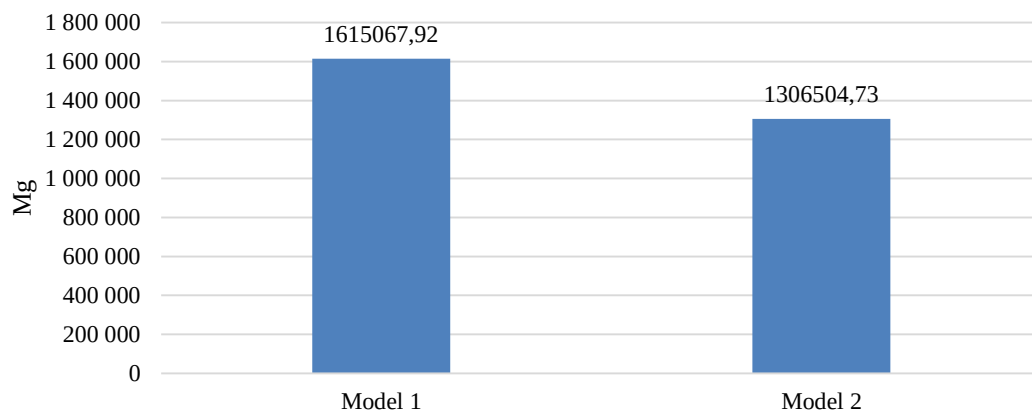


Fig. 4.6. Cumulative total carbon dioxide emissions from five landfill models in 157 years

Figure 4.6. shows that anaerobic conditions in 1st and 2nd landfill model would carbon dioxide to minimum level. Second landfill model would emit 19,1 % less carbon dioxide emissions in 157 years than the 1st landfill model.

4.2 Forth chapter's results

1. LandGEM program helped to model only two anaerobic landfill models and to get a prognosis of methane and carbon dioxide generation amounts from real size landfill;
2. First landfill model results showed that in total it would emit the largest amount of methane emissions ($33 \cdot 10^4$ t) and almost the lowest amount ($16 \cdot 10^5$ t) of carbon dioxide from all five landfill models;
3. Second landfill model in total would emit smaller methane ($30 \cdot 10^4$ t) amount than the 1st landfill model and the lowest amount of carbon dioxide ($13 \cdot 10^5$ t) emissions amount from all landfill models;
4. Very low composition amounts of methane do not insure proper calculations of 3rd, 4th and 5th landfill models by program LandGEM, because this program was created for traditional landfills without aeration modeling. For this reason, it is recommended to create new modeling program for sustainable landfills.

5. ECONOMIC EVALUATION

5.1 4th landfill model's economic evaluation

4th landfill model is a model that provides high quality engineering solutions for leachate, air, water and gas management systems. In order to evaluate landfill financial efficiency, it is important to indicate landfill parameter (Table 5.1) needs and its operational costs (Table 5.2).

In general, 10 years of landfill operational cost will be estimated, because this period in the most sensitive from environmental view and it is a period of active waste acceptance to the landfill. In this period of time, engineering solutions can reduce environmental impact in real size landfill and this period has the main difference in comparison of traditional landfill operational cost.

Table 5.1. Landfill parameters (Berge et al. 2009; Beaven et al. 2014)

Parameter	Value
Waste acceptance	550 t/day; 846 m ³ /day
Volume	1,8 · 10 ⁶ m ³
Density	650 kg/m ³
Landfill area	8 ha
LandGEM k value for 4 rd landfill	0,15

All parameters were collected from theoretical research articles (Table 5.2), which sustainable landfill cost calculations. It was estimated, that aeration cost will conclude coefficient of 0,6 , because 4th landfill model is semi-aerated model, which means that it will be aerated more than a half time of the landfill operation period (10 years). It was assumed that leachate recirculation does not require additional treatment and only non-recirculated leachate required treatment. It was also assumed that only 40 % of leachate will be recirculated and the other part will be treated separately.

Table 5.2. Landfill operation costs (Berge et al. 2009; Beaven et al. 2014)

Parameter	Amount	Value
Combined cost for leachate recirculation and treatment	0,88	EUR/L
Leachate generation	4	m ³ /t of waste
Recirculated leachate proportion	40	%
Leachate recirculation period	10	Years
Cost of on-site leachate treatment	0,002	EUR/L
Cost of in situ aeration	3	EUR/ m ³ of waste
Aeration period	6	Years
Tipping fee	55,0	EUR/t of waste

All values were calculated by proportion principle (Table 5.3), so it would easier to evaluate exact costs for 4th landfill model in a real state. Using this kind of table is easier to find a connection between used values.

In landfill with such parameters, leachate recirculation method saves leachate treatment cost (about 48 048 000,00 EUR), because it is not needed to treat 40 % of leachate that is being recirculated. Total price for leachate recirculation would reach 72 072 000,00 EUR. On

the other hand, aeration process might cost around 5 542 992,00 EUR. Total expenses amount for this type of landfill operation would reach 41,2 EUR/t in a ten years – the most important landfill operational period for sustainable landfill approach.

Table 5.3. Landfill lifetime costs

Landfill treatment and costs	Proportional calculations
Volume of waste accepted to the landfill	846 m ³ – 1 day 307 944 m ³ - 1 year 1 847 664 m ³ -6 years 3 079 440 m ³ - 10 years
Amount of waste accepted to the landfill	550 t -1 day 200 200 t – 1 year 600 600 t – 3 years 1 201 200 t – 6 years 2 002 000 t - 10 years
Aeration price for 10 years duration, when aeration coefficient is 0,6	1 m ³ of waste – 3,00 EUR 3 079 440 m ³ waste – 9 238 320,00 EUR $9\,238\,320,00 \cdot 0,6 = \mathbf{5\,542\,992,00\,EUR}$
Leachate generation amount in 10 years	1 t of waste– 3 m ³ of leachate 2 002 000 t – <u>6 006 000 m³</u>
Leachate recirculation proportion for 10 years	6 006 000 m ³ – 100 % <u>2 402 400 m³</u> - 40 % 3 603 600 m ³ - 60 %
Cost for installation, operation and maintenance of leachate recirculation infrastructure	2,00 EUR - 1 m ³ of leachate <u>4 804 800,00 EUR</u> – 2 402 400 m ³ ; 1 m ³ /leachate – 1500 L/leachate 2 402 400 m ³ /leachate - <u>3 603 600 000 L/leachate</u>
Price for leachate treatment on site (60 %)	0,02 EUR – 1 L of leachate treatment <u>72 072 000,00 EUR</u> - 3 603 600 000 L

Proportion of general investment to sustainable landfill are showed in Figure 5.1.

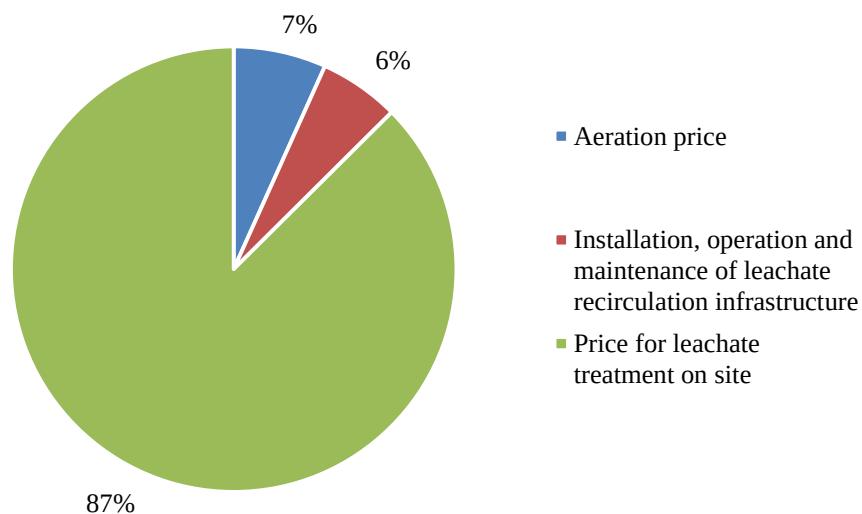


Fig. 5.1. Investment to sustainable landfill

On the other hand, it is important to evaluate economic benefits of sustainable landfill engineering solutions in comparison to costs of a traditional sanitary landfill. Traditional landfills have high costs experienced by municipal governmental authority, not landfill operator itself. Looking from a historical view, this type of landfilling was assumed as the cheapest solution, but in nowadays, governments and European Union is looking for sustainable development opportunities that would include not only economic, but also environmental (reduction of leachate, gas emissions, odour, ect.) and social benefits. This happens because talking about society goods, traditional landfill create disease dispersion around disposal site and as it so increase local health care expenses who have to be covered by governmental budget or health care insurance. Traditional landfill creates a negative approach for real estate in a local area, because society with knowledge are opposed to live near polluted places.

Also one of the biggest cost benefit for the government is that a sustainable landfill would create additional green work places which would increase local municipality's economic growth. Such landfill's as in New York State worker as itself becomes a worker of a green thinking workplace - sustainable landfill. In this way he represent his work place as green due to less harmful working environment (Beyond waste 2010). For example, waste acceptance taxes can be affected and grow up with relation of reduced environmental impacts (Municipal solid...2014). In this case, political decisions can increase landfill profit for accepting waste and use this money for a better landfill treatment (Santucci 2014). If the average gate fee of waste acceptance to a traditional landfill with leachate treatment and right construction is 47,00 EUR/t (Dél komunalinių atliekų...2014), then 4th type of model could require to increase this price to 55,00 EUR/ t (Sustainable Queensland 2015) of waste. The price was selected by evaluating that landfill capacity is large – more than 100 000 t per annum (200 200 t/annum). As it so, this landfill would get 13,8 Eur/t and as it so 27 627 600 EUR profit in a ten years period of active waste acceptance to the landfill. This profit in total would not cover other project construction and maintenance costs so sustainable landfill is not a project with an economical payback approach.

Recommendations

The main economic benefit of 4th type of landfill model application is that it can come with rebates. It could be a governmental authority payment for landfill operator for saving society from aspects like greenhouse gas emissions, leachate. The rebates can be payments for such aspects like increased amount of leachate recirculation, for every tone of methane or carbon dioxide reduction or collection, every measurement made for indicating environmental aspects of a landfill or every year reduced for a landfill's lifetime period. Recommendations are to divide rebate payments into time periods in a proportion of - shorter landfill age vs achieved environmental aspects. Shorter landfill lifetime would let to accelerate new landfill building works and this aspect would be included to landfill construction costs, which were not included in this thesis landfill economic evaluation. It could be set by government and adjust by main authorities who have evaluated theoretical and practical knowledge of mentioned landfill operations. It would be financially attractive for operators to implement sustainable landfill approach and would encourage engineering improvements of technologies such as recirculation, in situ aeration, and accelerated flushing. Stegmann et al. (2011) reported a whole site generation rate of 25 m³CH₄/hour as a criterion below which sites might be classed as entering a passive management phase where the rebate would stop to be applied. Consequently, landfill aeration may be one of the cheapest available GHG avoidance technologies. Rebate tax recommendations (Table 5.4) were suggested by Beaven et al. (2014) and could be adjusted for countries with higher economic income. Higher economic income is needed in order to succeed full sustainable landfill concept and to prepare successful operation recommendations.

Table 5.4. Suggested rebates for landfill operations (Beaven et al. 2014)

Rebate type	Cost
Cost of rebate at proposed level per tonne of MSW	30 EUR/tonne MSW
Cost of in situ aeration, per tonne of carbon released	120- 718 EUR/tonne C
Proposed rebate, allowing for uncertainties in performance etc.	500 EUR/tonne C

The easiest application of the operational system would be to new landfills. There is also an option that 4th type of landfill model could be applied to old landfills. This could include recently closed sites that have made financial provisions. It is also recommended to apply this type of landfills for countries that have high GDP (gross domestic product) value. Funding this type of project would help to introduce the proof that landfill aeration may be one of the cheapest carbon and methane abatement technologies.

5.2 Fifth chapter's conclusions

1. Total expenses amount for 4th type of landfill model application including aeration and leachate recirculation and treatment would reach 82 419 722,00 EUR in a ten years;
2. Landfill would get 27 627 600 EUR profit in a ten years period of active waste acceptance to the landfill;
3. Construction expenses were not evaluated;
4. The main economic benefit of 4th type of landfill model application is that it can come with rebates. Such investment can be adjust for new landfills. Old landfills are not an exception if country is strong economically;
5. The recommendation would be to prepare legislations and directives for sustainable landfill development and to provide parameter and technology suggestions for such landfill modeling and operational care.

CONCLUSIONS

1. Municipal solid waste amounts are growing up all around the world. For this reason, Europe has set Waste Landfill Directive, Waste Framework Directive and European Seventh Action Programme. The aim is to reduce organic waste disposal in landfills which emit greenhouse gases and causes global warming. Developing country such as Lithuania disposes 58 % municipal biodegradable waste into landfills. Lithuania has to be more strict on its municipal solid waste treatment strategy.

2. First and second landfill models can be used for biogas production, not for sustainable landfill approach. The anaerobic process strongly depends on the pH. Hydrolysis of the fermentation takes place in an acid environment at pH $5 \div 7,1$ and 2 landfill models complies with the required values because it is ranging 5,8 and 6,7 pH. Aerobic process needs to stay between 6 -8 pH values. During the experiment, three anaerobic landfill models stayed in a pH range between – 6,6 to 7,6 pH. For pH modification no additional changes was necessary;

3. First landfill model reached the highest amount of carbon dioxide (39%). Third landfill model had the lowest level (10%), because of instant aeration. After day 91, all amount values decreased. First and second anaerobic landfill models emitted the largest amount of methane (60 %). The lowest amount of methane was emitted from 5th (0,4 %) and 3rd (0,6 %). Oxygen amount in anaerobic landfill models was decreasing, in 3rd stable. H₂S emission amount was low during all experimental time (0-0,0085 %). 3th model with intensive aeration and 5th model with normal aeration and leachate flushing have reduced impact for the environment;

4. Two anaerobic full-scale landfill models LandGem modeling showed that real size 2nd traditional landfill model would emit the lowest amounts of carbon dioxide and methane than the 1st landfill model.

5. 4th landfill model was selected for further economical evaluation towards a sustainable model suggestion and recommendations, because it is a model that provides high quality engineering solutions for leachate, air, water and gas management systems.

6. It was estimated, that 4th type of landfill model application including aeration and leachate recirculation and treatment would reach 82 419 722,00 EUR in a ten years period. Landfill would get 27 627 600,00 EUR profit in a ten years period of active waste acceptance to the landfill. The main economic benefit of 4th type of landfill model application is that it can come with rebates.

RECOMMENDATIONS

1. Sustainable landfill is considered as the best alternative for developed countries firstly. Developing countries should overview an opportunity for old landfill remediation, in order to control the landfilling process;
2. European countries have already overviewed and planed the sustainable landfill and waste minimization concept but the implementation of it is still weak. Afterwards it would help to succeed environmental, social and economic benefits;
3. European Union needs to increase research interests into sustainable landfill development and research on greenhouse gas emissions from municipal solid waste landfills evaluation on laboratory scale.
4. Such investment for sustainable landfill model application including aeration and leachate recirculation and treatment can be adjust for new landfills. Old landfills are not an exception if the country is strong economically;
5. Very low composition amounts of methane do not insure proper calculations of program LandGEM, because this program was created for traditional landfills (without aeration) modeling. It is recommended to create new modeling program for sustainable landfills, which would indicate results with low methane amounts or would have user inputs for compositions of more possible gas types.
6. The recommendation would be to prepare legislations and directives for sustainable landfill development and to provide parameter and technology suggestions for such landfill modeling and operational care.

REFERENCES

- 7th EAP priority objectives, 2015. Available on the internet: <http://ec.europa.eu/environment/action-programme/objectives.htm>.
- Batarseh, E.S., Reinhart, D.R. & Berge, N.D., 2010. Sustainable disposal of municipal solid waste: Post bioreactor landfill polishing. *Waste Management*, 30(11), pp.2170–2176. Available at: <http://dx.doi.org/10.1016/j.wasman.2010.06.015>.
- Beaven, R. P., Knox, K., Gronow, J.R., Hjelm, O., Greedy, D., Scharff, H., 2014, A new economic instrument for financing accelerated landfill aftercare, p. 20.
- Bentley, E. & a, J.B., 2007. Improving Landfill Methane Recovery - Recent Evaluations and Results of Large Scale Tests, p.22.
- Berge, N.D., Reinhart, D.R. & Batarseh, E.S., 2009. An assessment of bioreactor landfill costs and benefits. *Waste Management*, 29(5), pp.1558–1567. Available at: <http://dx.doi.org/10.1016/j.wasman.2008.12.010>.
- Beyond waste, A sustainable materials management strategy for New York State, 2010. Available at: http://www.dec.ny.gov/docs/materials_minerals_pdf/frptbeyondwaste.pdf.
- Biodegra TIPK papildymas, 2015. pp. 6.
- Bo-feng, C.A.I. et al., 2014. Estimation of Methane Emissions from Municipal Solid Waste Landfills in China Based on Point Emission Sources, pp.81–91.
- Chen, Y. & Wu, W., 2015. Constructing an effective prevention mechanism for MSW lifecycle using failure mode and effects analysis. *Waste Management*, 46, pp.646–652.
- Cossu, R. et al., 2015. Biogas production enhancement using semi-aerobic pre-aeration in a hybrid bioreactor landfill. *Waste management*. Available at: <http://dx.doi.org/10.1016/j.wasman.2015.10.025>.
- "Dėl komunalinių atliekų tvarkymo tarifų ir įkainių patvirtinimo" pakeitimo ir taikos sutarties projekto tvirtinimo, 2014 m. Available on the internet: <https://www.vilnius.lt/vaktai2011/Defaultlite.aspx?Id=3&DocId=30237372>.
- Du, Y. et al., 2014. Role of iron in H₂S emission behavior during the decomposition of biodegradable substrates in landfill. *Journal of Hazardous Materials*, 272, pp.36–41. Available at: <http://dx.doi.org/10.1016/j.jhazmat.2014.02.040>.
- EC, Living well within the limits of our planet, 2012. Available from the internet <http://ec.europa.eu/environment/pubs/pdf/factsheets/7eap/en.pdf>.
- Erses, A. S., Onay, T. T., Yenigun, O. 2008. Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. *Journal of Bioresource Technology*. 9. vol. 99. pp. 5418-5426.
- Eurelco, Landfills in Europe, 2015. Available on the internet: <http://www.eurelco.org/news/new-data-launched-landfill-situation-eu-28>.
- European Commission, Being wise with waste: the EU's approach to waste management, 2010 <http://ec.europa.eu/environment/waste/pdf/WASTE%20BROCHURE.pdf>.

- European Commission, 2014, Biodegradable waste. Available on the internet: <http://ec.europa.eu/environment/waste/compost/index.htm>.
- European Commission, 2008. Available on the internet: http://ec.europa.eu/environment/waste/framework/pdf/guidance_doc.pdf.
- Fei, X., et al. Quantification of parameters influencing methane generation due to biodegradation of municipal solid waste in landfills and laboratory experiments. *Waste Management* (2015), <http://dx.doi.org/10.1016/j.wasman.2015.10.015>
- Feng, S. & Zheng, Q., 2015. Computers and Geotechnics A two-dimensional gas flow model for layered municipal solid waste landfills. *Computers and geotechnics*, 63, pp.135–145. Available at: <http://dx.doi.org/10.1016/j.compgeo.2014.09.004>.
- Friedrich, E. & Trois, C., 2013. GHG emission factors developed for the collection , transport and landfilling of municipal waste in South African municipalities. *Waste Management*, 33(4), pp.1013–1026. Available at: <http://dx.doi.org/10.1016/j.wasman.2012.12.011>.
- GDP per capita, consumption per capita and price level indices, 2015. Available on the internet:http://ec.europa.eu/eurostat/statistics-explained/index.php/GDP_per_capita_consumption_per_capita_and_price_level_indices.
- Gentil, E.C., Gallo, D. & Christensen, T.H., 2011. Environmental evaluation of municipal waste prevention. *Waste Management*, 31(12), pp.2371–2379.
- Guerrero, L.A., Maas, G. & Hogland, W., 2013. Solid waste management challenges for cities in developing countries. *Waste Management*, 33(1), pp.220–232. Available at: <http://dx.doi.org/10.1016/j.wasman.2012.09.008>.
- He, R. et al., 2012. Evaluation of methane oxidation activity in waste biocover soil during landfill stabilization. *Chemosphere*, 89(6), pp.672–679. Available at: <http://dx.doi.org/10.1016/j.chemosphere.2012.06.008>.
- Heyer, K.U., Hupe, K. & Stegmann, R., 2013. Methane emissions from MBT landfills. *Waste Management*, 33(9), pp.1853–1860. Available at: <http://dx.doi.org/10.1016/j.wasman.2013.05.012>.
- Hickory Ridge Landfill solar energy cover. 2012. Available at: <http://www.hdrinc.com/portfolio/hickory-ridge-landfill-solar-energy-cover>.
- Hooge Maey – redeveloping a landfill site. 2012. Available at: <http://fca.be/en/article/hoogemaey-%E2%80%93-redeveloping-landfill-site>.
- Hudgins, M., Law, J., Ross, D., Su, J., 2010. The Sustainable Landfill becomes a reality. Available from the internet: <http://www.waste-management-world.com/articles/print/volume-11/issue-3/Features/the-sustainable-landfill-becomes-a-reality.html>.
- Jeong, S. et al., 2015. Field assessment of semi-aerobic condition and the methane correction factor for the semi-aerobic landfills provided by IPCC guidelines. *Waste Management*, 36, pp.197–203. Available at: <http://dx.doi.org/10.1016/j.wasman.2014.10.020>.
- Kumar, A. & Sharma, M.P., 2014. Estimation of GHG emission and energy recovery potential from MSW landfill sites. *Sustainable Energy Technologies and Assessments*, 5, pp.50–61. Available at: <http://dx.doi.org/10.1016/j.seta.2013.11.004>.

- Landfills continue to rule despite EU recycling target. 05 Mar 2013 Available on the internet: <http://www.euractiv.com/sustainability/landfills-continue-rule-despite-news-518229>.
- Landfilling, Fact sheets, 2015, 4p. Available on the internet: http://en.european-bioplastics.org/wp-content/uploads/2011/04/fs/Landfill_FactSheet.pdf.
- Lithuania's national inventory report, 2014, Vilnius, pp. 513. Available from: <http://klimatas.gamta.lt/files/NIR%20%202014.pdf>.
- Lombardi, L., Carnevale, E. & Corti, A., 2006. Greenhouse effect reduction and energy recovery from waste landfill. *Energy*, 31, pp.3208–3219.
- M. A. Memon, Integrated Solid Waste Management Based on the 3R Approach In: Sustainable Solid Waste Management, S.A.Unnisa, S.Bhupatthi Rav (eds.), Apple Academic Press, 2012.
- Managing municipal solid waste – a review of achievements in 32 European countries, *EEA report*, 2013. 40 p. Available on the internet: <http://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=tsdpc240&language=en>.
- Marshall, R.E. & Farahbakhsh, K., 2013. Systems approaches to integrated solid waste management in developing countries. *Waste Management*, 33(4), pp.988–1003. Available at: <http://dx.doi.org/10.1016/j.wasman.2012.12.023>.
- Meima, J. a., Naranjo, N.M. & Haarstrick, a., 2008. Sensitivity analysis and literature review of parameters controlling local biodegradation processes in municipal solid waste landfills. *Waste Management*, 28, pp.904–918.
- Moreno, a. I. et al., 2014. Chemical characterization of emissions from a municipal solid waste treatment plant. *Waste Management*, 34(11), pp.2393–2399. Available at: <http://www.sciencedirect.com/science/article/pii/S0956053X14003109>.
- Morrissey, a. J. & Browne, J., 2004. Waste management models and their application to sustainable waste management. *Waste Management*, 24, pp.297–308.
- Municipal solid waste landfills, Economic impact analysis for the proposed new subpart to the new source performance standards, Office of Air and Radiation, U.S. Environmental Protection Agency, 2014. p. 62.
- New York's largest landfill will become a sustainable eco-park. 2013. Available at: <http://www.powerclouds.com/index.php/new-yorks-largest-landfill-will-become-a-sustainable-eco-park/>.
- Odor Away. 2015. Available from: < <http://www.scdprobiotics.com/SCD-Odor-Away-Slicks/343.htm> >.
- Office of Air Quality Planning and Standards, U.E.O. of A. and R., 1995. 2.4 Municipal Solid Waste Landfills. *Compilation of Air Pollutant Emission Factors: AP-42*, pp.1–19.
- Open Path Siting Criteria Proposal, 1999. Available from: <http://www.epa.gov/ttnamti1/files/ambient/longpath/fropenph.pdf>.
- Pratt, C. et al., 2013. CH₄/CO₂ ratios indicate highly efficient methane oxidation by a pumice landfill cover-soil. *Waste Management*, 33(2), pp.412–419. Available at: <http://dx.doi.org/10.1016/j.wasman.2012.10.020>.
- Raga, R. et al., 2015. Landfill aeration for emission control before and during landfill mining. *Waste Management*, 46, pp.420–429. Available at:

- <http://dx.doi.org/10.1016/j.wasman.2015.09.037>.
- Regioninių atliekų tvarkymo sistemų veikla, 2013, p. 44. Available on the internet: <https://www.vkontrole.lt/failas.aspx?id=3045>.
- Review of waste, 2014. Available from internet: http://ec.europa.eu/environment/waste/landfill_index.htm.
- Rigamonti, L., Sterpi, I. & Grosso, M., 2016. Integrated municipal waste management systems : An indicator to assess their environmental and economic sustainability, 60, pp.1–7.
- Rolph, D., Kirac, M. & Hublin, A., 2012. Cost-effectiveness of GHG emission reduction measures and energy recovery from municipal waste in Croatia. *Energy*, 48(1), pp.203–211. Available at: <http://dx.doi.org/10.1016/j.energy.2012.02.008>.
- Santucci, L., Puhl, I., Sinha A. H. M.M., Enayetullah, I., Agyemang-Bonsu, W. K., 2014, Valuing the sustainable development co-benefits of climate change mitigation actions, p. 39.
- Sri Shalini, S., Karthikeyan, O.P. & Joseph, K., 2010. Biological stability of municipal solid waste from simulated landfills under tropical environment. *Bioresource Technology*, 101(3), pp.845–852. Available at: <http://dx.doi.org/10.1016/j.biortech.2009.08.104>.
- Sustainable Queensland, What is air worth? Appropriately pricing landfills, 2015. [online]. [Cited November 20 2015]. Available at: <http://sustainablequeensland.info/what-is-air-worth-appropriately-pricing-landfills/>.
- Tascione, V., Mosca, R. & Raggi, A., 2016. Optimizing the environmental performance of integrated waste management scenarios by means of linear programming : a case study. *Journal of Cleaner Production*, 112, pp.3086–3096. Available at: <http://dx.doi.org/10.1016/j.jclepro.2015.10.016>.
- Team Acumen – Waste Management. 2014. [online]. [Cited February 20 2014]. Available from the internet: <http://www.thealternative.in/society/team-acumen-waste-management/>.
- Valstybinis atliekų tvarkymo planas. Available from: <https://www.e-tar.lt/portal/legalact.html?Documentid=d833b6d0cfa811e3a8ded1a0f5aff0a9>.
- Wilts, H. et al., 2013. Science of the Total Environment Eco-innovations for waste prevention — Best practices , drivers and barriers. , 462, pp.823–829.
- Wu, C. et al., 2014. Influence of aeration modes on leachate characteristic of landfills that adopt the aerobic – anaerobic landfill method. *Waste Management*, 34(1), pp.101–111. Available at: <http://dx.doi.org/10.1016/j.wasman.2013.10.015>.
- Yazdani, R., Imhoff, P., 2010. Biocovers at landfills for methane emissions reduction demonstration. pp. 77. Available at: <http://www.calrecycle.ca.gov/Publications/Documents/Organics%5C2011004.pdf>.
- Zhang, H. et al., 2011. Environmental and economic assessment of combined biostabilization and landfill for municipal solid waste. *Journal of Environmental Management*, 92(10), pp.2533–2538. Available at: <http://dx.doi.org/10.1016/j.jenvman.2011.05.018>.
- Zhang, Y., Yue, D., Liu, J., et al., 2012. Effect of organic compositions of aerobically pretreated municipal solid waste on non-methane organic compound emissions

during anaerobic degradation. *Waste Management*, 32(6), pp.1116–1121. Available at: <http://dx.doi.org/10.1016/j.wasman.2012.01.005>.

Zhang, Y., Yue, D. & Nie, Y., 2012. Greenhouse gas emissions from two-stage landfilling of municipal solid waste. *Atmospheric Environment*, 55, pp.139–143. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2012.03.056>.

Zorpas, A.A. & Lasaridi, K., 2013. Measuring waste prevention. *Waste Management*, 33(5), pp.1047–1056. Available at: <http://dx.doi.org/10.1016/j.wasman.2012.12.017>.

APPENDICES

Appendix 1

List of author's publications

1. Rasinskaitė, M., Vaiškūnaitė, R. 2016, Analysis and assessment of gas emissions from municipal solid waste landfill models. Proceedings of the 19th Conference for Junior Researchers „Science – Future of Lithuania” (paper in review).
2. Rasinskaitė, M., Dace, E., Vaiškūnaitė, R. 2016. Analysis and assessment of gas emissions from municipal solid waste landfill models. RTU “The Conference of Environmental and Climate Technologies CONECT 2016” (prepared for submission).

List of author's presentations in the local conferences

1. Rasinskaitė, M., Vaiškūnaitė, R. 2015, Municipal solid waste evaluation through sustainable development approach. 18th Conference of Lithuanian junior researchers Science - Future of Lithuania in 9 April 2015, at Vilnius Gediminas Technical University, Vilnius, Lithuania.

Copies of publications and contributions

1. Rasinskaitė, M., Vaiškūnaitė, R. 2015, Municipal solid waste evaluation through sustainable development approach. 18th Conference of Lithuanian junior researchers Science - Future of Lithuania in 9 April 2015, at Vilnius Gediminas Technical University, Vilnius, Lithuania.

Municipal solid waste evaluation through sustainable development approach

Rasa Vaiškūnaitė, Monika Rasinskaitė

Department of Environmental Protection, Faculty of Environmental Engineering, Vilnius Gediminas Technical University, Saulėtekio al. 11, Vilnius, Lithuania

E-mail: rasa.vaiskunaite@vgtu.lt, monika.rasinskaite@stud.vgtu.lt



INTRODUCTION

Unsorted or untreated municipal solid waste (MSW) landfills have an influence on forcing air quality rates down to low levels [1]. By the year 2025 European Union has an aim to phase out landfilling recyclable (glass, paper, plastics, metals and biodegradable waste) waste in municipal landfills to a maximum 25% landfilling rate [2]. For this reason in 2030 EU has the aim to increase MSW recycling and re-use to 70 %. Low income countries like Lithuania is not an exception. According to country's national greenhouse gas inventory report municipal solid waste landfill's surface nowadays mainly releases greenhouse gases like CH_4 and CO_2 [3]. Nevertheless, in such countries around 54 % of biodegradable waste are flowing into the landfill.

The research aim is to use landfill prototypes for finding better conditions for quicker waste degradation and reduce gas emissions. Different landfill waste compositions require its sustainability strategy. For this reason a goal is to suggest a modern landfill strategy, which would reduce greenhouse gas emissions, will stabilize its waste state and will shorter landfill aftercare time period.

METHODOLOGY

The research study is investigating the behaviour of the different prototypes available for sustainable landfill. The in situ treatment processes contains anaerobic, aerobic, semi-aerobic and flushing bioreactor technology. For the experiment mechanical biological pre-treated (MBP) municipal solid waste were taken from JSC "Biodegra" which is placed in Lithuania, Medzuku village. The company separates, mills and sieves organic municipal solid waste (paper, cardboard, wood, textile, food and green wastes) and packages.

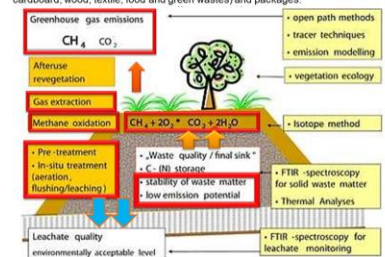


Fig. 1. Development of a sustainable landfill strategy [4]

Nowadays European Union Landfill directive require that all MSW disposed to the landfill would be pre-treated. In order to simulate laboratory landfills prototypes, statistically proved MSW composition proportions disposed in Lithuanian landfills were used. The evaluation mass were being composed from JSC "Biodegra" pre-treated waste (Table 1).

Table 1. Composition of used pre-treated organic MSW in 10 kg plexiglass columns [5]

Material	Paper/Cardboard	Wood waste	Textile waste	Food waste	Green waste	Total
For 1st filled with %	9,0	3,1	6,0	21,8	14,1	54,0

Measure	Plastic waste with packaging	Metal waste with packaging	Glass waste with packaging	Inert waste	Other non-haz. waste	Other MSW	Composite waste packaging	Total
kg	1,5	0,28	0,68	1,02	0,33	0,57	0,22	4,6

Rainfall is being simulated with distilled water, in order to feed the columns. The amount is calculated to simulate long term landfill behaviour of the liquid/solid (L/S) ratio. B and E columns were fed three times higher than the others, to reach L/S = 7,5. [6]

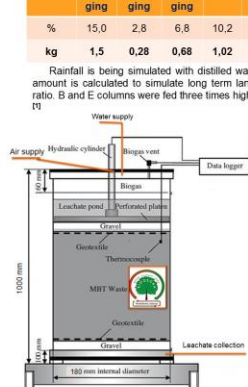


Fig. 2. Reactor scheme with an improvement adapted for the research [6]

Table 3. Landfill prototypes conditions

Material Column	Operating conditions	Landfill prototypes
A MBP	Anaerobic	Pre-treated waste landfill
B MBP	Anaerobic with high water input	Flushing bioreactor
C MBP	Aerobic with high air inflow	Aerated landfill
D MBP	Aerobic with low air inflow	Semi-aerobic landfill
E MBP	Aerobic with low air and high water input	Semi-aerobic and flushing landfill

The columns were equipped with three ports. One port was used for drainage and its sampling. Other two were used to collect gas samples and add liquid. C, D and E columns were equipped with an air compressor and air inflow meter. Aerated landfill prototype (C column) was fed with air continuously. All testing parameters are given in table 4.

Table 3. Landfill prototype conditions for the column testing

Column	Waste (kg)	Air inflow	Water flow (L/d)
A	±10,0	-	0,188
B	±10,0	-	0,563
C	±10,0	100 N/h, continuously	0,188
D	±10,0	50 N/h, 4h/d, 5 d/week	0,188
E	±10,0	50 N/h, 4h/d, 5 d/week	0,563

The columns are kept in 35 °C temperature to establish a favorable growth environment for the microorganisms in columns [7]. The research will take 120 days. After this time period, the columns will be emptied and residual waste samples will be analyzed for evaluation of biological stability. Total organic compounds will be measured for mass balance calculations. The research will result gas behaviour of MBT in sustainable landfill (Fig. 3).

The long term pollution potential remains from mechanical biological waste treatment to landfilling. The landfills prototypes will assess the risks and purpose an effective design, operation and aftercare duration.

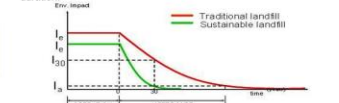


Fig. 3. Aftercare and environmental impact dependency between traditional and sustainable landfill strategies [8]

CONCLUSIONS

1. The columns will be filled with 5,4 kg of organic and 4,6 inorganic mechanical biological pre-treated (MBP) municipal solid waste taken from JSC "Biodegra".
2. Columns will be kept in 35 °C temperature for 120 days with the conditions of anaerobic, anaerobic with high water input, aerobic with high air inflow, aerobic with low air inflow and aerobic with low air and high water input.
3. One port will be used for drainage and its sampling gas, TOC. Other two will be used to collect gas samples (CH_4 , CO_2 , O_2) and add liquid (0,188 and 0,563 L/day).
4. Total organic compounds will be measured for mass balance calculations.

REFERENCES

- [1] Olyszko, A. S., Olyszko, T. T., Vengas, G. 2008. Comparison of waste and emission separation of municipal solid waste in domestic landfill. *Journal of Bioremediation Technology*, 3, vol. 30, pp. 2419-2420.
- [2] European Commission (EC). Biodegradable waste. Available from: <http://ec.europa.eu/environment/landfills/landfills.htm>
- [3] European Commission (EC). Biodegradable waste. Available from: <http://ec.europa.eu/environment/landfills/landfills.htm>
- [4] European Commission (EC). Biodegradable waste. Available from: <http://ec.europa.eu/environment/landfills/landfills.htm>
- [5] European Commission (EC). Biodegradable waste. Available from: <http://ec.europa.eu/environment/landfills/landfills.htm>
- [6] European Commission (EC). Biodegradable waste. Available from: <http://ec.europa.eu/environment/landfills/landfills.htm>
- [7] European Commission (EC). Biodegradable waste. Available from: <http://ec.europa.eu/environment/landfills/landfills.htm>
- [8] European Commission (EC). Biodegradable waste. Available from: <http://ec.europa.eu/environment/landfills/landfills.htm>