MSc Program
Environmental Technology & International Affairs

# LANDFILLING IN TROPICAL CLIMATES - AN ANALYSIS OF ISSUES TO BE SOLVED

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
Dipl.-Ing.Dr.techn. Johann Fellner

Anna Kubin

0612365

Vienna, 11.06.2012

# Affidavit

I, **ANNA KUBIN**, hereby declare

1. that I am the sole author of the present Master's Thesis, "LANDFILLING IN TROPICAL CLIMATES - AN ANALYSIS OF ISSUES TO BE SOLVED", 115 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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## Abstract

On a global level, landfilling is still the main method to dispose of waste. In particular low- and middle-income countries almost exclusively depend on landfilling, due to its low costs and convenient operation and management. Regulations and guidelines exist for landfills in moderate climates (Western Europe, United States). These guidelines, nevertheless, cannot be applied in tropical countries, as the behaviour of landfills there is different.

The aim of the present thesis was to provide an overview over the problems concerning landfilling in tropical countries. A special focus was laid on the characteristics of emissions of tropical landfills since a good understanding of these is of paramount importance. The methodology used was an analysis of literature reporting on problems for landfills in tropical climates as well as a comparison of the specific characteristics of landfill emissions.

The results can be summarized as follows: The specific behaviour of tropical landfills refers mainly to landfill emissions and waste mechanics. Leachate quantities are much higher than in temperate climates and vary depending on the season. This variation is also observed for its composition. Leachates of the dry season have a much higher concentration of pollutants than those produced during the rainy season. The higher precipitation of the tropics leads to a higher rate of waste decomposition in the landfill. This influences methane production, which occurs faster, in larger quantities and lasts for a shorter time than in temperate landfills.

The mechanical stability of landfills is another issue that is influenced by the higher moisture level of tropical landfills. Almost all dump slide disasters occurred after periods of extreme precipitation or due to an increased moisture level in the waste. To prevent future disasters, the climate zone is a factor that has to be considered when designing a landfill.

Possible solutions to a few of the issues analysed include an adequate design of the landfill cover, a system for storing and recirculating leachates and finally, it will be necessary to develop an international landfill classification that considers the climate, the development level of the country as well as the type of waste that shall be deposited. According to these landfill classes, appropriate national and international guidelines could be designed that fit for every country of this planet.

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## List of Acronyms

| | |
|---|---|
| BOD-5 | Biochemical Oxygen Demand in 5 days |
| CDM | Clean Development Mechanism |
| $CH_4$ | Methane |
| $CO_2$ | Carbon Dioxide |
| COD | Chemical Oxygen Demand |
| DOC | Dissolved Organic Carbon |
| ET | Evapotranspiration |
| GDP | Gross Domestic Product |
| GNI | Gross National Income |
| JI | Joint Implementation |
| LFG | Landfill Gas |
| MAT | Mean Average Temperature |
| MSW | Municipal Solid Waste |
| TKN | Total Kjeldahl Nitrogen |
| TVA | Total Volatile Acids |
| WIP | Waste In Place |

# 1. Introduction

Within our changing environment and growing economy more waste is produced every day. The amount of waste that our world has to deal with is growing, and due to an on-going growth of population and urbanization, another problem arises: the waste generated is quickly filling up the existing landfills. Space is becoming scarce since it is needed for housing and other services for people. Additionally, the existing landfills or waste dumps are not well operated, leading to severe negative impacts on the environment (e.g., groundwater pollution, greenhouse gas emissions) and the human health (e.g., landfill fires, landslides). For example in Indonesia, in most cases only about 60% of all municipal solid waste (MSW) is collected and deposited in a landfill. The rest is put into open or illegal dumpsites. (State Ministry of Environment 2008)

Landfills in countries with moderate climates (Western Europe, United States) are scientifically well researched and their behaviour is investigated in depth so as to provide clear guidelines and methods for their operation and management. On the contrary, in tropical climate zones, landfill behaviour is genuinely different and as a rule, little information about landfills (including their emissions) is available at present. However, in order to enable an environmentally friendly operation of landfills, comprehensive knowledge about the behaviour of the landfilled waste is crucial and a set of completely different rules and regulations is required when one is concerned about their appropriate management.

When discussing landfilling in tropical countries, it first has to be explained that of the countries with a tropical climate, only two (Hong Kong and Singapore) can be found among the 30 high-income countries defined by the World Bank. High-income regions (North America, Western Europe, Northeast Asia, the Southern Edge of Latin America, and Oceania) all have temperate climates. Some of the poorest countries of the World lie actually in a tropical climate and are land-locked (Bolivia, Uganda, Burundi, Lesotho and Laos) (Sachs 2001). This explains the fact that in many of these countries handling of MSW is not the number one priority when it

comes to governments' environmental budgets. Little financial support, therefore, makes landfilling on a global scale still the main disposal method for MSW. In particular low- and middle-income countries are almost exclusively depending on landfilling, since it represents by far the cheapest and easiest method of waste disposal.
Additionally to the growing waste masses, also the characteristics of this waste are changing. While in less developed economies organic waste makes up a major part of the total waste generated, this fraction tends to drop once the economy develops. Besides the composition of the deposited waste, the main factor determining landfill emissions (and thus the environmental pollution) is the quantity of water entering the waste body. Water is essential for microbial biodegradation and, thus, not only for the production of landfill gas, but also for the generation of leachate. Hence, the behaviour of a landfill is strongly dependent on the prevailing climate.

The thesis is separated into the following parts. Chapter 2 discusses the aim of the thesis in more depth. Chapter 3 describes the methodology used for obtaining the results which are presented in chapter 4. This part is subdivided into a number of subchapters, starting with the discussion of tropical climates in subchapter 4.1, followed by a subchapter on legal aspects of waste management in the EU (4.2). In comparison to this, subchapter 4.3 discusses the waste management in developing countries. Subchapter 4.4 describes how the waste characterization differs according to the GDP of a country. Subchapter 4.5 examines the emissions of landfills in tropical countries by shedding more light on leachate and landfill gas emissions. Finally, subchapter 4.6 discusses the impacts of tropical climates on the mechanical stability of landfills and open waste dumps. In chapter 5, the results shall be discussed by putting a special emphasis on the fact whether the issues encountered are related more to the level of development of a country or to its climate zone and certain propositions and recommendations are presented such as an international classification system. Chapter 6 concludes and summarizes the most important findings.

## 2. Aim of the Thesis

The thesis gives an overview of the problems that are related to tropical landfills, how they are related to the GDP of a country and how they are dealt with at the moment. The aim of the thesis is to establish which problems for landfills in tropical climates have been reported in the literature and what differences exist to landfilling operations in temperate (= well-researched) climates. Thus, a basis of issues that need to be considered for landfilling operations in tropical countries will be established which could further be used as a guideline when creating international regulations or recommendations.

## 3. Methodology

The thesis presents preliminary results of an on-going research project that aims at establishing a knowledge base for the construction and operation of landfills under tropical climate conditions. The research is funded by an ISWA project grant and conducted by Vienna University of Technology (Austria) and Syiah Kuala University (Indonesia). The knowledge base developed within the study will consider the specific demands and problems of tropical landfills. In particular the status quo of landfilling in Indonesia and current efforts concerning the transition of waste disposal practice to sophisticated sanitary landfills are taken into account as a case study.

The methods applied within the study include

- literature research addressing landfilling in tropical climates and associated problems as well as major differences in comparison to landfills in temperate climates,
- a field survey investigating the current status of landfilling in tropical climates (using the example of Indonesia), and
- a detailed analysis of landfill legislation and its recent development, again using the example of Indonesia.

The focus of this thesis will be on a literature research on the topics of tropical landfills, developing countries and problems with landfilling in tropical countries.

Furthermore, national guidelines and regulations have been screened for information on the differences between landfilling guidelines in the European Union and a developing country (Indonesia).

In the frame of the literature study research work accomplished in different countries with tropical climates, such as Brazil, Mexico, Nigeria, Malaysia, Thailand and Indonesia has been analysed. Besides the tropical climate most of those countries are characterized by low to medium economic development.

Finally, the project includes also the task of disseminating the information obtained during a seminar in Banda Aceh, Indonesia, in August 2012 and the annual ISWA conference in Florence, Italy, in September 2012.

# 4. Results

This chapter is divided into subchapters to provide for a clear reasoning and comprehensive arguments. In the beginning, a definition for tropical climates is given to understand the conditions a landfill in these climate zones is exposed to. The second subchapter details the European landfill directive which, to a great extent, coincides with the way landfills are managed in developed countries with a temperate climate. The third subchapter describes waste management in developing countries in order to display issues encountered with the management and operation of landfills in countries with a lower GDP. The second and third subchapter should detail the differences that exist between industrialized and developing countries when it comes to waste management. Moreover, they show why laws and regulations from industrialized countries cannot simply be transferred to developing countries.

The fourth subchapter then analyses the waste compostion in developing countries since this has a high influence on the emissions of landfills. These emissions are further investigated in subchapter five. The chapter is divided into one part about leachate and one about landfill gas. A general introduction about how the emissions are produced starts off the separate parts, which is followed by a description of how these emissions deviate from temperate "normal" values when examining them in a tropical climate. This style was chosen in order to present clearly the differences that exist between landfill emissions in temperate and in tropical climate zones. The sixth and final subchapter deals with landfill stability and the dangers of landfill slides. These can also be affected by tropical climates.

## 4.1. What is a tropical country?

The word "climate" comes from the old Greek language and can be translated as "to incline". Hippocrates and Aristotle used this word to describe the inclination of the Earth's axis towards the sun and to explain the dependence of weather phenomena on the angle of incidence of solar radiation.

Climate in a narrow sense is today defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state of the climate system, including a statistical description. (Definition from the Intergovernmental Panel of Climate and Climate Change)

From both definitions it can be derived that climate is a function of time and space. For this paper, the differentiation according to space is relatively more important since it focuses on problems with landfills in tropical climate zones. Nevertheless, time plays an essential role when discussing seasonal changes and variations in the climate of the tropical zones. Issues like global climate change, although of primary importance, shall be left out in this paper.

When classifying according to space one can distinguish between

- A microclimate: for example, a forest or agricultural space
- A city climate: which exists due to urban influences on atmospheric conditions
- A regional climate: taking into account orography
- A macroclimate: changes through maritime or continental influences
- The hemispherical climate: including land-sea mass influences
- The global climate: important when discussing climate change

Wide parts of the Earth show similar features when it comes to temperature, humidity, evapotranspiration and precipitation. A classification of these macroclimates into climatic zones has been done starting with Aristotle in 400 BC who used the relative position of the sun and the earth. 2400 years later a great variety of different classification systems exists, some using mathematical models, others using hydrological models or temperature threshold values. Each has its advantages and inconveniences but for this paper the system of Wladimir Köppen, a plant scientist, was chosen. The system was introduced in 1918 and is still seen as the most important classification system for the world's climate by many scholars (Peel, Finlayson und McMahon 2007, Pidwirny 2012). The system differentiates between five main climatic types, which are defined according to monthly and annual averages of precipitation, temperature and vegetation. The five climatic types are

**A – the Tropical Moist Climates** which have high average temperatures (above 18° Celsius) and high precipitation all year. See below for an in-depth discussion.

**B – the Dry Climates** with high temperatures but very low precipitation and big fluctuations in daily temperatures.

**C – the Moist Mid-Latitude Climates with mild winters**: They have moderate temperatures (at least one month below 18°C but not below -3°C) and are categorized according to the month with the lowest temperature level.

**D – the Moist Mid-Latitude (Snow-Forest) Climates with cold winters** which have an average temperature of below -3°C in their coldest month and regularly have snow, but in the warmest summer month reach average temperatures of above 10°C. The frontier of this climate zone towards the poles is identical with the tree line but because the land mass does not reach that far towards the pole in the southern hemisphere, there exists no D-Climate in the southern hemisphere.

**E – the Polar (Snow-Ice) Climates** that have extremely cold winters and summers. Permanent ice and tundra can be found in these climates where a maximum of four months in the year are above 0°C but no 30-day period reaches an average of 10°C. Precipitation is low and only occurs in the form of snow. (Malberg 2007, Peel, Finlayson und McMahon 2007, Pidwirny 2012)

### The tropics (*A*-climates)

A-climates can be divided into the tropical wet (*Af*) and the tropical wet and dry (*Aw*) climate zones. Some authors add a third sub-zone, the tropical monsoon climate (*Am*). Characteristic for the tropical wet climate are not the extremely high temperatures but the consistently high temperatures all year round. The yearly average temperature is 25°C, ranging daily from 20 to 30°C. The yearly precipitation totals to 1500 mm or higher and can show 2 maxima and 2 minima throughout the year. The reason for this is the seasonal shift of the equatorial through, or the *intertropical convergence zone* (ITCZ). The weather is uniform throughout the whole year with convergence and high maritime humidity creating cumulus clouds and thunderstorms almost daily. Vegetation can grow without stop, creating the evergreen, abundant tropical rainforest such as in the Congo or Amazonas basin or on the islands of Indonesia.

The intertropical convergence zone also influences the tropical wet and dry climate zone, yet the effects follow each other more closely the farther the region is from the equator. This creates one single rainy season and one dry season when the sun and therefore the ITCZ are found above the longitude of the other hemisphere. The temperatures of the *Aw*-climates are still tropically high, especially during the wet season when almost no differences to the *Af*-climates can be established. The difference between the months increases and the daily fluctuations in temperature as well: during the dry season daily temperatures of 35°C can be encountered, while they decrease to 15-20°C during the night-time. Due to the semi-desert conditions, vegetation growth encounters a periodical pause that leads to the development of a savannah instead of a rainforest. Examples for the *Aw*-climates are the Sudan, the dry forests of East Africa, parts of India, and the Campos of Brazil. (Malberg 2007, Peel, Finlayson und McMahon 2007, Pidwirny 2012)

In Figure 1 the Köppen climate classification map that has been updated in 2007 by Peel et al. demonstrates the climate zones of the world. Note that Peel et al. use a Köppen-Geiger classification in which the tropical climates are divided into *Af* – Rainforest climates, *Am* – Monsoon climates and *Aw* – Savannah climates.

Next to the climatic classification of the tropics, tropical climates also refer to a geographic region. The tropics lie to both sides of the equator and are separated in latitude from more polar climate zones through the tropic of the Cancer in the north and the tropic of the Capricorn in the south. They lie at about 23.5°, a latitude where the sun reaches the zenith only once a year. This is also the defining point for the tropics: the sun has to reach the zenith at least once a year. The word “tropics” comes from the Greek word “trope” which means “turning point”. (Feulner 2010)

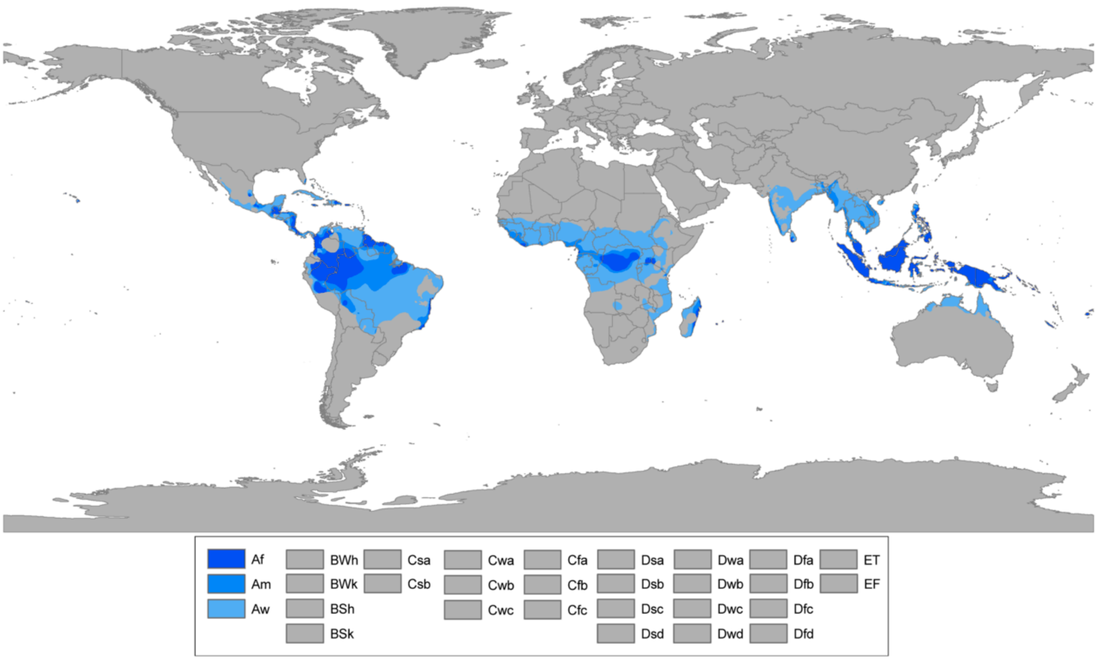



**Figure 1: Tropical climates according to Köppen (Peerl et al. 2007)**

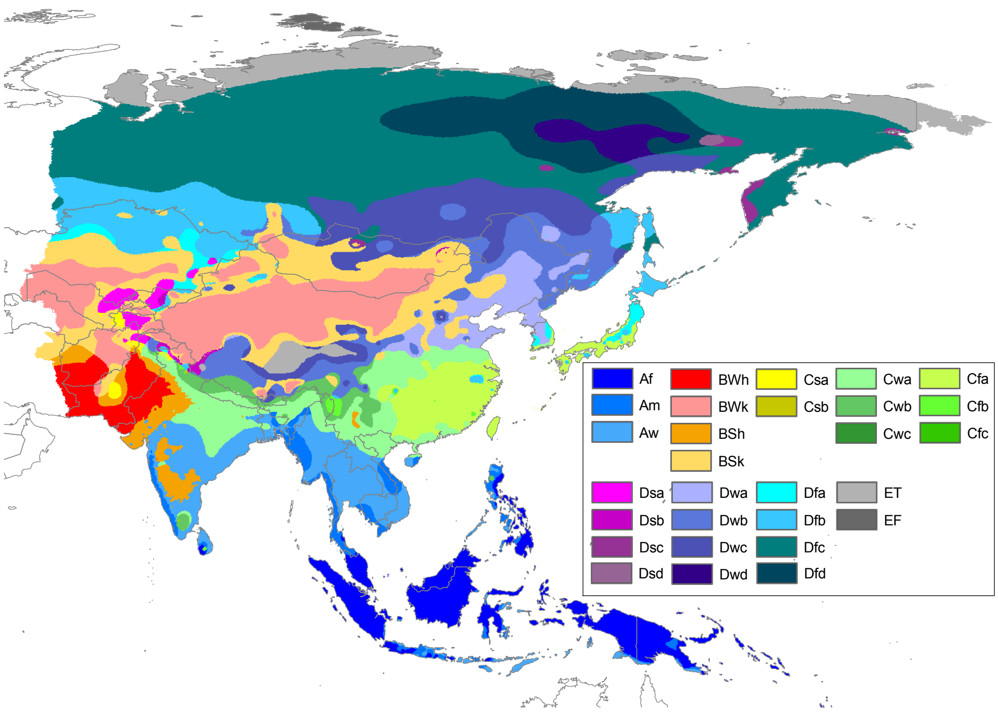



**Figure 2: Climate map of Asia according to Köppen (Peel et al. 2007)**

Figure 2 shows that Indonesia as well as a lot of its neighbouring countries (e.g., India, Malaysia, Thailand) is part of the tropical zone.

As indicated above, the tropical climates are distinguishable by the amount of precipitation and their temperatures. In Figure 3 a typical evolution of precipitation is given for Jakarta in Indonesia. It shows only one rainy season from December to March and a distinct dry season from June to September.

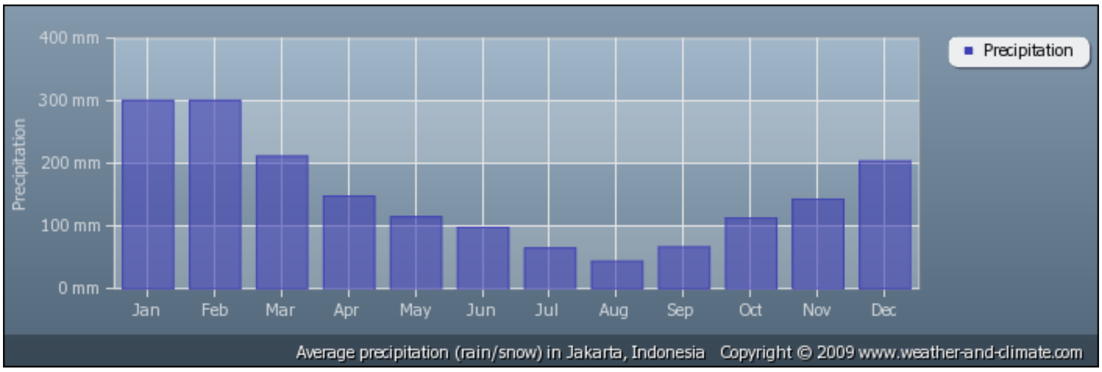



**Figure 3: Precipitation in Jakarta (average mm per month) (Weather-and-Climate.com 2012)**

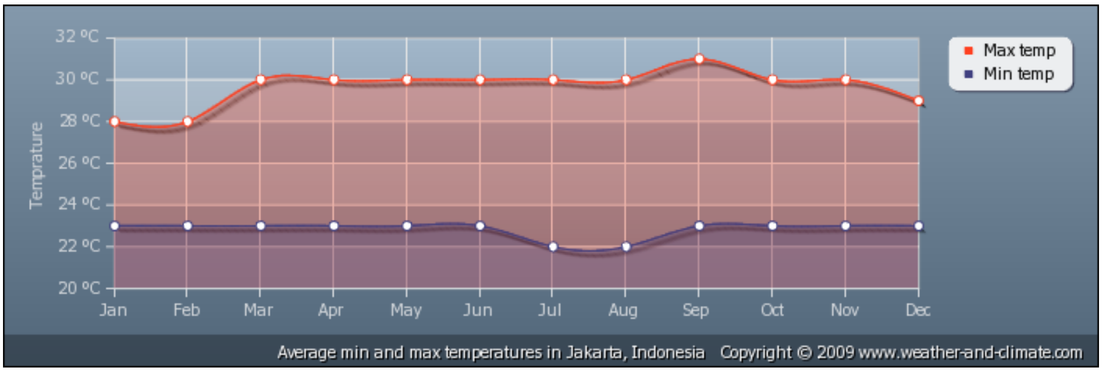



**Figure 4: Temperatures in Jakarta (minimum and maximum °C per month) (Weather-and-Climate.com 2012)**

In Figure 4 the temperature for Jakarta is given. As indicated in the Köppen climate classification, the temperature is constantly between 20° and 30° Celsius with almost no variations. Indonesia, of course, is an extremely large country; nevertheless, these climatic indications, by and large, can be generalized for the whole country.

After having established what defines a tropical country the next step is now to determine what differences there are in landfilling procedures in temperate and tropical climates.

## 4.2. Legal Aspects of Waste management in the EU

Waste management comprises a whole range of elements. It starts with the waste separation at household level, includes collection, recycling, and treatment of the waste; and finally the disposal of the residues and the aftercare of landfills. Since waste collection, treatment and recycling is almost no issue anymore in the EU, these topics will not be discussed in this chapter. In developing countries, these factors influence the whole system and will, therefore, be included in the analysis. This chapter will mainly treat the EU Directive on Landfills, as well as the way landfills are designed and constructed in the EU, since this stands in grave contrast to the construction of landfills in developing countries.

The goals of waste management for the European Union according to the waste framework directive are (COUNCIL DIRECTIVE 1999/31/EC 1999)

1. To protect men and the environment
2. To conserve resources (materials, energy or space)
3. That recycling products should not cause a higher risk to the environment than primary materials
4. To dispose of waste without it having an impact on future generations (after-care free).

Waste management is not as advanced in all parts of the world, especially not the fact that waste should be disposed of in a way that leaves no burden on future generations. In industrialized countries and especially in Europe though, waste management is already quite sophisticated. Landfills are required to emit only environmentally sound emissions, to ensure that the used space is as small as possible, and to guarantee long-term safety for the people. This means high levels of recycling, composting and incineration in most member states. Consequently the named waste management goals are attained to a great extend in the EU. (COUNCIL DIRECTIVE 1999/31/EC 1999)

### 4.2.1. Legislation in Europe on landfilling

The Council Directive 99/31/EC of the 26th of April 1999 on the landfill of waste aims at providing

> "for measures, procedures and guidance to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect, as well as any resulting risk to human health, from landfilling of waste, during the whole life-cycle of the landfill." (COUNCIL DIRECTIVE 1999/31/EC 1999)

It classifies three different kinds of landfills

- Landfills for hazardous waste,
- Landfills for non-hazardous waste,
- Landfills for inert waste.

Landfills for non-hazardous waste are intended for municipal solid waste, other non-hazardous waste or stable, non-reactive hazardous waste that has been solidified or vitrified and that would not produce emissions with different characteristics than MSW. The following types of wastes are banished from landfills: liquid waste; wastes which are explosive, corrosive, oxidising or flammable; hospital or clinical wastes which are infectious, or used tyres. Also any dilution of such wastes to meet the criteria is forbidden. Furthermore, it is ensured that any waste that does reach a landfill has received pre-treatment and the amount of biodegradable waste is reduced to 30% of its 1995 values within 15 years.

Applications for a landfilling permit have to provide information about the identity of the operator, the type and total quantity of the waste to be landfilled, the capacity and a description of the planned landfill site, means to prevent pollution as well as a plan for control, closure and aftercare. The national governments also have to ensure that the applicant possesses the financial means to provide for an aftercare period of at least 30 years or as long as required by the competent authority.

Although this directive should harmonize waste management across the European Union, the costs of landfilling still differ strongly amongst EU member countries, which induces the exporting of wastes to countries with a low price. (COUNCIL DIRECTIVE 1999/31/EC 1999, Committee of the Regions of the European Union 2006)

### 4.2.2. Landfill construction

For landfill construction, the EU framework directive states four issues are of relevance: site investigation, base liner and drainage construction, and the covers and geotechnical aspect. When investigating the site, care needs to be taken since there are zones prohibited for landfills by law such as water protection- or flood prone areas. Also regions close to residential areas or on fissured rocks are banned from landfilling activities. The distance of the landfill base to the highest groundwater level has to be at least one meter to hinder possible groundwater pollution. These areas are described in Annex 1 of the EU Landfill Directive.

The geological and artificial base and sides have to adhere to the specific rules of the EU Landfill Directive. For MSW, these require that the hydraulic conductivity – measured through the Darcy coefficient K – has to be smaller or equal to $1{,}0 \times 10^{-9}$ m/s, with a thickness of larger or equal to one metre. In case the geological barrier does not adhere to these rules by itself, an artificial barrier has to be added. Here, as an example for the base liner, a landfill in Austria was chosen. Normally it would consist of 3m of clay, then a layer of compacted clay (the mineral base liner), a layer of High Density Poly Ethylene, a layer of geotextile and then a gravel layer (with less than 30% lime) for drainage. In the drainage layer there are pipes with holes on their top to collect the leachate generated. For the landfill cover, first a layer of shredded waste is used as a compensation layer, then a gravel layer to collect the gas, a mineral layer, a sheet of High Density Poly Ethylene, another gravel layer to drain incoming precipitation and a re-cultivation layer with soil and vegetation. The function of a landfill cover is to prevent the ingression of rainfall, to prevent the emission of landfill gas by oxidizing methane and to provide a medium for plant growth. Current research is focusing on the alternatives existing next to traditional landfill covers such as geo-synthetic clay liners, asphalt liners, capillary layers or evapotranspiration layers. However, in tropical climates the precipitation in the rainy season could result in too much moisture for an evapotranspiration cover layer – the leachate quantity produced would be simply too great (equalling open dump sites). The issue of geotechnical aspects refer to the stability of the landfill and the aim of reducing the possibility of landfill slides. This can be done by being attentive to the slopes of the waste piles as well as to the waste's compaction. Especially after strong weather events (heavy rainfall), landfill slides are more probable to happen – particularly in developing countries. (COUNCIL DIRECTIVE 1999/31/EC 1999, Fellner 2011)

#### 4.2.3. Landfill barriers

The protection of the soil and water from landfill emissions is covered in article 3 of Annex 1 of the EU Directive. The protection is mainly achieved through the landfill barriers. A single safety layer is not enough since a lot of physical and chemical reactions are occurring in landfills. The Directive describes of two barriers, yet, in total, one can speak of three separate layers: The pre-treated waste, which is the first and best barrier possible. Stable waste by itself is the best security against any emissions that might escape the site. The second barrier is the natural barrier such as the geology and the hydrology of the site (e.g., how far the level of the lowest waste layer is in comparison to the highest groundwater level). The third barrier, the human-made artificial barrier includes several sub-layers: First, the base liner of the landfill with leachate collection, secondly, the cover layer and the separate collection of precipitation and finally, the fact that barriers are controllable and reparable. Artificial barriers should, in the best case, only pose as reinforcement barrier. The actual protection in the EU happens through the stabilized waste body. (Bilitewski et al. 2000, Fellner 2011, COUNCIL DIRECTIVE 1999/31/EC 1999)

## 4.3. Waste management in developing countries

### 4.3.1. Waste generation

Waste management in developing countries was relatively absent up to now, but with their improving situation, it will become an ever greater issue. The fast growing economies and the changing lifestyle that accompanies such transformation will equally imply a rethinking, as well as a difference in the waste generation of these countries. First of all, the amount of waste generated is directly proportional to the GDP of a country, therefore, the more developed a country becomes, the more waste will be produced. This can be read in Table 1 by Zurbrügg (2002). Secondly, the increasing population growth makes space a rare and sought-after good that will become more expensive. The availability of disposal sites will decrease as more space is needed for living and agriculture. (Idris, Inanc und Nassir Hassan 2004)

**Table 1: Waste generations rates (kg/cap*day) of some Asian countries, sorted by ascending Gross National Income (GNI per capita, in US$) (Zurbrügg 2002)**

| Country | GNI[a] | Waste generation [kg/capita day] | Reference |
|---|---|---|---|
| Nepal | 240 | 0.2 - 0.5 | (UNEP, 2001) |
| Cambodia | 260 | 1.0 | (Yem, 2001) |
| Lao PDR | 290 | 0.7 | (Hoornweg, 1999) |
| Bangladesh | 370 | 0.5 | (Hoornweg, 1999) |
| Vietnam | 390 | 0.55 | (Hoornweg, 1999) |
| Pakistan | 440 | 0.6 - 0.8 | (World Wildlife Fund, 2001) |
| India | 450 | 0.3 - 0.6 | (Ahmed, 2000; Akolkar, 2001) |
| Indonesia | 570 | 0.8 - 1.0 | (Mukawi, 2001) |
| China | 840 | 0.8 | (Hoornweg, 1999) |
| Sri Lanka | 850 | 0.2 - 0.9 | (Jayatilake, 2001; Hoornweg, 1999) |
| Philippines | 1040 | 0.3 - 0.7 | (World Bank, 2001) |
| Thailand | 2000 | 1.1 | (Hoornweg, 1999) |

Thirdly, while in rural areas more organic waste but fewer recyclable items are produced, with the increasing growth of urban centres, the size of the organic fraction will be reduced while giving way to an increasing amount of packaging material such as plastics, papers and metal cans. These wastes are more complex and cannot simply be transformed back into useful products by composting. To recycle these types of wastes, a more complex and costly system of waste collection and treatment needs to be in place. (Idris, Inanc und Nassir Hassan 2004)

Data on waste management in developing countries is relatively difficult to obtain since a lot of the activities are not documented or the information is not regularly updated. Moreover, the data that is collected is rarely similar across different studies or reports leading to even less comparability amongst countries. Neither is the information usable for enforcement of waste management standards. (Idris, Inanc und Nassir Hassan 2004)

Inanc, et al (2004) established a tentative database on landfills and dump sites in Asian countries. Included are China, Hong Kong, India, Malaysia, Philippines, Taiwan, Thailand, Turkey, South Korea, Japan, giving a good mix of developed and developing countries in Asia. The database gives information on the population and the surface of the country, the climate, the waste generation, the collection rate, the amount of waste recycled, relevant legislation concerning landfills, the types of landfills and the total amount of sanitary landfills and open dumps. When analysing these tables, it is visible that the biggest lack of information exists for the percentage of waste that is recycled. This is probably due to the scavengers who unofficially are responsible for recycling. Consequently, the materials are recycled, yet information about this recycling rate is lacking. The second issue on which information is scarce is the amount of sanitary landfills that are operated in a country, followed by the amount of open dumps. It is not a surprise that the amount of open dumps is a number that is not kept track of. Open dumps are not planned but simply appear wherever it is convenient to people. They still are the common option for disposing of waste (Inanc, et al. 2004, Visvanathan, Karthikeyan und Park 2010).

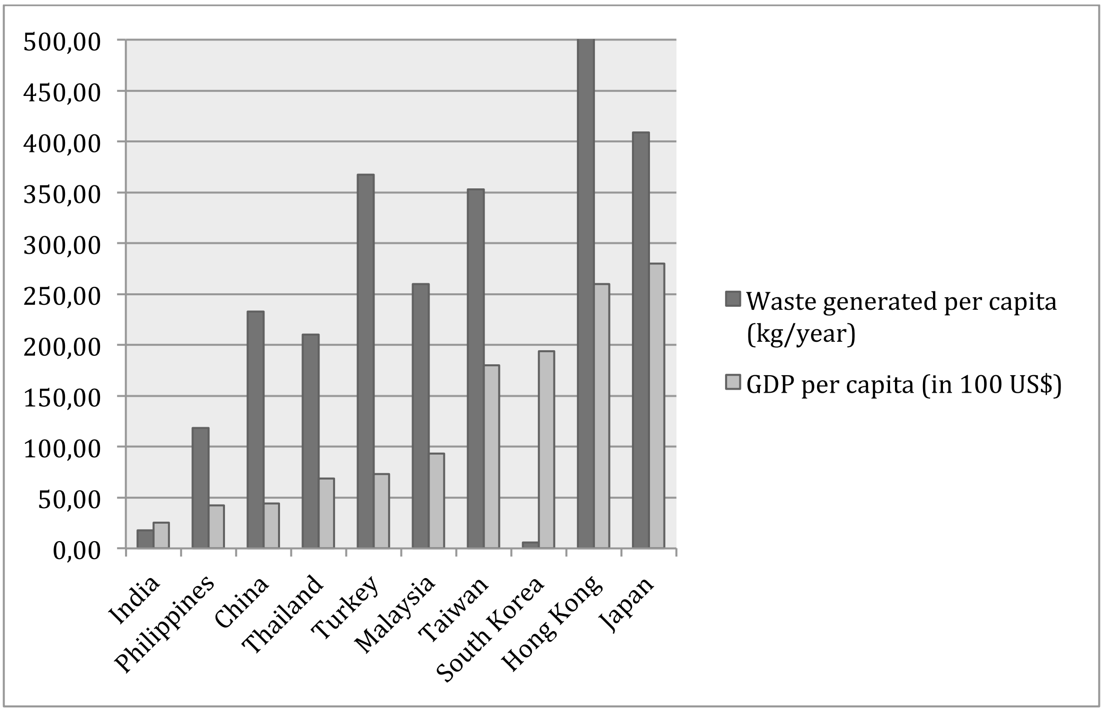



**Figure 5: GDP (per capita in US$; Purchasing Power Parity 2003) vs. waste generated (Inanc, et al. 2004)**

When analysing the information from the database, a basic correlation can be proven. With the increasing GDP per capita of a country, the general trend shows that larger amounts of waste are generated per person[1]. This trend is clearly visible, yet shows some discrepancies, since the data reported to the authors was not similar from country to country.

When comparing the amount of waste produced per year, one will find insecurities as to what data should be included in this number. The provided data ranges from only the amount of municipal solid waste to the quantities of MSW and industrial waste. Some even mentioned the amount of hazardous or liquid waste. A conclusion from these findings can be that the provision of comparable data shall have highest priority.

[1] It should be noted that the axis was cut and that the waste generated in Hong Kong per capita in fact amounts to 813 kg/y.

### 4.3.2. Waste collection

Waste collection in developing countries is rarely extended beyond the urban centres. While in Indonesia 75 to 80% of the total waste come from households, only 60% of the MSW is collected and disposed of properly. The rest lands on the streets or – in rural areas – next to rivers, roads or on the outskirts of villages. The difficulty is that solid waste management is not the task of a special ministry but several ministries have to develop new policies together and the implementation and enforcement is the task of each single municipality or regency. No strategy to reform the long-term system of waste management in Indonesia has been notably successful. These failures stem partly from relying too heavily on Western waste management technologies that are costly and unfit for the tropical climate. Also, since these projects are centrally organized and lack cooperation amongst communities and ownership within the community, their failure does not come as a big surprise. (Supriyadi, Kriwoken und Birley 2000, State Ministry of Environment 2008)

In Indonesia, waste collection is currently taken care of by local communities, called neighbourhood associations. Households collect their waste in containers or in community storage containers. The collection then happens either by scavengers hired by the neighbourhood association or by the official Cleaning Department. This collection service does not happen on a regular basis and is done using handcarts. It is transported to the next transfer point or to any open dump close by. In the worst case, these transfer points are simply larger spots on a street or, in better cases, concrete bins with one open side. Scavengers as well as animals then scan through the waste for valuable material or food. Disease vectors breed in such waste piles. The waste is picked up by a truck onto which the waste is loaded manually by workers; it is transported to the next landfill site where it is unloaded. (Supriyadi, Kriwoken und Birley 2000, State Ministry of Environment 2008)

The rate of collection is usually very low; that is made clear when considering the number of people working as waste collectors and the amount of people that need to be provided with this service. In Semarang, Indonesia, one collector would need to serve more than 10.000 people if they tried to serve 90% of the population. Waste collection fees are quite low and it is rather difficult to collect them in developing countries. The people of Semarang, for example, have to pay a fee for the waste collection and other waste services which differs according to property values. Rp.

5000[2] per month have to be paid by a resident on a first or second class street, Rp. 3000[3] per month are charged from residents on a third class street. This money is collected together with the piped water supply bill. People not having access to piped water supply, thus, would not pay the charge.

### 4.3.3. Waste treatment

Waste treatment and recycling do exist in developing countries but are not undertaken for a very big part of the waste. 50% of the collected waste in Asia is dumped in landfills without any type of pre-treatment or compaction (Visvanathan, Karthikeyan und Park 2010).

In Indonesia there are 243 composting facilities, 64 incinerators (probably mainly used for hospital waste), and 22 other treatment facilities. Figure 6 shows the amount of waste that is actually treated by these facilities. Only 2.72% of all the waste is accepted by composting plants and of this only 0.70% is actually processed. Far lower values are realized for incineration: 0.08% of all waste is accepted into an incinerator, but only 0.04% is really incinerated. Other treatment facilities take up 0.02% of the waste where the entire 0.02% is processed. (State Ministry of Environment 2008)

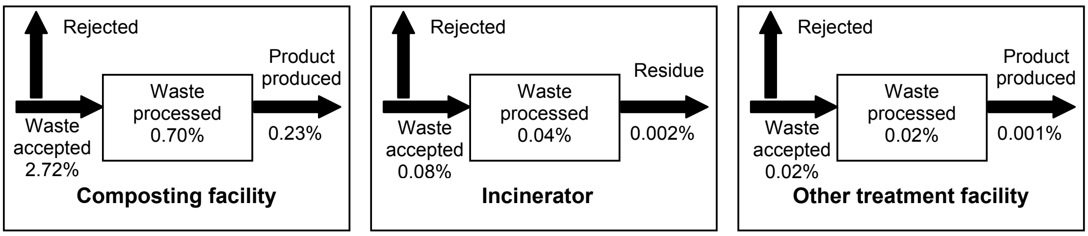



**Figure 6: Proportion of waste treatment at facility (State Ministry of Environment 2008)**

The official recycling rate is quite high. The Indonesian Domestic Solid Waste Statistics from 2008 give a rate of 57% excluding waste pickers' activities except when they followed official government activities. This number is relatively unbelievable, especially when comparing it with findings by other authors who

[2] 0.42€
[3] 0.26€

basically state that recycling is only provided by scavengers. Supriyadi, et al (2000), for example, declared that the local government of Semarang had not considered recycling as a valuable option at all. This is due to several reasons. Firstly, recycling seems to contribute only very little to waste reductions. Second, collection problems are still more pressing and hinder any furthering of waste recycling. Thirdly, landfilling is still the cheapest option for disposing of wastes. Currently, waste reutilization happens in the following way: Households collect newspapers and glass bottles separately and sell them to waste collectors called "tukang rombeng" or they simply trash it with the rest of the garbage. Scavengers scan this waste during collection or at the landfill.

In general, there are some problems when it comes to scavengers. Their reputation is relatively bad; they are described as jobless and homeless, and considered a public nuisance. With increasing resource prices for raw materials and the development of the economy, more industries become interested in the products sold by scavengers. As recycling becomes more attractive, also their function is perceived with more respect. They are now officially allowed by the government to work at waste disposal sites. This new regulation means that the 40.000 people working as scavengers in Jakarta, for example, do not have to do it illegally anymore. (Supriyadi, Kriwoken und Birley 2000, Poerbo 1991)

### 4.3.4. Waste storage

Supriyadi, et al. (2000) found a number of problems with the landfill in Semarang, Indonesia. Firstly, the waste is dumped directly over the edge of a very steep, almost vertical slope. Compaction does happen but no daily soil cover is applied on the waste. This is why a great number of rodents, insects and other disease vectors are breeding at the landfill site. The operators of the landfill included a leachate treatment but it is not working as desired. Surface waters in the surroundings are often contaminated. Another project that was established but is not functioning as it should is the waste compostion plant that was added to the site. Finally, in the dry season, landfill fires are common on the site due to uncontrolled methane emissions. (Supriyadi, Kriwoken und Birley 2000)

Ashford, et al. (2000) found that Thailand encountered similar problems and open dumping was standard throughout the whole country even in large cities. Yet, as the country realized that for a sustainable economic growth, environmental protection played an important role, new landfills are all engineered in a way to reduce environmental impacts to an absolute minimum. It was further found that the standard of engineered landfills in Thailand was getting closer to international standards, but that only 10% of landfills were operated as an engineered landfill.

#### 4.3.5. Impact on the environment

Most of the adverse environmental impacts from MSW in developing countries are derived from the uncontrolled discharge of the waste (in open dumps, next to drinking water sources) and from co-disposal of hazardous wastes. Also landfill fires cause unwanted emissions with adverse effects on the environment and the human health. The ways landfills impact human lives is through the spreading of diseases, the possibility of inflicting injuries, or by affecting the local economy.

First of all, the transmission of diseases becomes much easier and faster through open dumps. This can happen along three different pathways. First of all, there are air pollution disease links that might damage the respiratory system. To this category belong bio-aerosols (microorganisms, toxins, mould spores), particulate matter (diesel exhaust fumes, airborne bacteria, endotoxins, fungi, and dust), volatile organic compounds (alcohols, aldehydes, ketones, carboxylic acids and esters, as well as landfill decomposition gases like dichloromethane, benzene, and toluene), and lead. All these compounds are potentially toxic, carcinogenic, affecting the kidney or causing – amongst other diseases – leukaemia. 23 to 53% of dumpsite workers in India, Thailand and the Philippines have been diagnosed with abnormal pulmonary functions. 70% of dumpsite children waste pickers have blood lead levels of above WHO guidelines and 2.5 times higher than slum children not working on a landfill. As a second pathway, there are the direct contact disease links that transmit diseases via direct touching of the wastes. Parasitic infections are common, but also HIV or Hepatitis can be transmitted via direct contact. In Manila (Philippines), Olinda (Brazil) and Calcutta (India) about 95% of the waste pickers all had intestinal parasite infections. As the third pathway, there are water contamination disease links, including, on the one hand, vector disease links like rodents or mosquitos that spread the dengue fever, leptospirosis, the plague, or the hantavirus. On the other hand, these include animal feeding disease links. This describes the situation when domestic animals are feeding from the dumps or landfills (which often include faecal matter or slaughter wastes) and become then part of the diet of the people. Trichinella spiralis or taeniasis can be caused by this type of disease link.

A second negative effect of improper waste management is the possible increase in injuries to people and property. Injuries might occur during collection or disposal, or – especially – due to dump side slides or subsidence: Landslides and landfill fires can destroy houses or injure workers and people living (too) close to the landfill. Through waste piles on streets, drains might be clogged and local flooding can occur. Finally, improper waste management can also hurt the local economy through the discouragement of tourism or other businesses: Unpleasant or unsupportable odours and waste piles in a formerly beautiful environment can put an end to plenty of business opportunities. (Cointreau-Levine, Listorti und Furedy 1998)

### 4.3.6. Legislation

While a greater number of developing countries starts to see the importance of a good waste management plan and coherent legislation, the laws and regulations dealing with waste management are relatively young and implementation is not achieved on a national level. Furthermore, the enforcement of these laws seems to be almost completely absent.

In the Manual for Technical Operation for Municipal Solid Waste Management by the Indonesian Standardization Agency, there are three types of landfills classified: controlled landfills, sanitary landfills and anaerobic waste disposal sites in tidal areas. The manual also defines a number of issues that have to be tackled by a landfill operator, such as providing a soil cover every week or every day depending on the type of landfill. The distance to the next settlement should be more than 500 metres. Furthermore, Article 24 of the Indonesian Waste Act (2008) obliges the government to provide for all waste management costs, yet most landfills are permanently underfunded, since the government money is spent mainly on waste collection and transport. The Waste Act further demands that financial burdens shall be shared between the local government – providing for capital investment like landfill construction, the waste compactors and collection vehicles – and the global governments who shall run the waste management service. Insufficient funds seem to be the main issue for inappropriate waste management practices, especially since the money is only coming from the annual governmental budget and waste management authorities are not allowed to generate any revenues from the services they provide. (Munawar, Kubin und Fellner 2012)

## 4.4. Waste characterization

Solid waste usually consists of solid and semi-solid wastes. Domestic solid wastes can be further divided into garbage, rubbish/trash, ashes, and bulky wastes. Garbage consists of wastes from preparing, cooking and serving food and wastes from handling, storage and sale of food on markets. Rubbish or trash comprises paper, cartons, boxes, barrels, wood, tree branches, yard trimmings, metals, tin cans, glass, crockery and minerals. Bulky wastes are furniture, bedding, packing material and tires. (Supriyadi, Kriwoken und Birley 2000)

**Table 2: Sources and types of municipal solid waste (Shekdar 2009)**

| Sources | Typical waste generators | Types of solid waste |
|---|---|---|
| Residential | Single and multifamily dwellings | Food wastes, paper, cardboard, plastics, textiles, glass, metals, ashes, special wastes (bulky items, consumer electronics, batteries, oil and tires) and household hazardous wastes |
| Commercial | Stores, hotels, restaurants, markets, office buildings | Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes |
| Institutional | Schools, government center, hospitals, prisons | Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes |
| Municipal services | Street cleaning, landscaping, parks, beaches, recreational areas | Street sweepings, landscape and tree trimmings, general wastes from parks, beaches and other recreational areas |

As can be seen from Table 2 from Shekdar (2009) the main sources for MSW are households, the commercial sector (stores, hotels, restaurants, markets, office buildings), institutions (schools, government centres, hospitals, prisons), and municipal services (street cleaning, landscaping, parks, beaches, recreational areas). Households dispose of food wastes, paper, cardboard, plastics, textiles, glass, metals, ashes, special wastes (bulky items, consumer electronics, batteries, oil and tires) and household hazardous wastes. The commercial sector and institutions usually both discard paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, and hazardous wastes. The types of waste coming from municipal services are street sweepings, landscape and tree trimmings, and general wastes from parks, beaches and other recreational areas.

ARRPET (2004) and others recognized that the characteristics of MSW depend on a wide variety of factors. Amongst these are food habits, cultural traditions of the inhabitants, differing lifestyles, and the climate. Moreover, the composition is influenced by the income level of a country and its state of industrialization (The World Bank 1999). The income level influences the components of MSW: e.g. how much paper, plastic, carton, how many cans, and bottles are used for packaging or which type of containment is available at household level to keep the wastes (bins, plastic bags or simply open piles of garbage). The way the waste is kept in the household then affects the amount of soil or ash to be found in the waste. The waste composition is different in a developing country than in an industrialized country: the organic waste content (due to a high food and yard waste fraction) is higher. In contrast, developed countries have a large fraction of paper and plastic waste (ARRPET 2004, The World Bank 1999).

This correlation between industrialization/income level of a country and the type of waste it produces can also be supported when looking at historic figures of waste management in the US or EU. In the 1960s, the US had a waste composition as follows: metals: 12.3% (1996: 7.7%), plastics 0.4% (9.4%), yard trimmings 22.7% (13.4%). Not only the amount of plastics or organics in the MSW can be defined by the income level of a country; also the quantity of industrial waste (sludges & solids) depends on the country's GDP. The higher the GDP, the more industrial waste is produced; the poorer the country, the less. Furthermore, in almost a third of the countries in the study conducted by the World Bank, industrial waste was not discharged in accordance with national laws. It is either discarded in open dumps or co-disposed with normal MSW, a fact that should be regarded closely by national legislation. (The World Bank 1999)

In industrialized as well as in developing countries, a differentiation can be made between urban and rural regions and in general, the part of plastics has increased during the last 20 years. (The World Bank 1999)

**Table 3: Waste characterization from the literature comparison (waste fractions given in %)**

| Source | Country | Bio-degradable (%) | Plastics (%) | Paper (%) | Glass (%) | Metal (%) |
|---|---|---|---|---|---|---|
| ARRPET 2004 | Thailand | 57 | 12,50 | 13,4 | 13 | 3,7 |
| ARRPET 2004 | Sri Lanka | 64 | 6,25 | 12,00 | 3,45 | 6,9 |
| Henry et al. 2006 | Nairobi | 54,5 | 11,9 | 16,65 | 2,15 | 1,8 |
| Hernandez/Berriel et al. 2008 | Brazil | 50,5 | 23,4 | 13,1 | 4,7 | 1,9 |
| Pasang et al. 2007 | Jakarta | 55 | 13 | 21 | 2 | 1 |
| State ministry 2008 | Indonesia | 58 | 14 | 9 | 2 | 2 |
| Supriyadi et al. 2000 | Semarang, Indonesia | 71 | 11 | 10 | 1 | 1 |
| Tränkler 2001 | Phitsanulok landfill, Thailand | 55 | 24 | | | |
| Visvanathan et al. 2000/ Traenkler 2005 | Thailand | 59 | 24 | | 7 | 1 |
| Visvanathan et al. 2010 | Thailand | 52 | 29 | 5 | | |
| **Average (%)** | | **57,60** | **16,91** | **12,52** | **4,41** | **2,41** |

In Table 3 an overview is given of the literature survey that has been conducted. Although some authors gave a range of data, here only the average values were taken to provide simplicity as well as comparability with those authors that only gave one figure per waste fraction.

In a study in Semarang, Indonesia, by Supriyadi, et al (2000), putrescibles made up 71%; second were the plastics with 11%; third, paper products 10%. Glass, metal and textiles or leather all represented about 1% (Supriyadi, Kriwoken und Birley 2000). A waste analysis from Sri Lanka deduced that the organic waste mainly consists of king coconut shells, banana stalks and logs, tree cuttings, saw dust, wood chips and paddy husks. The moisture content is extremely high and the waste has a very low calorific value. Big differences were found between the cities in the report. Biodegradable waste was ranging from 48% in Trincomalee to 80% in Colombo. Plastics were ranging from 4 to 8.5%, paper from 6 to 18% and metals from 1.8 to 12%. The glass fraction was 1.6 to 5.3%. (ARRPET 2004)

Similar values were obtained from other authors. While most of the data reported came from Southeast Asian countries, reports from African (Henry, Yongsheng und Jun 2006) or South American countries present values that are similar to the ones in Table 3. Overall, the values for biodegradable waste ranged from 50.5% to 71%, plastics were in the range of 6.25% to 29%, the paper fraction was 5% to 21%, glass ranged from 1 to 13%, and the metal fraction was between 1% and 6.9%. The average of the values of the literature study are presented in figure 8.

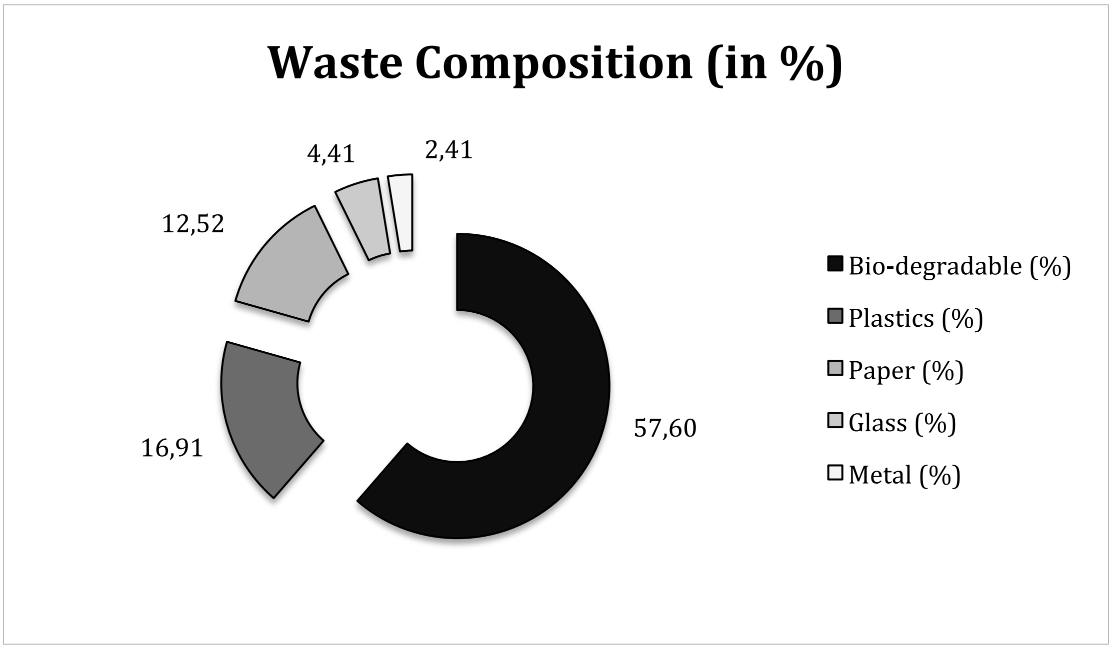



**Figure 7: Average waste composition from literature survey (waste fractions in %)**

Below, Table 4 by Cointreau-Levine, et al. (1998) gives values for low-, middle-, and high-income countries. The values seem to coincide with the values of Table 4; still, when looking closer at the amount of plastic, it is clear that the table dates from 1998. Even for high-income countries the authors only calculated a plastic fraction of 2 to 10%, a fact that is clearly dated. Even for low-income countries, the values given show that the average of plastic waste in MSW grew by more than 200%. (Cointreau-Levine, Listorti und Furedy 1998)

**Table 4: Global perspective on urban solid waste characteristics (waste fractions in %, moisture in kg/cm, heating value in kcal/kg) (Cointreau-Levine et al. 1998)**

| Composition of raw waste (by wet weight, %) country | Low-income country | Middle-income country | High-income |
|---|---|---|---|
| Vegetable/putrescible | 40 to 85 | 20 to 65 | 20 to 50 |
| Paper and carton | 1 to 10 | 15 to 40 | 15 to 40 |
| Plastic | 1 to 5 | 2 to 6 | 2 to 10 |
| Metal | 1 to 5 | 1 to 5 | 3 to 13 |
| Glass | 1 to 10 | 1 to 10 | 4 to 10 |
| Rubber, miscellaneous | 1 to 5 | 1 to 5 | 2 to 10 |
| Fines (sand, ash, broken glass) | 15 to 50 | 15 to 40 | 5 to 20 |
| Other characteristics: | | | |
| Moisture | 40 to 80 | 40 to 60 | 20 to 30 |
| Density in trucks (kg/cm) | 250 to 500 | 170 to 330 | 100 to 1 70 |
| Lower heating (kcal/kg) | 800 to 1100 | 1000 to 1300 | 1500 to 2700 |

Table 5 by Malakahmad, et al. (2011) comes closer to the actual fractions of the different types of waste in developing and industrialised countries. The plastic fraction found by the literature study was still higher than the one reported by the author, but the other values are very close. Moreover, a comparison between developing and industrialised countries is possible through this table. The organic fraction in developing countries is about three times higher than in industrialised countries. The paper fraction in industrialised countries is almost as high as their organic fraction, but in developing countries it is much lower. Glass and metal are overall quite low and the differences are not too significant. For the fraction of plastic waste, no clear differentiation can be made between developing countries and their industrialised counterparts. While this fraction generally increases with the growing of the economy, some European countries try to reduce that portion of their waste, such as the UK which produces a lower fraction of plastics than Malaysia. A final interesting factor is the moisture content. It demonstrates a clear differentiation between the countries: Industrialised countries' waste has a moisture content of around 30%, on the contrary, waste in developing countries is much wetter: The moisture content there is at least 55% and increasing up to 75%. (Malakahmad, Basri und Zain 2011)

**Table 5: Waste characteristics composition and comparison in developed and developing countries (waste fractions in %) (Malakahmad, Basri und Zain 2011)**

| Composition (% weight) | U.S.A. [10] | U.K. [11] | Malaysia [12] | Indonesia [13] |
|---|---|---|---|---|
| Organic | 22.6 | 19.0 | 45.5 | 60.0 |
| Paper | 37.6 | 29.0 | 30.0 | 2.0 |
| Metals | 8.3 | 9.0 | 5.10 | 2.0 |
| Glass | 6.6 | 8.0 | 3.9 | 2.0 |
| Textiles | 3.0 | 3.0 | 2.1 | NA |
| Plastic / leather / Rubber | 12.3 | 7.0 | 11.10 | 2.0 |
| Wood | 6.6 | 2.0 | NA | NA |
| Dust/ ash/ others | 3.1 | 21.0 | 4.3 | 33 |
| Refuse density (kg/m$^3$) | 100 | 147 | 230 | 200 |
| Per capita (kg/day) | 1.97 | 0.95 | 0.76 | 0.60 |
| Moisture content (%) | 20 | 30 to 35 | 65 | 55 to 75 |

The composition of MSW in Asia, as has been shown, has a very high organic fraction and a high share of recyclable materials. Appropriate processing, treatment and disposal technologies could, therefore, help retrieve a considerable amount of costs from waste recycling as well as save valuable space in the landfill. Notwithstanding what has been said above, one cannot simply aggregate over the whole of the Asian continent. Table 6 shall show the diversity of wastes across Asia.

**Table 6: Waste composition from various Asian countries (waste fractions in %) (Idris, Inanc und Nassir Hassan 2004)**

| Component (% by weight) | China (Shanghai) 1998 | India 1995 | Indonesia 1993 | South Korea 2001 | The Philippines 1999 | Turkey (Istanbul) 2000 | Japan 2000 |
|---|---|---|---|---|---|---|---|
| Organic matter | 67.3 | 41.8 | 70.2 | 32.8 | 49 | 43 | 34 |
| Paper and cardboard | 8.8 | 5.7 | 10.9 | 23.8 | 19 | 7.8 | 33 |
| Plastics | 13.5 | 3.9 | 8.7 | – | 17 | 14.2 | 13 |
| Glass | 5.2 | 2.1 | 1.7 | 2.8[a] | – | 6.2 | 5 |
| Metals | 0.7 | 1.9 | 1.8 | – | 6 | 5.8 | 3 |
| Textile and others | 4.5 | 44.6 (textile 4.3) | 6.2 | 40.6[b] | 9 | 23.1 | 12 |

[a] Metals and ceramics are included
[b] Ash is included

The differences are quite big, for example between Japan and South Korea on the one hand and the Philippines and Indonesia on the other hand. This is why the focus is put on developing tropical countries in this thesis. One consequence of the high fraction of putrescibles is that the waste is too wet to combust it in incinerators without the addition of fuel oil unlike waste in industrialized countries. For self-sustained incineration, the calorific value always has to be higher than 5,440kJ/kg. In case that the energy shall be used further a calorific value of 9,200 kcal/kg is needed. (The World Bank 1999, Idris, Inanc und Nassir Hassan 2004)

A short word to hazardous wastes: Hazardous waste is defined as toxic, inflammatory, reactive, explosive, or infectious waste. The lower level of legislation and surveillance in developing countries guarantees that batteries, bloody bandages, syringes, pesticides or hazardous solvents all find their way into the usual MSW. This endangers waste workers who usually handle the waste with their bare hands and can lead to infections or other occupational injuries.

Finally, in countries with low standards in their sanitation systems, human (and animal) faecal matter is a common part in MSW. It is collected either from the households together with the normal waste or through street-cleaning activities. In middle-income countries, faecal matter becomes part of the waste stream either by the disposal of used toilet tissue in the waste bin or by the discharge of the contents of septic tanks into open dumps. Even in high-income countries faecal matter can be found in the MSW due to the discarding of diapers into the garbage. (The World Bank 1999, Taylor und Allen 2006)

## 4.5. Emissions of landfills in tropical countries

Emissions from landfills influence the environment in a great number of ways: they can affect the soil, the atmosphere or the ground and surface water. The main emissions from a landfill are landfill gas and water trickling through the waste, called leachate. Besides these, there are also minor emissions like odours, aerosols, noise or vibrations.

The reactions occurring in a landfill that generate these emissions are either

- Physical processes such as the elution of readily soluble salts
- Biochemical processes, for example, the degradation of organic matter
- Chemical processes like redox-reactions
- Geotechnical processes, for example, consolidation processes
- Geochemical processes such as the formation of secondary compounds
- Geological processes like erosion of the soil

For all these processes water is needed which makes the water balance of landfills an important tool to predict emissions. A good overview of the emissions from a landfill is given in Figure 8 by Sanphoti, et al (2006):

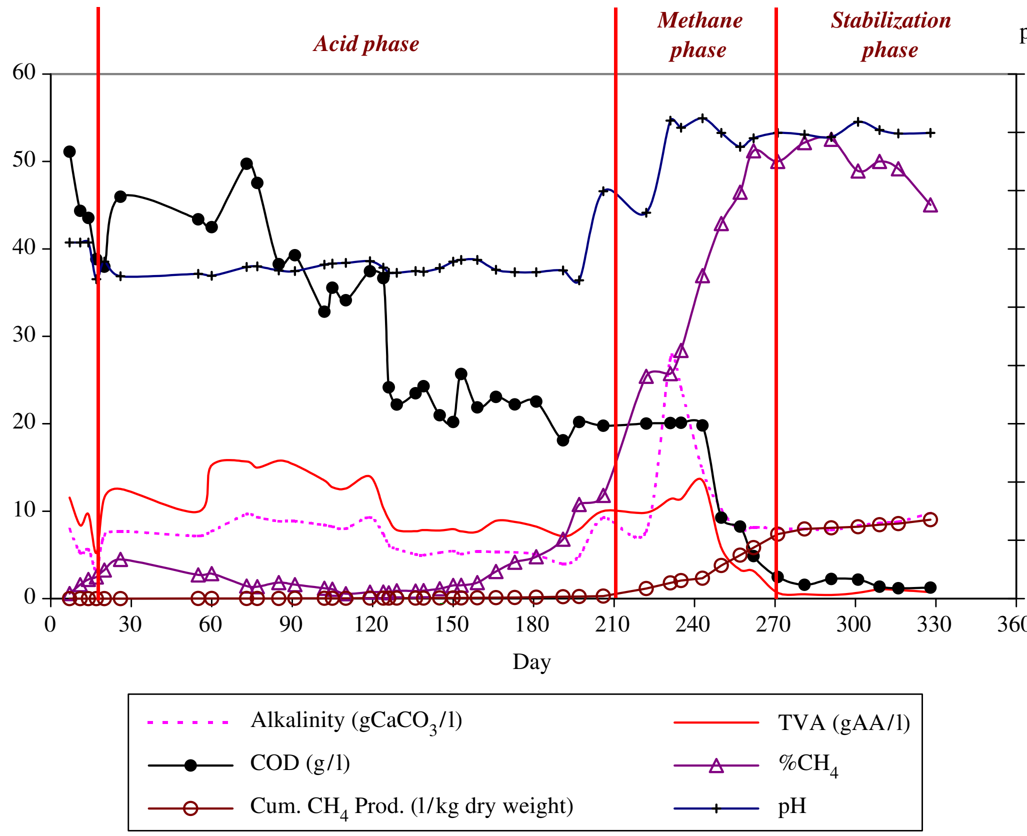



**Figure 8: Generalized phases and the changes in leachate, methane composition and production with time of the simulated landfill reactor without leachate recirculation (various units on vertical axis, see legend; Alkalinity given in grams Calcium Carbonate per litre, COD in gram per litre, the cumulative methane production in litre per kg dry weight, the total volatile acids in grams ascorbic acid per litre, methane in %, and pH-values) (Sanphoti, et al. 2006)**

The quantity and the quality of the emissions from landfills are determined by the composition of the waste input (compare with the chapter on Waste characterization), the amount of water infiltrated (compare with the chapter on the climatic water balance), the physical/chemical conditions (pH, redox, Leachate characterisation), and the water flow pattern (the moisture distribution). (Fellner 2011)

### 4.5.1. Leachate

#### *a. Leachate generation*

Introduction

As soon as waste is dumped, it becomes part of the hydrological system of the dumpsite. Most waste is not inert and, as such, consumes oxygen when degrading. This changes the redox potential of the liquid and mobilizes soluble material to be washed out in physical processes. On the other hand, water is also produced in biochemical processes such as the biodegradation of organic wastes. Furthermore, precipitation or ground water infiltrates the landfill and percolates through the waste. Additionally, this water provides a medium for organic wastes to degrade at a faster pace.

In total there are three stages of waste decomposition activity in a landfill:

1. Hydrolysis
2. Acidogenic phase
3. Methanogenic phase

In the first phase organic matter is decomposed aerobically through several hydrolysis reactions. The oxygen present in the waste is consumed and since ideally, the waste is compacted and in a closed cell, no fresh oxygen can be supplied. When the oxygen is depleted, it is replaced by nitrate ($NO_3^-$), manganese ($MnO_2$), iron (Fe(OH)3) and sulphate ($SO_4^{2-}$). Anaerobic conditions are normally reached within less than a month. In the hydrolysis stage intermediate products are formed such as amino acids, fatty acids, sugar and glycerine; almost no leachate is produced and the phase does not determine leachate quality strongly. The hydrolysis stage is exothermic which means that a lot of energy is generated and the landfill heats up. In case the heat can be kept within, this results in an acceleration of the next two stages.

In the acidogenic phase, cellulose and other putrescibles are hydrolysed to soluble organic compounds. During acidogenesis these products are fermented to volatile fatty acids (Proprionic acid, Butyric acid) and alcohols. In the acetogenesis they are further converted to acetic acid, $CO_2$ and $H_2$. When the potential for redox reactions decreases, sulphate ($SO_4^{2-}$) is reduced to sulphides which, in turn, can precipitate iron, manganese and heavy metals, which have been dissolved through acid fermentation. The higher the amount of putrescibles in the waste, the longer this acidogenic phase can last and the more food is produced for methanogens (bacteria that oxidize methane) in the third phase. Due to the high concentration of free fatty acids in the leachate and the high partial pressures of $CO_2$, the pH value of the leachate decreases to 5 or 6; it also contains high amounts of ammonia (NH3), total organic carbon (TOC), biochemical oxygen demand (BOD of usually >10 000 mg/l) and BOD5/COD ratios (usually >0.7).

At the limit between the acidogenic phase and the methanogenic phase lies the intermediate anaerobiosis. There the methane ($CH_4$) concentration slowly starts to increase while $H_2$, $CO_2$ and volatile fatty acids (VFA) are decreasing. pH values are rising and less calcium, iron, manganese and heavy metals are washed out.

During waste degradation processes, conditions become anaerobic and methanogenic bacteria start to inhabit the landfill. In the methanogenic phase they produce $CO_2$ and $CH_4$ by depleting organic compounds. The $CO_2$ can be found dissolved in water which produces carbonic acid ($H_2CO_3$) and then dissociates to the bicarbonate anion ($HCO_3^-$). This product is usually found in high concentrations in the leachate generated by the methanogenic phase. On the other hand, the leachate has quite low BOD values, low ratios of BOD/COD, low volatile acids and low TDS. This indicates that almost all of the organic compounds have been dissolved in the leachates, yet waste stabilization will not be completed for another few decades. Ammonia is still released from areas in the waste where the acidogenic stage has not been completed but also the third phase still releases some. The pH value is almost neutral and metals are immobilised as sulphides in the waste since redox reactions have halted. The rate at which the methanogenic phase is reached is controlled by a number of factors, including the content of readily putrescible waste. (Taylor und Allen 2006, Stuart und Klinck 1998, Fellner 2011)

Figure 9 by Farquhar (1998) summarizes these statements. It shows the different configurations of leachate according to the age of a landfill. In the beginning, mainly the easily soluble contaminants make up the leachate, followed by readily biodegradable contaminants. Finally, when the landfill reached a certain age, the contaminants that are easily dissolved have all been washed out and the leachate is made up of contaminants that are harder to dissolve or to biodegrade.

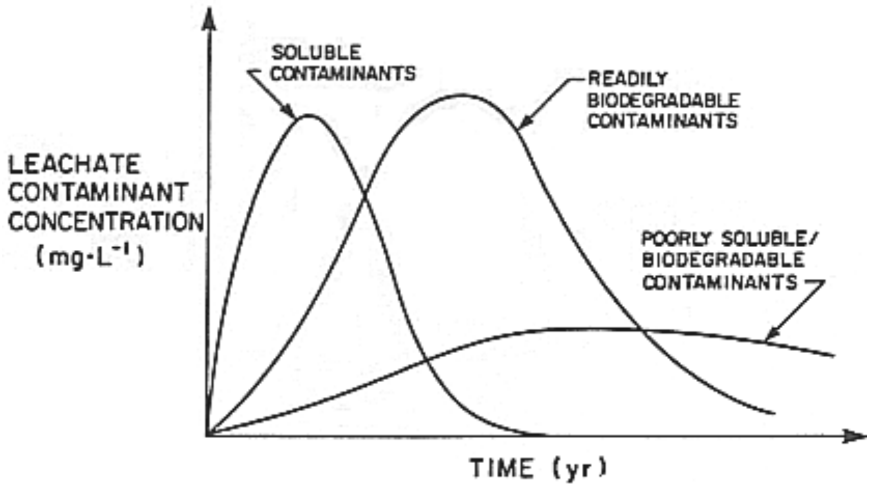



**Figure 9: Leachate concentration variation with time (Farquhar 1998)**

## Climatic water balance

The amount of leachate generated is determined by the water balance of a landfill:

Precipitation – Evapotranspiration – Runoff – Leachate + Water content of the waste + Recirculated Leachate +/- Storage = 0 (1.)

The climatic water balance is easily established for any site since it uses mainly published, easily available data. The general probability for a landfill to generate leachate can be broadly calculated by measuring whether evapotranspiration potential per annum is higher or lower than annual precipitation. The equation is summarized in Figure 10 by Farquhar (1998). While he omits recirculated leachate, he adds groundwater inflow which especially in developing countries where waste is dumped without any control or even close to rivers is a factor which must not be forgotten. Leachate is called percolation water in his graph.

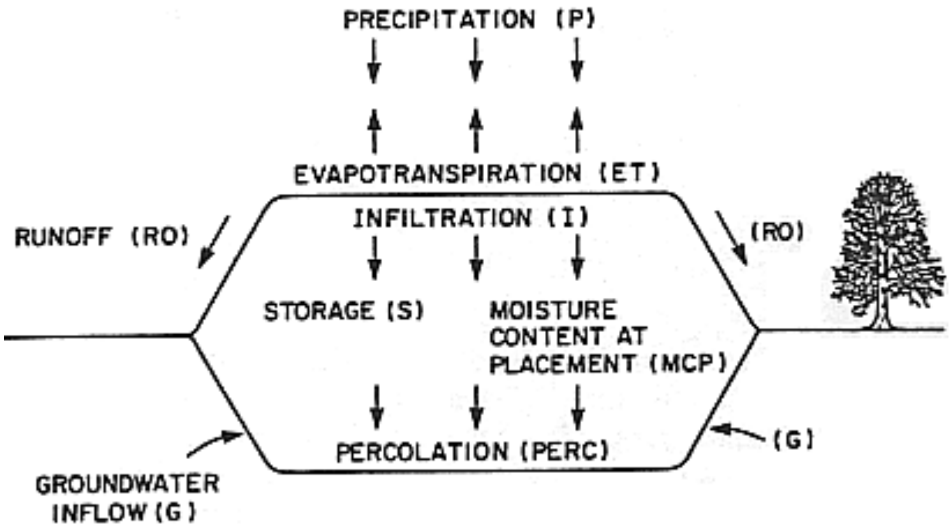



**Figure 10: Water balance (Farquhar 1998)**

In general, all the terms are relatively easy to calculate. An exception is the measurement of evaporation. Evaporation can be measured with an evaporation pan; commonly in use is a "Class A-evaporation pan" – a cylinder with a radius of 60.3cm and a depth of 25cm. It is placed next to or on the landfill on a level base and enclosed by a fence to prevent animals drinking from it. The pan is filled with water up to a height of 20cm in the beginning. Then, the daily evaporation is measured by the sinking of the water level. After 24 hours it is refilled to its original level. Evidently, also precipitation is taken into account. In tropical climates and/or during strong rainfall events, special care has to be taken that no spill-overs occur which would falsify the results of the measurement. In such a case, water might has to be decanted to keep the calculations correct. Other systems to measure evaporation are also common. Although evaporation is one of the factors which are more difficult to measure it is certainly one of the main influences that make a difference between emissions from temperate and tropical landfills. In Figure 11 (Fellner 2011), the difference between the water balance of an Austrian city, Linz, and the Syrian capital, Damascus, is depicted. It clearly shows that the amount of leachate mainly depends on the amount of precipitation and on how much of the incoming water is evapotranspirated again. Tropical climates have not only very high solar irradiation but also a longer sunshine duration than usual. Both factors are important for the value of evapotranspiration.

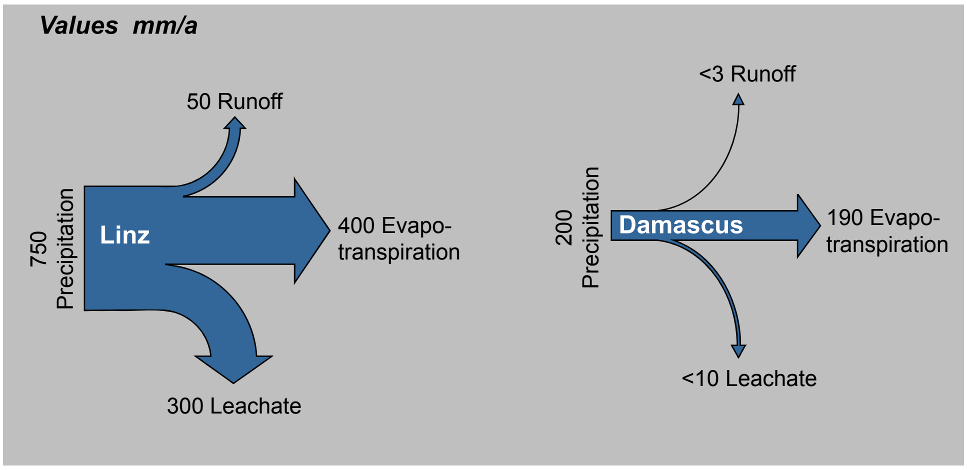



**Figure 11: Water balance for Linz and Damascus (mm/a is a measure for precipitation. 1 mm equals 1 litre per m²) (Fellner 2011)**

Since precipitation and evapotranspiration seem to be most important in the water balance, Blight (2006) proposes to ignore more difficult-to-measure factors such as moisture storage capacity of the waste, run-off and the upward capillary moisture movement. This does not alter the results strongly but provides a more conservative estimate of the amount of leachate that might be produced. Blight also proposes a classification for landfills according to the climatic water balance (B). In cases where in the simplified equation

$$B = R - E \qquad (2.)$$

(where *R* is the annual rainfall and *E* the corresponding evapotranspiration from the landfill surface), B is calculated as negative, the landfill is classified as B-. This means that no leachate will be generated or that it is generated less frequently than every five years (<20%). In such a landfill, no base liner or other leachate collection or treatment system is needed. In countries or regions with a wetter climate and more precipitation, the landfill might be classified as B+. These landfills need a base liner as well as a leachate collection system. Since actual evaporation from landfills is almost impossible to measure, either pre-calculated A-pan values are taken or the solar energy balance technique by Blight might be used. Normally a coefficient of 0.7 is used for the ratio between A-pan evaporation and the evaporation from soil or a landfill (Ariyawansha, et al. 2010, G. Blight 2006). In observations, Blight measured that actual evapotranspiration is much lower than the assumed 0.7 times of A-pan evaporation. The actual coefficient comes closer to 0.4. In general, what can be said is that evapotranspiration in the long run cannot be higher than precipitation. For calculating whether a landfill is B- or B+ the best solution is to take into account not only selected meteorological data but all data that is available for, e.g., 30 years or longer (or any data which is available, even if the period of time might be much shorter). (G. Blight 2006)

The rate for evapotranspiration could also be simply estimated by using a lysimeter. When determining the moisture content of the waste initially inputted into the lysimeter and the moisture content at the end, this gives, according to the mass balance, a coefficient for ET. In a study by Ariyawansha, et al (2010), this coefficient was 0.826 for a landfill in Sri Lanka (Ariyawansha, et al. 2010). The difference to the study by Blight (2006) may be explained by the different climatic conditions: In tropical countries the amount of precipitation is higher than in temperate climates, and, due to higher temperatures and higher solar radiation, evapotranspiration might be different and the water content of the waste is bigger owing to the larger fraction of organic compounds in the MSW. Consequently, the water balance of tropical landfills is quite different from landfills in more temperate climates. Sri Lanka is a tropical country with a lot of precipitation daily as well as yearly. South Africa, in comparison, is mainly a Semiarid Dry Climate (B on the Köppen map).

Ariyawansha, et al (2010) also found that although there are many factors influencing the quantity of leachate produced (precipitation, moisture content and density of waste, evaporation and gas production), the amount of precipitation is the factor with the highest (and almost the only) impact. Figure 12 by Sao Mateus, et al (2012) shall demonstrate this more clearly: cumulative rainfall and cumulative leachate production occurred throughout the whole time of the study (about 5 years) almost to the same extent and were clearly linked. (Sao Mateus, Machado und Barbosa 2012)

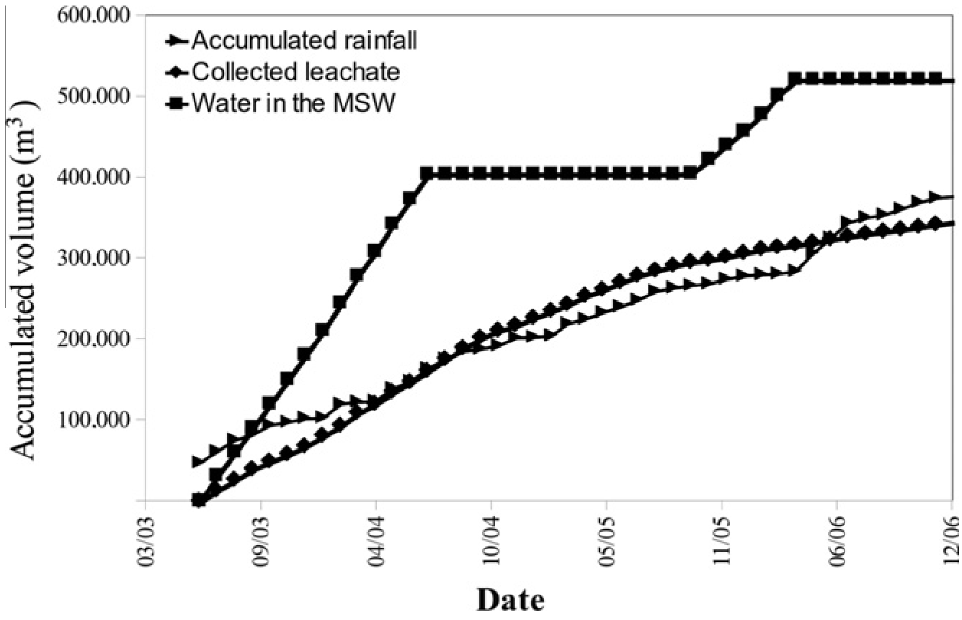



**Figure 12: Accumulated volumes of water in the cell (given in m³ for a cell surface of 4.06 hectares) (Sao Mateus, Machado und Barbosa 2012)**

Several authors have researched the water balance in MSW landfills, a few of which are named in Table 7 by Sao Mateus, et al (2012).

**Table 7: Research into municipal solid waste (MSW). Some of the papers dealing with the water balance (Sao Mateus, Machado und Barbosa 2012)**

| Author and year | Country |
|---|---|
| Blight and Fourie (1999) | South Africa |
| Capelo Neto et al. (1999) | Brazil |
| Monteiro et al. (2001) | Brazil |
| Dwyer (2001) | USA |
| Gomes et al. (2002) | Brazil |
| Pessin et al. (2002) | Brazil |
| Medeiros et al. (2002) | Brazil |
| Lange et al. (2002) | Brazil |
| Cortázar et al. (2003) | Spain |
| Visvanathan et al. (2003) | Thailand |
| Marques and Manzano (2003) | Brazil |
| Fellner et al. (2003) | Austria |
| Gisbert et al. (2003) | France |
| Blight et al. (2003) | South Africa |
| Albright et al. (2003) | USA |
| Hadj-hamou and Kavazanjian (2003) | USA |
| Marques and Vilar (2003) | Brazil |
| Simões et al. (2003) | Brazil |
| Padilla et al. (2007) | Brazil |
| Coelho et al. (2007) | Brazil |
| Catapreta (2008) | Brazil |

### Leachate in the tropics

From the results a clear difference in leachate generation was observed in tropical climates. On the one hand, there are differences in leachate generation between tropical and temperate climate zones. On the other hand, variations in leachate generation can be observed between the different seasons in tropical climates. A first overview shall be given in Figure 13 by Tränkler et al. (2001) which describes the monthly mean values of the different parameters of the climatic water balance in the tropics throughout the year, on a basis of 20 years.

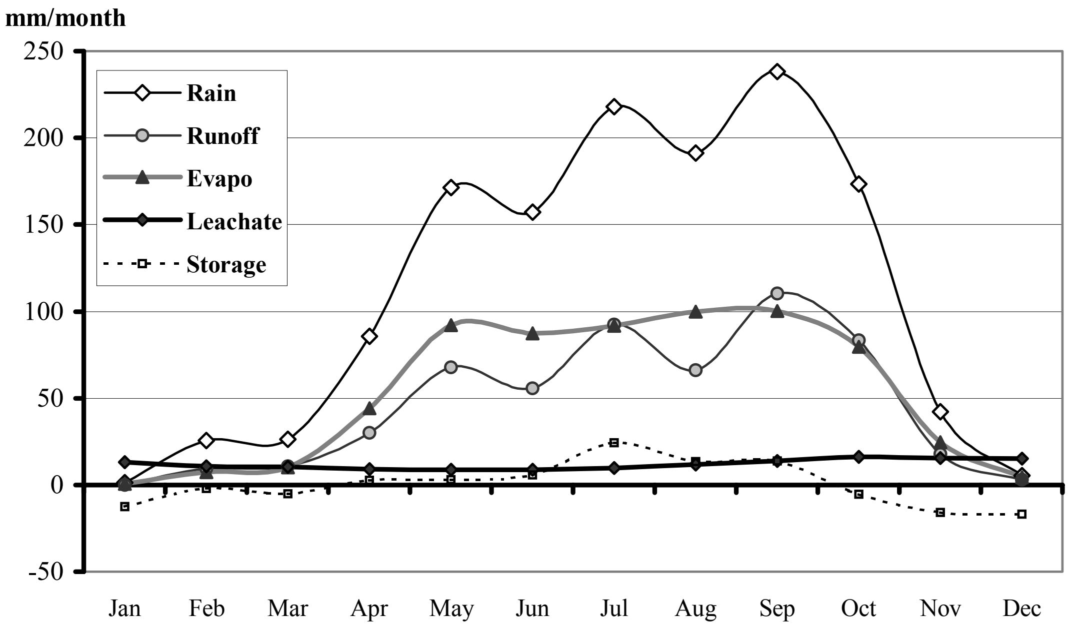



**Figure 13: Monthly mean values of water balance elements (basis 20 years) (Tränkler, Manandhari, et al. 2001)**

Hernández-Berriel, et al. (2008) determined from bioreactor studies that, in the dry season, landfill sites will produce smaller leachate volumes, which are more concentrated (Hernández-Berriel, et al. 2008). In another study from South America, Machado, et al. (2010) noted that during the prolonged dry periods the generation of leachate was stopped or strongly reduced, owing to a lack of moisture in the lysimeters. Furthermore, in the open-dump cell in their experiment, nearly 70% of the rainfall was turned into leachate (Machado, et al. 2010, Sao Mateus, Machado und Barbosa 2012). Other authors experienced similar outcomes (Tränkler, Manandhari, et al. 2001, Kuruparan, et al. 2003, Visvanathan, Tränkler, et al. 2002, Visvanathan, Tränkler, et al. 2003). They showed that biological decomposition and, therefore, leachate generation stopped completely during the dry season due to low soil moisture levels (several metres down in the landfill) and started to increase shortly after the beginning of the rainy season.

Ariyawansha, et al. (2010) showed that one of the biggest influences for leachate generation was precipitation. In Figure 14 it can be seen that the factors rainfall, evapotranspiration and leachate are strongly correlated. From year two of the experiment, the values for rainfall and leachate started to vary and the leachate production almost stagnated starting at about 4 years – maybe indicating that the landfill had stabilized and would not produce such high emissions of leachate anymore in the future. In total, almost 6000 mm of cumulative leachate was produced during the five years. This equals 1200mm per year (Ariyawansha, et al. 2010).

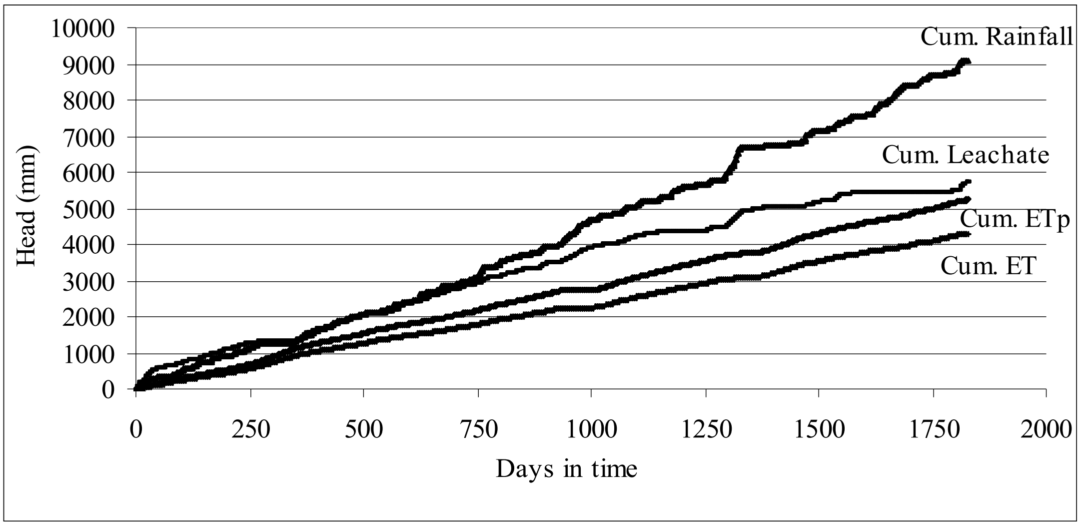



**Figure 14: Temporal variations of components of water balance (1mm being 1 litre per $m^2$) (Ariyawansha, et al. 2010)**

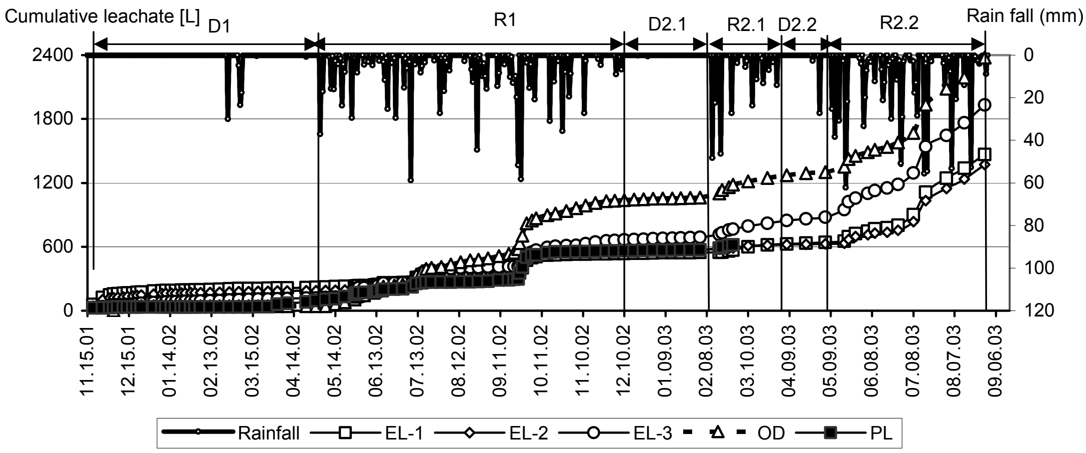
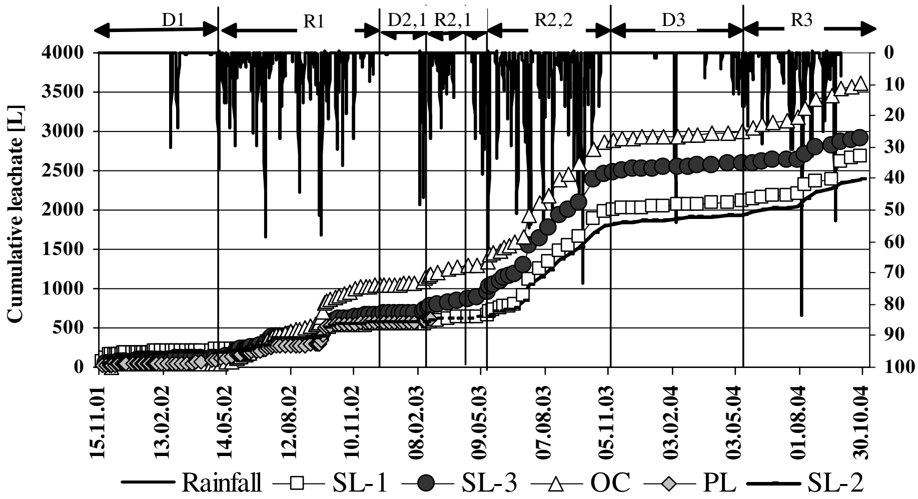



**Figure 15: Relationship between rainfall and cumulative leachate production from lysimeters (The litres given in this graph are produced from 1.54m$^2$, since the lysimeter is a circle with 1.4m diameters. 1 litre from this graph therefore compares to 0.65mm.) (Kuruparan, et al. 2003)**

In the lysimeter study by Kuruparan, et al. (2003), leachate generation from five different lysimeters was compared with the amount of rainfall. All of them showed direct correlations between the amount of leachate produced and the amount of precipitation. As one would expect the highest amount of leachate was generated by the open dump simulation, reaching a cumulative value of 2400 litres after almost two years of operation. This can be expressed as 780 mm of leachate per year (Kuruparan, et al. 2003).

Tränkler, et al. (2005) also were able to show clear connections between the rainy seasons and an increase in cumulative leachate, on the one hand, and dry seasons and a stagnation in cumulative leachate, on the other. After almost three years of operation, a total amount of 3500 litres of leachate has been generated by the open cell lysimeter. This equals 760 mm per year (Tränkler, Visvanathan, et al. 2005).



* D- Dry season, R- Rainy season

**Figure 16: Relationship between rainfall and cumulative leachate production from landfill lysimeters (The litres given in this graph are produced from 1.54m², since the lysimeter is a circle with 1.4m diameters. 1 litre from this graph therefore compares to 0.65mm.) (Tränkler, Visvanathan, et al. 2005)**

Also the authors Visvanathan, et al. (2003) proved a strong correlation between seasonal variations and leachate generation. Most pronounced in the open dump simulation, whenever a rainfall event occurred, the cumulative amount of leachate would also increase. In warm climates, this increase after precipitation events occurred relatively fast (Visvanathan, Tränkler, et al. 2002). This trend was also clearly observable in the other lysimeters. The open dump generated 1,200 litres of leachate after one and a half years of operation. This equals 520mm per year (Visvanathan, Tränkler, et al. 2003).

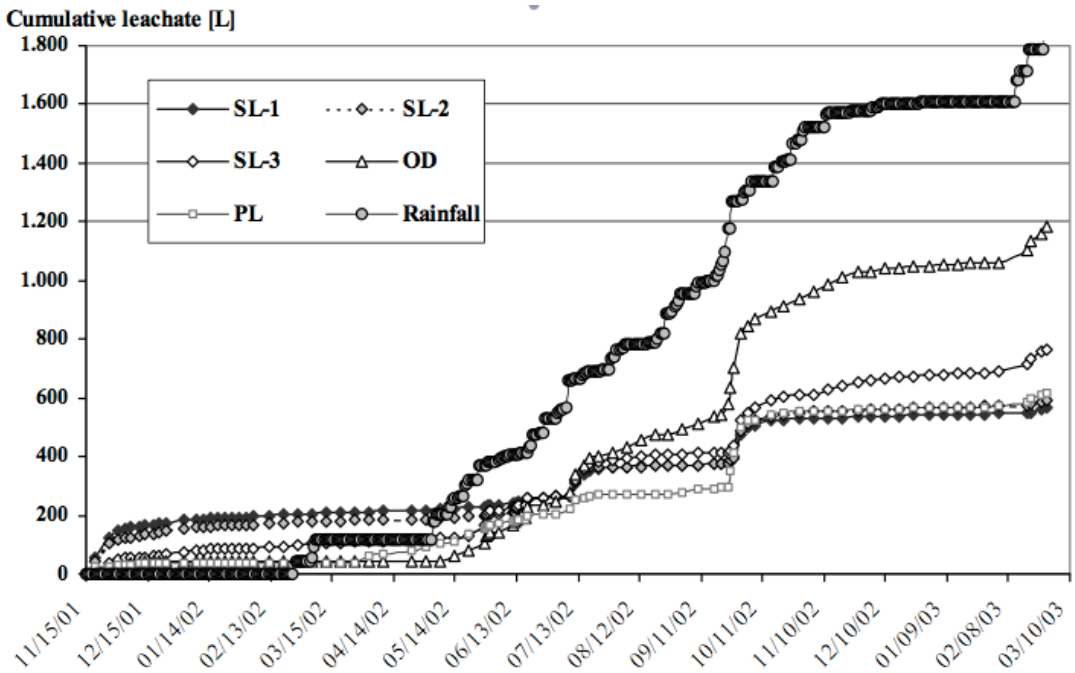



**Figure 17: Leachate generation with rainfall (The litres given in this graph are produced from 1.54m$^2$, since the lysimeter is a circle with 1.4m diameters. 1 litre from this graph therefore compares to 0.65mm.) (Visvanathan, Tränkler, et al. 2003)**

Madera and Valencia-Zuluaga (2009) provided a value for leachate generation in a landfill in Colombia. At the Presidente Regional Landfill, receiving 500 tons of solid waste per day, 2.0 to 2.5 litres of leachate are produced per second (Madera und Valencia-Zuluaga 2009). Tränkler, et al. (2001) found different results: they were not able to prove a direct relationship between leachate generation and total precipitation, but a connection was visible between the run-off and evapotranspiration with the leachate generation (Tränkler, Manandhari, et al. 2001).
In young landfills, more leachate might be produced due to the fact that the structures are still coarser or non-homogenous (Visvanathan, Tränkler, et al. 2002). Plastic further increases the amount of water that is released by a landfill before the field capacity is reached.

To compare these findings with the quantity of leachate produced in temperate climate zones, the cumulative leachate data of some authors (Ehrig und Witz 2004, Koss und Trapp 2003, Kuruparan, et al. 2003, Schachermayer und Lampert 2010, Tränkler, Visvanathan, et al. 2005, Visvanathan, Tränkler, et al. 2003, Visvanathan, Karthikeyan und Park 2010) have been taken to calculate the yearly average leachate production. For tropical climates, these values vary between 760 mm per year and 1200 mm per year. In temperate climates these rates are much lower. An average landfill in the East of Austria, for example, might produce 150 mm of leachate per year, in Salzburg or Tyrol, due to the higher precipitation about 500 mm can be produced per year. Those are older landfill types that do not yet adhere to the newer Austrian legislation which limits the maximum leachate emissions to 5% of the yearly precipitation. In Salzburg, with 1200mm the allowed emission would be 60 mm.

These discoveries are found in Figure 18 and Figure 19. It is obvious that the cumulative yearly leachate generation is much higher in the tropics albeit the sustained dry phase each year. Not only the cumulative leachate quantity over the year has been analysed but also the leachate generation per month, to take seasonal variations into account. (Ehrig und Witz 2004, Koss und Trapp 2003, Kuruparan, et al. 2003, Schachermayer und Lampert 2010, Tränkler, Visvanathan, et al. 2005, Visvanathan, Tränkler, et al. 2003, Visvanathan, Karthikeyan und Park 2010)

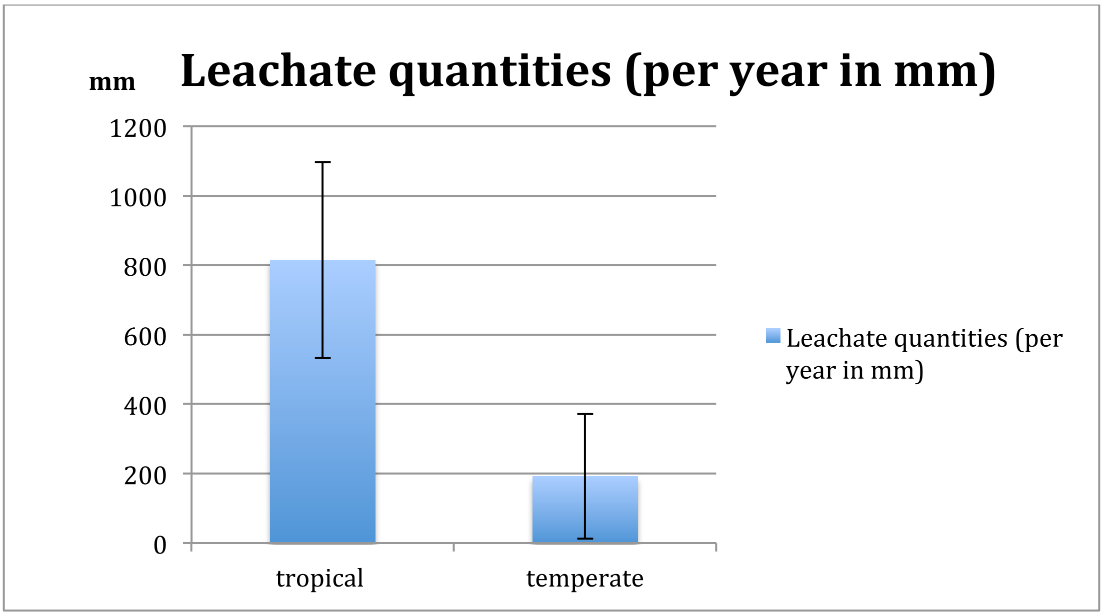



**Figure 18: Leachate quantities per year in tropical or temperate countries (in mm). Temperate leachate quantities (Ehrig und Witz 2004, Koss und Trapp 2003, Schachermayer und Lampert 2010) and tropical leachate quantities (Kuruparan, et al. 2003, Tränkler, Visvanathan, et al. 2005, Visvanathan, Tränkler, et al. 2003, Visvanathan, Karthikeyan und Park 2010).**

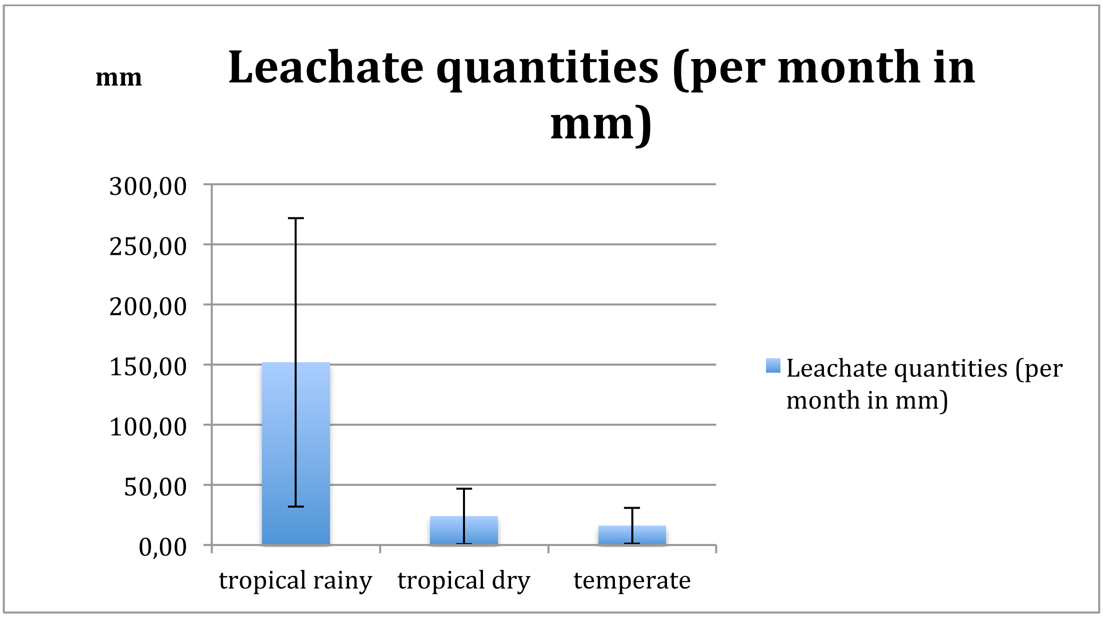



**Figure 19: Leachate quantities per month according to season (in mm). For the values of the temperate leachate quantities, the values of the previous table have been divided by 12 (Ehrig und Witz 2004, Koss und Trapp 2003, Schachermayer und Lampert 2010). For tropical leachates, values from different studies have been taken and divided by the number of months the rainy or dry season was experienced in the respective year (Kuruparan, et al. 2003, Tränkler, Visvanathan, et al. 2005, Visvanathan, Tränkler, et al. 2003, Visvanathan, Karthikeyan und Park 2010).**

### *b. Leachate characterization*

#### Leachate composition

Not only the generation of leachate varies in the tropics but also its composition is different from leachates in more temperate climates and depending on the season. As Umar, et al. (2010) stated, the characteristics of landfill leachate depend on a number of factors such as the waste composition, the amount of precipitation, the hydrology of the landfill site, the waste compaction, the landfill cover design, procedures for leachate sampling, and the interaction of leachate with the environment, landfill design and operation. Additionally, leachates vary depending on the phase of decomposition of the landfill and the oxygen level in the waste pile. (Umar, Aziz und Yusoff 2010, Aziz, et al. 2010). This shall be demonstrated by Table 8 (Kjeldsen, et al. 2002)

**Table 8: Leachate composition with differences between acid and methanogenic phase (in mg/l except when stated differently) (Kjeldsen, et al. 2002)**

| Parameter | Acid phase | | Methanogenic phase | | Average |
|---|---|---|---|---|---|
| | Average | Range | Average | Range | |
| pH | 6.1 | 4.5-7.5 | 8 | 7.5-9 | |
| Biological Oxygen Demand ($BOD_5$) | 13000 | 4000-40000 | 180 | 20-550 | |
| Chemical Oxygen Demand (COD) | 22000 | 6000-60000 | 3000 | 500-4500 | |
| $BOD_5$/COD (ratio) | 0.58 | | 0.06 | | |
| Sulfate | 500 | 70-1750 | 80 | 10-420 | |
| Calcium | 1200 | 10-2500 | 60 | 20-600 | |
| Magnesium | 470 | 50-1150 | 180 | 40-350 | |
| Iron | 780 | 20-2100 | 15 | 3-280 | |
| Manganese | 25 | 0.3-65 | 0.7 | 0.03-45 | |
| Ammonia-N | | | | | 740 |
| Chloride | | | | | 2120 |
| Potassium | | | | | 1085 |
| Sodium | | | | | 1340 |
| Total phosphorus | | | | | 6 |
| Cadmium | | | | | 0.005 |
| Chromium | | | | | 0.28 |
| Cobalt | | | | | 0.05 |
| Copper | | | | | 0.065 |
| Lead | | | | | 0.09 |
| Nickel | | | | | 0.17 |
| Zinc | 5 | 0.1-120 | 0.6 | 0.03-4 | |

The pH value is one of the first indicators of the transition from the acidogenic to the methanogenic phase. It normally moves from 6 or lower to about 8. The biological oxygen demand moves from above 10,000mg/l to below 500mg/l along with the chemical oxygen demand which decreases from 22,000mg/l to 3,000mg/l. The $BOD_5$/COD ratio changes from 0.6 to 0.05 which indicates that the degradability of organic carbon decreases strongly. Measurements for inorganic compounds all decrease due to the fact that the leachate is less acid and therefore less capable of mobilizing these compounds. Magnesium decreases from 470mg/l to 180mg/l, Iron from 780mg/l to 15mg/l, and manganese from 25mg/l to 0.7mg/l. Zinc is reduced from 5m/l in the acidogenic phase to 0.6mg/l in the methanogenic phase. Ammonia-nitrogen and total phosphorus are only measured on an overall basis, not separately according to decomposition phase of the landfill, since this does not influence their values to a measurable extend. The value of ammonia-N is 740mg/l, and total phosphorus amounts to 6mg/l. (Kjeldsen, et al. 2002)

Globally, leachate consists of certain contaminants that can be summarized in four groups. The biggest group owing to the decomposition reactions occurring in the landfill is the dissolved organic carbon. Dissolved organic carbon is a parameter that includes a wide variety of organic compounds such as small volatile acids or – more commonly – fulvic and humic acids. These colour the leachates yellowish-brown and increase its COD level. Up to date it is quite difficult to determine exactly which components are in the DOC; achieving this would increase the predictability of leachate characteristics highly. The second biggest group are the inorganic macro components. These include nitrogen, ammonium, calcium, magnesium, iron, manganese, sulphates as well as bicarbonates. The third group are the heavy metals such as cadmium, copper, lead, nickel and zinc. These exist in trace amounts in the leachate. The last – because smallest – group are the anthropogenic organic compounds (hydrocarbons, chlorinated solvents and phenols). (Kjeldsen, et al. 2002, Stuart und Klinck 1998)

The overall characteristics of leachate from landfills from temperate climates are listed in Table 9 adapted from Kjeldsen, et al. (2002), Taylor and Allen (2006), and Robinson (2005).

### Table 9: Leachate composition of temperate landfills

| Leachate composition (in mg/l except mentioned differently) of temperate landfills | |
|---|---|
| *Parameter* | *Value* |
| **pH [ ]** | 6.75 |
| **Electrical conductivity [µS/cm]** | 18750 |
| **Total solids** | 31000 |
| *Organic matter* | *Value* |
| **BOD5** | 28510 |
| **COD** | 76070 |
| **BOD5/COD ratio** | 0.41 |
| *Inorganic compounds* | *Value* |
| **Total nitrogen** | 2382 |
| **Ammonia-N** | 1125 |
| **Total phosphorus** | 11.55 |
| **Total iron** | 2752 |
| *Heavy metals* | *Value* |
| **Zink** | 500 |

In temperate climates, pH-values are on average between 6 and 8; the electrical conductivity lies between 2,500 and 35,000µSievert/cm and total solids are calculated as lying between 2,000 and 60,000mg/l. $BOD_5$ levels in leachates of temperate climates are situated between 20 and 57,000mg/l, COD levels between 140 and 152,000/l and the ratio between the two ($BOD_5$/COD ratio) lies at around 0.40. The leachate comprises between 60 and 4,700mg/l of total nitrogen of which between 50 and 2,000mg/l are ammonia-nitrogen. Other inorganic compounds like phosphorus make up around 12mg/l, iron between 3 and 5,500mg/l, and magnesium between 30 and 15,000mg/l. Heavy metals range from very low levels in landfills that ensure the quality of waste that gets dumped there (0.03mg/l) to extremely high levels at landfills with less stringent control (1000mg/l). The average level of zinc can therefore be found at 500mg/l. These leachate levels are ordinarily a factor 1000 to 5000 higher than the value of the same compounds found in the groundwater. (Kjeldsen, et al. 2002)

As the landfills get older and the waste deposited in it stabilizes, the leachate composition changes and the emissions tend to decrease strongly. Sanphoti, et al. (2006) found that this fact might be useful when considering using old landfills for the cleaning of leachates from young landfills (Sanphoti, et al. 2006).

### Table 10: Leachate composition of tropical landfills

| Leachate composition (in mg/l except mentioned differently) of tropical landfills | |
|---|---|
| *Parameter* | *Value* |
| **pH [ ]** | 7.41 |
| **Electrical conductivity [µS/cm]** | 3517 |
| **Total solids** | 7529 |
| *Organic matter* | *Value* |
| **BOD5** | 3882 |
| **COD** | 11217 |
| **BOD5/COD ratio** | 0.45 |
| *Inorganic compounds* | *Value* |
| **Total nitrogen** | 919 |
| **Ammonia-N** | 967 |
| **Total phosphorus** | 11.42 |
| **Total iron** | 720 |
| *Heavy metals* | *Value* |
| **Zink** | 35 |

The characteristics of leachate from landfills in tropical climates are listed in Table 10. Broadly speaking, most values are much lower for tropical landfills than for landfills in temperate climates. This stems from the greater amount of water that flows through a landfill in a tropical climate as shown in the chapter on Leachate in the tropics. The averaged pH-value of 7.4 is higher than in temperate climates. This might be because the landfills – due to the higher water contents – go through the biodegradation processes faster and reach the methanogenic phase faster. Electrical conductivity gives values from as low as 12 to as high as 28,000µSievert/cm versus 18,000 in temperate landfills. Also the amount of total solids is much lower (2,500 to

12,500mg/l) than in landfills in temperate climates; yet there were only very few measurements of this factor in the studies included in the calculation for the table.

The biochemical oxygen demand in 5 days was lower by almost a factor 10: averaged 4,000mg/l versus 28,000mg/l in temperate landfills. The chemical oxygen demand varied strongest from source to source with values ranging from 200mg/l to 100,000mg/l for tropical leachate. The BOD5/COD ratio, however, was quite similar to temperate situations: an average of 0.45 in comparison to an averaged 0.41. This can indicate that, while the processes within landfills occur at different speeds and need a different amount of time, the resulting stage of the landfill is similar all over the globe. The concentration of the leachate might be similar at the end but the duration in which the drop occurred is much shorter compared to temperate landfills. Also, the bigger amount of water leads to a dilution effect where, although the concentrations are similar, the total amount of pollutants is higher in the leachates of the tropical climates due to the bigger cumulative amount of leachate produced (Tränkler, Visvanathan, et al. 2005).

Total nitrogen, ammonia-nitrogen and iron are equally lower in tropical climates, with an average of 900mg/l, 950mg/l and 700mg/l respectively (each ranging from low numbers such as 6 and 50 to high levels such as 1500mg/l), yet the amount for phosphorus is quite similar for tropical and temperate leachate, with 11mg/l approximately. Also the value for zinc (which has been chosen to represent the heavy metals simply due to the fact that most data was provided) is comparatively lower (around 2mg/l) than the zinc concentrations in leachate of temperate landfills (500mg/l).

### Seasonal variation in the leachate composition

Leachate characteristics vary not only according to the climate in which the landfill can be found but they also change with the various seasons. To compare such differences, research work focusing on leachate characteristics in the tropics and especially their seasonal variations have been analysed. When there are blanks in the tables this means that the authors did not provide any figures for this factor.

Aluko et al. (2003) researched a landfill in Ibadan, Nigeria. They seem to always have opposite results for all the parameters assessed. Chiemchaisri and Srisukphun

(2003) did a study in Bangkok, Thailand with six different lysimeters researching the performance of a soil and compost mixture in leachate purification at an intermediate cover layer in a tropical landfill (Chiemchaisri und Srisukphun 2003). Hernández-Berriel, et al. (2008) studied the effect of two different moisture regimes on the anaerobic degradation of MSW with two lysimeters in Metepec County, in the State of Mexico (Hernández-Berriel, et al. 2008). Mangimbulude, et al. (2009) studied the leachate characteristics of Jaribarang landfill near Semarang, Indonesia. Kuruparan, et al. (2003) and Tränkler, et al. (2005) both studied lysimeters in the tropical environment of Bangkok, Thailand. Both continued their experiments for at least two years and were able to observe more than one dry and one rainy season. In fact, over the course of two years, three dry and three rainy seasons where examined and also changes in leachate observed for six consecutive seasonal changes (Kuruparan, et al. 2003, Tränkler, Visvanathan, et al. 2005, Mangimbulude, et al. 2009).

### Table 11: Seasonal pH variations

| Seasonal pH [ ] | Results |
|---|---|
| Aluko et al. 2003 | |
| dry | 8 |
| rainy | 8.3 |
| Chiemchaisri, Srisukphun 2003 | |
| dry | 5.3 |
| rainy | 5.3 |
| Hernandez-Berriel et al. 2008 | |
| dry | 6.25 |
| rainy | 6.325 |
| Mangimbulude et al. 2009 | |
| dry | 8.3 |
| rainy | 8.2 |

The pH-values are quite similar. An obvious result since the pH-value is not affected by the amount of water in the landfill, but simply by the degradation stage of the landfill.

**Table 12: Seasonal electrical conductivity variations**

| Electrical conductivity (µS/cm) | Results |
|---|---|
| Aluko et al. 2003 | |
| dry | 4807 |
| rainy | 5662 |
| Hernandez-Berriel et al. 2008 | |
| dry | 21.65 |
| rainy | 20.25 |
| Mangimbulude et al. 2009 | |
| dry | 12.4 |
| rainy | 11.7 |

Electrical conductivity also does not react strongly to seasonal changes. While Aluko et al. (2003) found slightly lower values for the dry season, Hernández-Berriel, et al. (2008) and Mangimbulude, et al. (2009) found that electrical conductivity was higher in the dry season (surely due to higher concentrations of contaminants in the leachate and probably due to a lower rate of dilution).

The organic factors reacted more according to what was expected.

**Table 13: Seasonal BOD variations**

| Seasonal BOD5 (mg/l) | Results |
|---|---|
| Aluko et al. 2003 | |
| dry | 675.6 |
| rainy | 990.6 |
| Chiemchaisri, Srisukphun 2003 | |
| dry | 4990 |
| rainy | 3040 |
| Hernandez-Berriel et al. 2008 | |
| dry | 23380 |
| rainy | 17120 |
| Mangimbulude et al. 2009 | |
| dry | 435 |
| rainy | 303 |

Aluko et al (2003) again had differing values from the other authors who agreed on the fact that the BOD5 levels were definitely lower during the rainy season.

### Table 14: Seasonal COD variations

| Seasonal COD (mg/l) | Results |
|---|---|
| Aluko et al. 2003 | |
| dry | 2802 |
| rainy | 3066 |
| Chiemchaisri, Srisukphun 2003 | |
| dry | 20000 |
| rainy | 10000 |
| Hernandez-Berriel et al. 2008 | |
| dry | 31730 |
| rainy | 23080 |
| Mangimbulude et al. 2009 | |
| dry | 1883 |
| rainy | 1260 |
| Kuruparan et al. 2003 open dump | |
| 1st dry | 9812 |
| 1st rainy | 6366 |
| 2nd dry | 1354 |
| 2nd rainy | 584 |
| 3rd dry | 748 |
| 3rd rainy | 358 |
| Kuruparan et al. 2003 sanitary | |
| 1st dry | 35188 |
| 1st rainy | 16525 |
| 2nd dry | 2074 |
| 2nd rainy | 2542 |
| 3rd dry | 1422 |
| 3rd rainy | 1182 |
| Tränkler et al. 2005 open dump | |
| 1st dry | 10000 |
| 1st rainy | 8000 |
| 2nd dry | 1000 |
| 2nd rainy | 600 |
| 3rd dry | 700 |
| 3rd rainy | 450 |
| Tränkler et al. 2005 sanitary | |
| 1st dry | 37500 |
| 1st rainy | 10000 |
| 2nd dry | 2000 |
| 2nd rainy | 1000 |
| 3rd dry | 7500 |
| 3rd rainy | 7500 |

COD levels varied strongly from season to season but showed a strong correlation between lower COD levels and the rainy season on the one hand, and higher COD levels and the dry seasons on the other hand. Only Aluko et al. (2003) found different values and the sanitary landfill of Kuruparan, et al. (2003) in the second rainy season showed inexplicable high COD levels, higher than the dry season levels. Especially when looking at the values from Kuruparan, et al. (2003) and Tränkler, et al. (2005) with several rainy and dry seasons, the trend becomes very clear. COD concentrations in the leachate sometimes are almost double in the dry seasons compared to the rainy seasons. As mentioned above, figures like the third dry and rainy season from the sanitary landfill lysimeters by Tränkler, et al. (2005) show that leachate concentrations phase out and while this might take longer in temperate climates, the drop in tropical leachates occurs much faster.

**Table 15: Seasonal variations of the BOD5/COD ratio**

| Seasonal BOD5/COD ratio | Results |
|---|---|
| Hernandez-Berriel et al. 2008 | |
| dry | 0.735 |
| rainy | 0.74 |
| Kuruparan et al. 2003 open dump | |
| 1st dry | 0.48 |
| 1st rainy | 0.48 |
| 2nd dry | 0 |
| 2nd rainy | 0 |
| 3rd dry | 0.25 |
| 3rd rainy | 0.25 |
| Kuruparan et al. 2003 sanitary | |
| 1st dry | 0.88 |
| 1st rainy | 0.88 |
| 2nd dry | N/A |
| 2nd rainy | N/A |
| 3rd dry | 0.3 |
| 3rd rainy | 0.3 |
| Tränkler et al. 2005 open dump | |
| 1st dry | 0.5 |
| 1st rainy | 0.5 |
| 2nd dry | N/A |
| 2nd rainy | N/A |
| 3rd dry | 0.2 |
| 3rd rainy | 0.2 |
| Tränkler et al. 2005 sanitary | |
| 1st dry | 0.9 |
| 1st rainy | 0.9 |
| 2nd dry | N/A |
| 2nd rainy | N/A |
| 3rd dry | 0.2 |
| 3rd rainy | 0.2 |

For the BOD5/COD ratio almost no seasonal variation has been found. Kuruparan, et al. (2003) and Tränkler, et al. (2005) both only give values for the ratio at the beginning of the experiments and for after nearly two years, but they do not distinguish between whether this is in the rainy or in the dry season. Also Hernández-Berriel, et al. (2008) do not observe a great difference in the BOD5/COD ratio during dry or rainy season.

**Table 16: Seasonal total nitrogen variations**

| Seasonal Total Nitrogen (mg/l) | Results |
|---|---|
| Chiemchaisri, Srisukphun 2003 | |
| dry | 189.1 |
| rainy | 64.8 |
| Kuruparan et al. 2003 open dump | |
| 1st dry | 587 |
| 1st rainy | 1138 |
| 2nd dry | 480 |
| 2nd rainy | 517 |
| 3rd dry | 578 |
| 3rd rainy | 648 |
| Kuruparan et al. 2003 sanitary | |
| 1st dry | 1779 |
| 1st rainy | 1861 |
| 2nd dry | 1733 |
| 2nd rainy | 1509 |
| 3rd dry | 1523 |
| 3rd rainy | 899 |
| Tränkler et al. 2005 open dump | |
| 1st dry | 600 |
| 1st rainy | 1200 |
| 2nd dry | 500 |
| 2nd rainy | 400 |
| 3rd dry | 350 |
| 3rd rainy | 350 |
| Tränkler et al. 2005 sanitary | |
| 1st dry | 2000 |
| 1st rainy | 1900 |
| 2nd dry | 1600 |
| 2nd rainy | 1200 |
| 3rd dry | 450 |
| 3rd rainy | 650 |

The inorganic compounds, in general, behaved more erratic. Chiemchairsri and Srisukphun (2003) found higher values of total nitrogen for the dry season than for the rainy season – expected results. In the open dump simulation from Kuruparan, et al. (2003) the nitrogen levels were all higher for the rainy season than for the dry season – clearly unexpected. For their simulation of the sanitary landfill, only the nitrogen levels of the first dry season were lower than for the first rainy season, the other measurements showed the expected outcome. In the open dump simulation from Tränkler, et al. (2005) the values were lower in the first dry season than in the first rainy season, during the second pair of seasons, dry season concentrations were higher, and from the start of the third dry season, the values for total nitrogen did not change anymore. Their sanitary landfill simulation behaved in a more expected way, except for the third dry season, which showed extremely low levels of nitrogen compared to the following rainy season.

**Table 17: Seasonal ammonia-N variations**

| Seasonal Ammonia-N (mg/l) | Results |
|---|---|
| Aluko et al. 2003 | |
| dry | 1316 |
| rainy | 633 |
| Chiemchaisri, Srisukphun 2003 | |
| dry | 82.8 |
| rainy | 51.8 |
| Mangimbulude et al. 2009 | |
| dry | 678 |
| rainy | 580 |

The values found for the ammonia-nitrogen behaved as expected: all of the studies found that concentrations are higher in the dry season than in the rainy season.

**Table 18: Seasonal total iron variations**

| Seasonal total iron (mg/l) | Results |
|---|---|
| Aluko et al. 2003 | |
| dry | 122 |
| rainy | 180 |
| Mangimbulude et al. 2009 | |
| dry | 15 |
| rainy | 12.5 |

From the numbers for total iron concentration, no clear conclusion can be drawn. While Aluko et al. (2003) found that the iron concentration was lower in the dry season (122mg/l) than in the rainy season (180mg/l), Mangimbulude, et al. (2009) found the opposite to be true. Dry season concentrations were 15mg/l, and rainy season iron concentrations 12.5mg/l.

**Table 19: Seasonal zinc variations**

| Seasonal zinc (mg/l) | Results |
|---|---|
| Aluko et al. 2003 | |
| dry | 1,4 |
| rainy | 2,3 |
| Hernandez-Berriel et al. 2008 | |
| dry | 6,64 |
| rainy | 2,21 |

For the values of zinc concentration in the leachate, only two authors provided numbers. Aluko et al. (2003), as usual, found lower levels for the dry season, but Hernández-Berriel, et al. (2008) found higher zinc values in the leachate of the dry season (6.64mg/l) in comparison to the leachate of the rainy season (2.21mg/l). Judging from the fact that Aluko et al. (2003)'s findings always stated the opposite of what the other authors found, the proposition is to follow in the case of iron, Mangimbulude, et al. (2009) and in the case of zinc the findings of Hernández-Berriel, et al. (2008). When omitting the findings of Aluko et al. (2003) for all the values mentioned above, the overall conclusion can be drawn that contaminant concentration values in the leachate are higher during dry seasons than during rainy season. A clear explanation to this finding is the fact of increased precipitation during the rainy season and the increased amounts of leachate produced. Due to the higher dilution of the pollutants, their overall concentration is lower.

To conclude, one should mention that variations do not only occur due to the overall seasonal trends but also as a reaction to longer dry periods in the rainy season or to sudden rainfall events during the dry season. In some studies, the pattern during the rainy season was even too complex to draw a clear conclusion from (Kuruparan, et al. 2003, Tränkler, Visvanathan, et al. 2005).

Probably most important was that the leachate showed peak concentrations lower than those known from landfills in developed countries. Also, in some cases, the concentrations showed extreme peaks at the beginning of the rainy season, contrary to what one might expect, (Tränkler, Visvanathan, et al. 2005) and once the rainfall stopped, concentrations increased rapidly. This can be due to specifically intense activity of the methanotrophic bacteria (Tränkler, Manandhari, et al. 2001).

After this detailed discussion of the individual results, a statistical analysis shall be presented to allow for a comparative synopsis. Figures 20 to 28 demonstrate how the single leachate characteristics vary depending on the climate zone and the season. One conclusion to be drawn from the figures is that the variance for the pollutant concentration in temperate climate landfill-leachate is considerably greater than for the values from tropical landfill-leachate. The pH values from tropical leachates probably are higher because the methanogenic phase is reached faster in tropical landfills. The general trend of higher pollutant concentrations in temperate climate leachates is as apparent as in the tables giving the full data set above. Compared to the values from temperate leachates, both, the zinc and the iron values were too low in the tropical leachates to draw any conclusion.

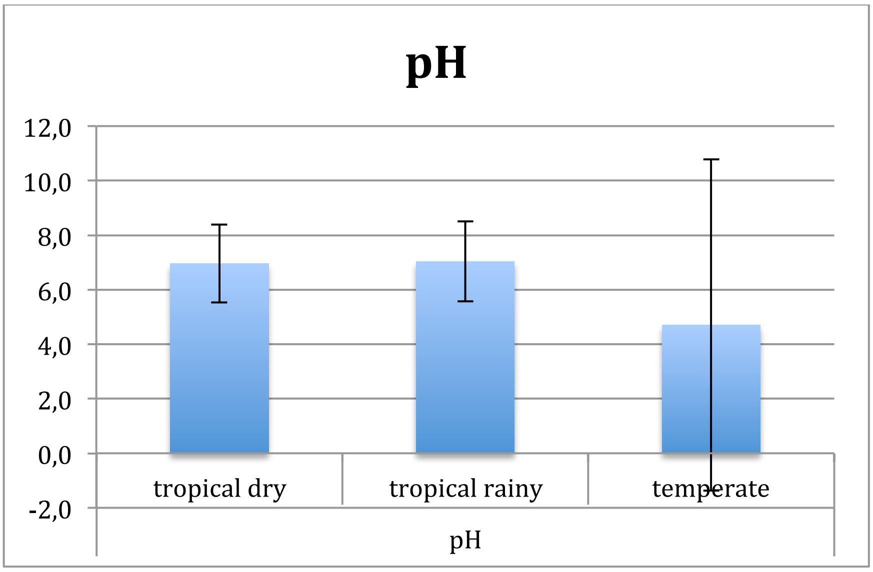



**Figure 20: Varying pH values [ ] in tropical dry and rainy seasons and in temperate climates**

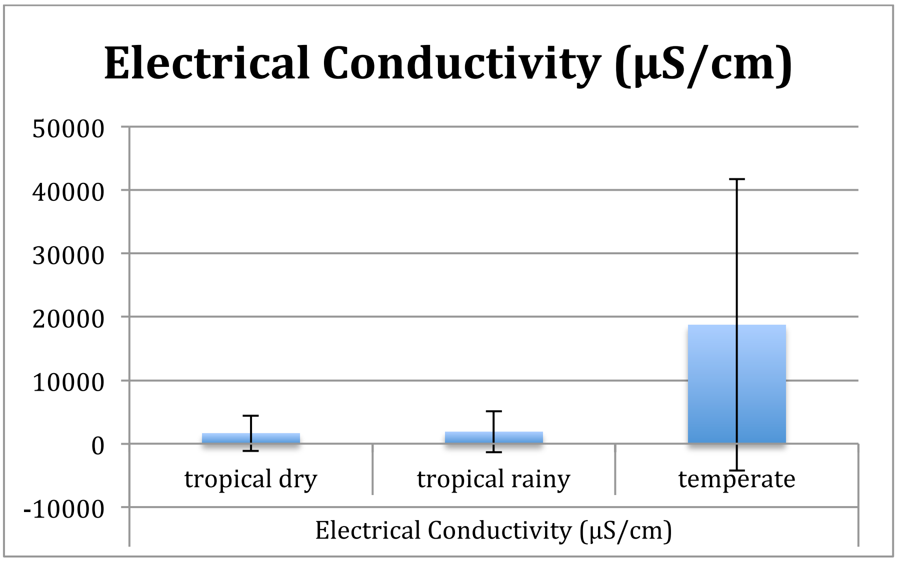



**Figure 21: Varying electrical conductivity values [µS/cm] in tropical dry and rainy seasons and in temperate climates**

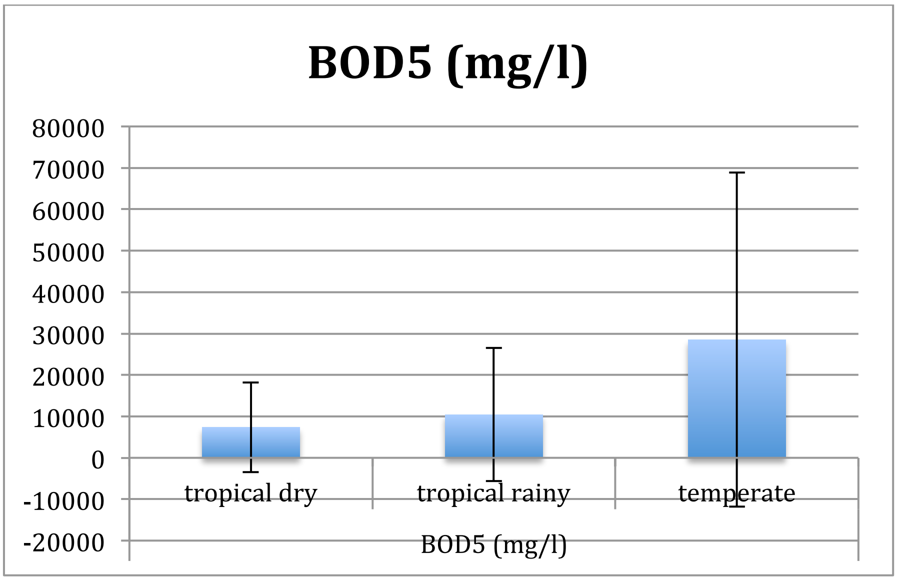



**Figure 22: Varying BOD5 values [mg/l] in tropical dry and rainy seasons and in temperate climates**

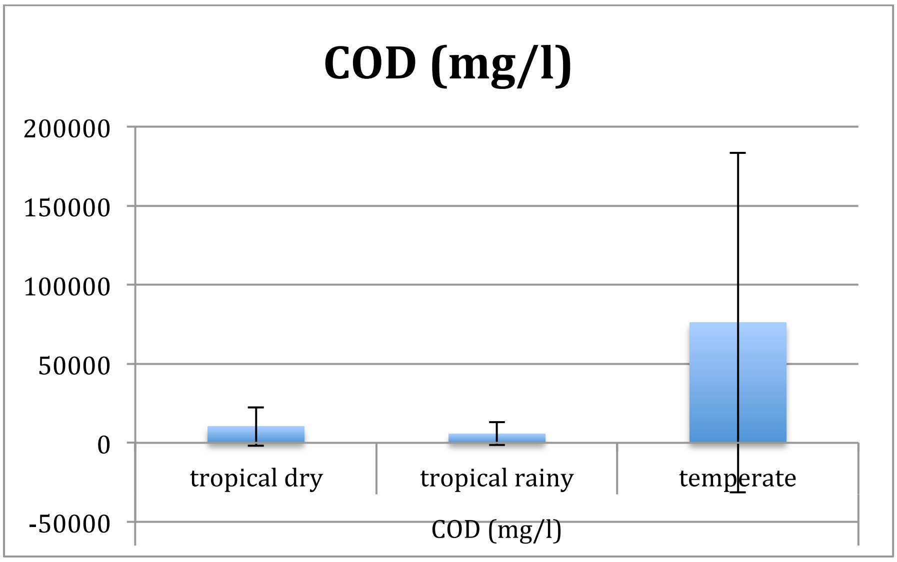



**Figure 23: Varying COD values [mg/l] in tropical dry and rainy seasons and in temperate climates**

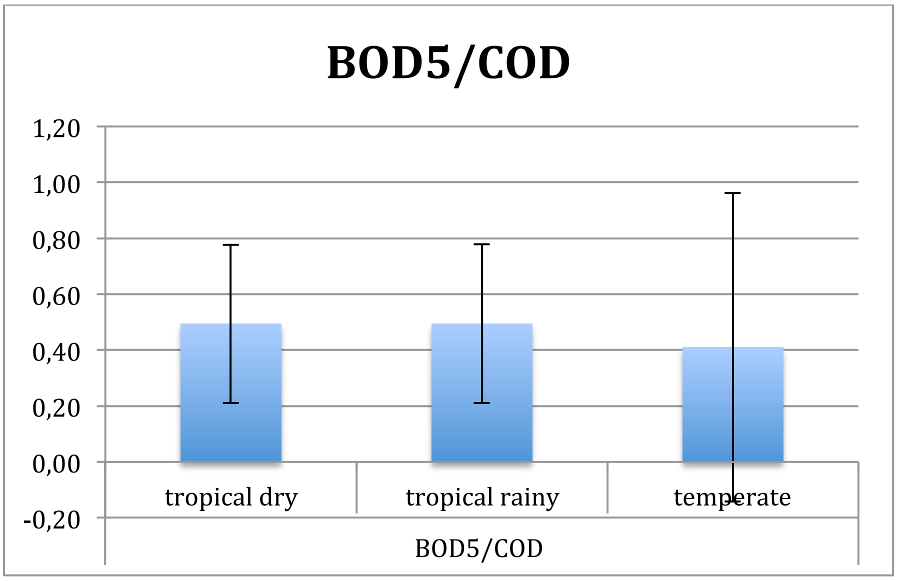



**Figure 24: Varying BOD5/COD ratio in tropical dry and rainy seasons and in temperate climates**

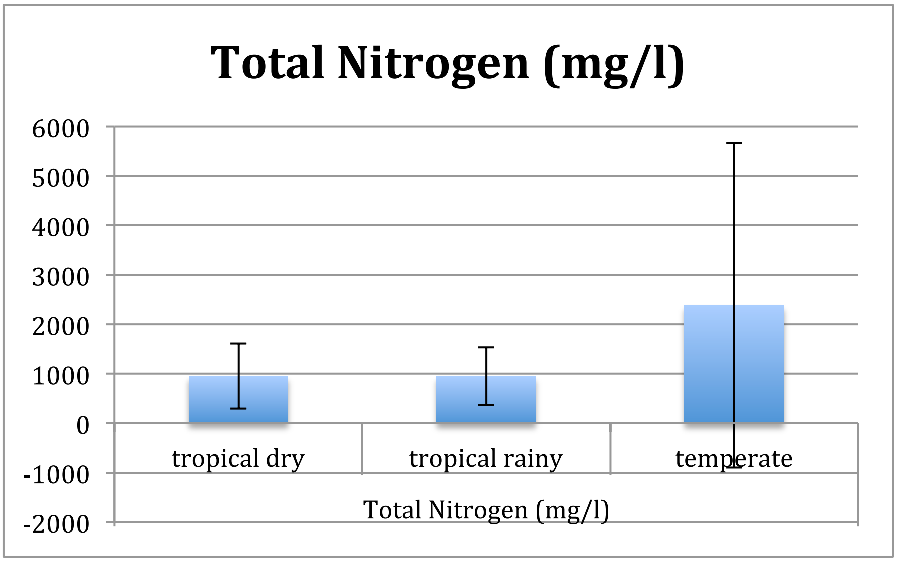



**Figure 25: Varying total nitrogen values [mg/l] in tropical dry and rainy seasons and in temperate climates**

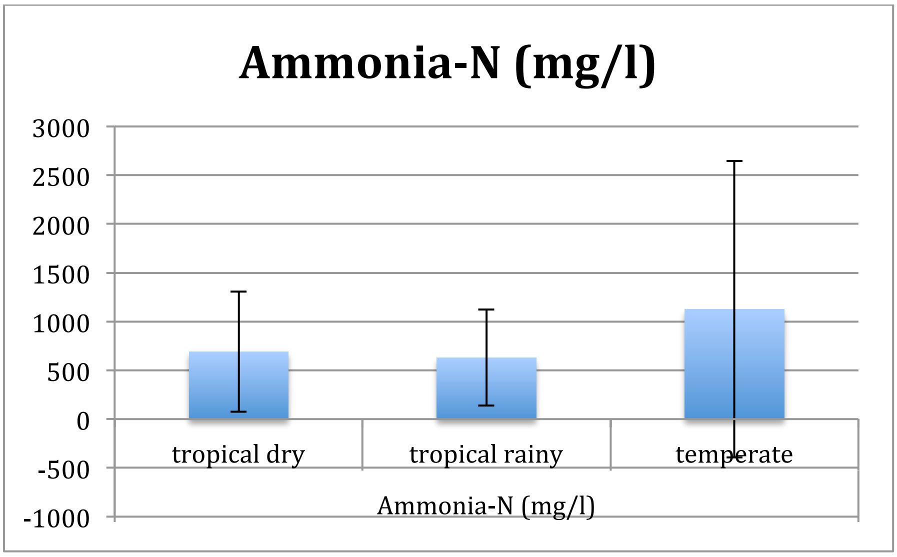



**Figure 26: Varying ammonia-N values [mg/l] in tropical dry and rainy seasons and in temperate climates**

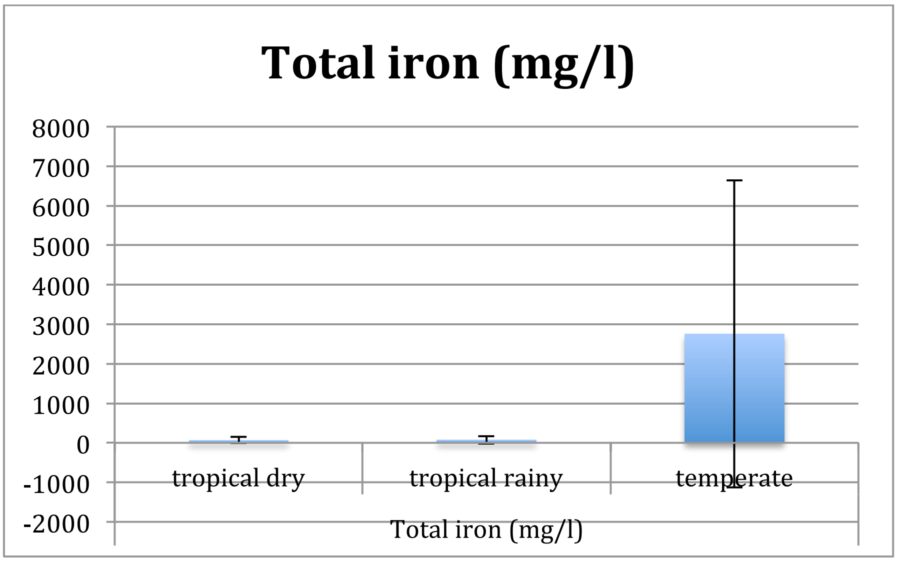



**Figure 27: Varying total iron values [mg/l] in tropical dry and rainy seasons and in temperate climates**

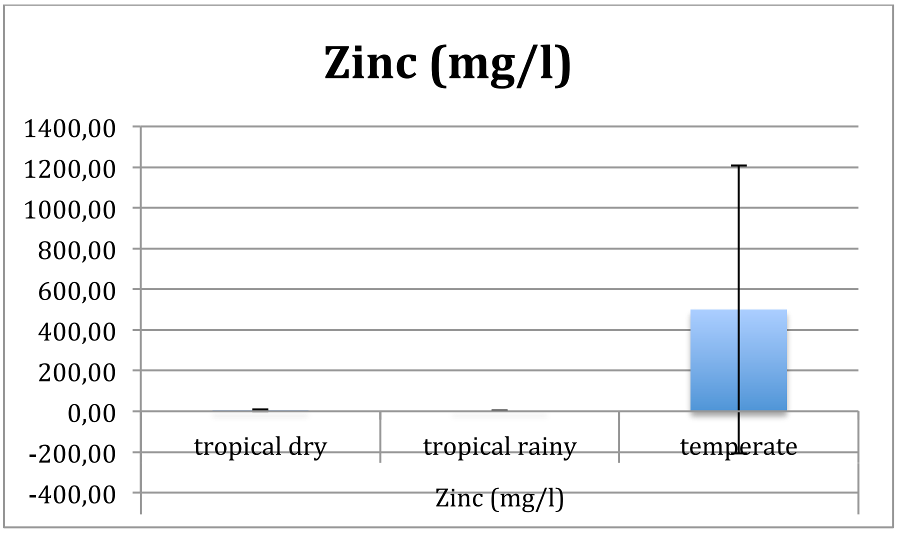



**Figure 28: Varying zinc values [mg/l] in tropical dry and rainy seasons and in temperate climates**

### *c. Effect of leachate on the environment*

The main effect of leachate on the environment is the effect of a possible contamination of surface or ground waters. This could happen through downward or sideward flows of leachates. Downward flows would threaten the quality of bypassing groundwater sources. Sideward flows might cause springs on the surface with very bad water quality or simply pure leachate springing from them. These springs might be present during the whole year or only in the wet season or after a heavy rainfall event. During the dry season – when they dry out – they will leave behind only a spot of discoloured, contaminated soil.

The leachate plume, after escaping from the landfill, will go through a couple of processes and chemical reactions, similar to those that the waste undergoes in the landfill but in the opposite direction. While in a landfill the conditions get more anaerobic with time, the leachate plume returns to aerobic conditions with time and the farther away it has flown from the landfill. The leachate becomes less reducing, therefore making methane and ammonia (chemically reduced products) change into nitrate and sulphate and oxidize the organic carbon to CO2. Depending on their chemical properties, certain contaminants remain in their original form longer than others: Iron oxidizes quite quickly and can be found in the leachate as a precipitate; on the other hand, manganese remains in its dissolved state longer and can be found in this form farther away from the origin of the leachate plume. As a consequence, the concentration of reactive species of the leachate is reduced rather quickly after the leachate has reached aerobic conditions (only a few hundred metres from the origin). On the contrary, the concentration of unreactive constituents stays the same as long as the leachate plum does not mix with other waters. Their concentration is only reduced through dilution or dispersion which both depend on the size of the receiving waters. Figure 29 (Taylor und Allen 2006) summarizes these findings.

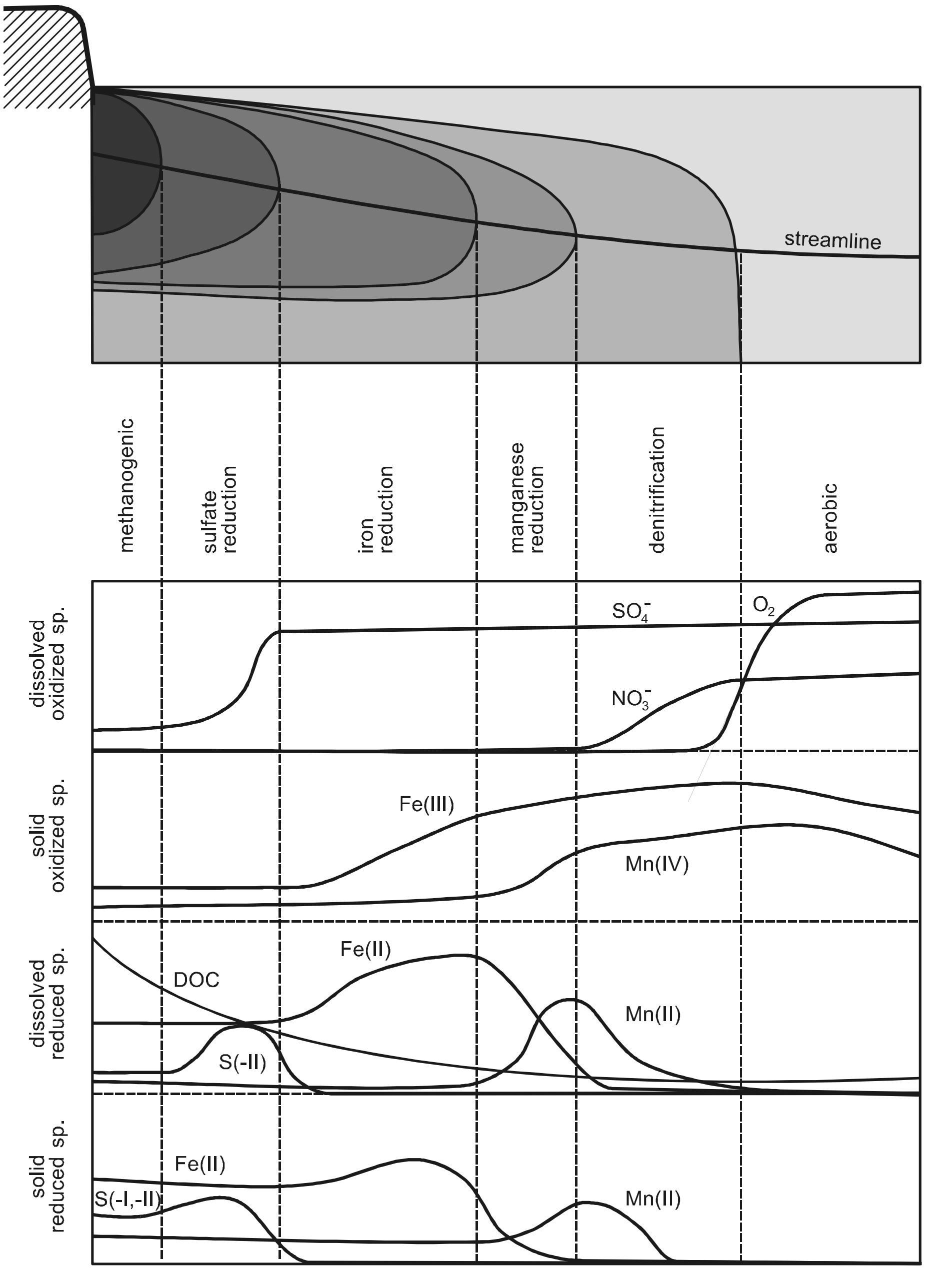



**Figure 29: Leachate migration (Taylor und Allen 2006)**

Visvanathan, et al. (2010) studied the groundwater quality near to their experimental landfill test cells in Thailand. pH-Values did not differ greatly from the leachate pH-values nor were there any seasonal variations notable. For the other values, it was found that they were lower during the rainy season, showing – as mentioned above – that the dilution is greater due to the increased amount of water percolating through the landfill. Highest values for electrical conductivity were measured close to the bottom of the closed test cell with values of 115mS/cm (during the dry season). The highest values for COD (1.570mg/l) and TKN (17mg/l), however, were found next to the open test cell. Heavy metal concentrations were mainly below 1mg/l and they showed no significant seasonal variation. Exceptions were zinc, manganese, and nickel (Visvanathan, Karthikeyan und Park 2010).

Mangimbulude, et al. (2009) studied the impact of the emission of leachates on the surrounding neighbourhood and environment in Semarang, Indonesia. While leachate treatment ponds existed, the time the leachate spends in these can be quite short leaving almost no time for natural attenuation through physical, physic-chemical, chemical, or biological processes. The minimum hydraulic retention time during the rainy season was 17.5 days, the longest during the dry season was 67 days. Small differences in the redox conditions (as mentioned by Taylor and Allen 2006) were found, but the main factor reducing contaminants in the leachate was dilution. The highest reductions in pollutants concentrations were examined at a point where spring water was lead into the leachate collection system and when concentrations where diluted by 99% by mixing with the receiving river. The only pollutants that already were exceeding regulations of the Indonesian government were the heavy metals and those of pathogens. In the long term, the accumulation in the river as well as the possible negative health impacts, of course, have to be taken into account. The other pollutants should be reduced as much as possible as well (Mangimbulude, et al. 2009).

### *d. Treatment & Disposal*

Most of the landfills studied in this work have leachate collection systems and some of them also a system for gas collection. This eases scientific investigation on the amount and the concentration of leachate or gas generated but it is, of course, a strong derivation of the regular case seen in practical operation where 90% of landfills in developing countries are still operated as open dumpsites (Visvanathan, Tubtimthai und Kuruparan 2004). Therefore, results have to be carefully interpreted when predicting how measured emissions would adversely affect the environment in the case of open dump landfilling.

Besides the pre-treatment of MSW, also the top cover design influences leachate generation to a certain level. Seeing that the highest degradation of waste can be achieved during the rainy season, the open system – allowing for a higher moisture level in the landfill – provides enhanced possibilities to operate landfills. Combining the open system with leachate recirculation and evaporation, a certain kind of pre-treatment and natural compaction can be achieved within the landfill due to bio-degradation when choosing the right cover design. Furthermore, using a soil or soil/compost mixture as an intermediate cover layer of the landfill can increase leachate purification and efficiently remove COD (Chiemchaisri und Srisukphun 2003, Visvanathan, Tränkler, et al. 2003).

The main solutions proposed to handle leachate emissions include certain landfill cover designs and leachate storage during the wet season to allow for recirculation throughout the dry season so as to

- avoid cracking of the landfill material (e.g., clay),
- promote continuation of biodegradation reactions within the landfill,
- attain purification and cleaning of the leachate and
- achieve stabilization of the landfill waste.

Ensuring good management and operational practices for leachate control also guarantees better results for landfill gas production and collection. Leachate accumulation in the waste pile hinders the flow of the gas. In tropical climates it was further found that the leachate level lays five to seven metres below the top of the landfill but during the rainy season the level rose to one to two metres below the surface. Leachate collection and treatment systems will have to take this finding into account. (Eam-o-pas, Wetherill und Panpradist 2000, Ishigaki, Hirata, et al. 2011)

Table 20 shows a comparison between the behaviour of a sanitary landfill simulation and an open dump[4]. Special attention has also been taken to include seasonal variations in the examination. Only two factors, nitrogen and chemical oxygen demand, have been chosen in this analysis in order to simplify it. In the first table, the TKN and COD values have been described for the sanitary landfill lysimeter according to seasons. Also the average values of both studies for each phase have been included. What can be seen from these tables is that first of all, the two studies come up with relatively similar results for the respective values of Nitrogen and COD according to each season. The only bigger differences that exist are the values for nitrogen in the leachate of the 3rd dry season of the sanitary landfill and of the 3rd rainy season of the open dump; and the values for COD of the sanitary landfill starting at the 2nd rainy season with incomprehensively high values from Tränkler, et al, (2005) in the 3rd seasonal pair.

**Table 20: Comparison - leachate characteristics between sanitary landfills and open dumps (Kuruparan, et al. 2003, Tränkler, Visvanathan, et al. 2005)**

| Sanitary Landfill | Total nitrogen (mg/l) | COD (mg/l) |
|---|---|---|
| 1st dry | 1889.5 | 36344 |
| Kuruparan et al. 2003 | 1779 | 35188 |
| Tränkler et al. 2005 | 2000 | 37500 |
| 1st rainy | 1880.5 | 13262.5 |
| Kuruparan et al. 2003 | 1861 | 16525 |
| Tränkler et al. 2005 | 1900 | 10000 |
| 2nd dry | 1666.5 | 2037 |
| Kuruparan et al. 2003 | 1733 | 2074 |
| Tränkler et al. 2005 | 1600 | 2000 |
| 2nd rainy | 1354.5 | 1771 |
| Kuruparan et al. 2003 | 1509 | 2542 |
| Tränkler et al. 2005 | 1200 | 1000 |
| 3rd dry | 986.5 | 4461 |
| Kuruparan et al. 2003 | 1523 | 1422 |
| Tränkler et al. 2005 | 450 | 7500 |
| 3rd rainy | 774.5 | 4341 |
| Kuruparan et al. 2003 | 899 | 1182 |
| Tränkler et al. 2005 | 650 | 7500 |
| **Average** | **1425.3** | **10369** |

[4] Open dump simulation by a lysimeter: Of course, the simulation can never adequately depict the real situation due to the fact that it will always be a closed container.

| Open Dump | Total nitrogen (mg/l) | COD (mg/l) |
|---|---|---|
| 1st dry | 593.5 | 9906 |
| Kuruparan et al. 2003 | 587 | 9812 |
| Tränkler et al. 2005 | 600 | 10000 |
| 1st rainy | 1169 | 7183 |
| Kuruparan et al. 2003 | 1138 | 6366 |
| Tränkler et al. 2005 | 1200 | 8000 |
| 2nd dry | 490 | 1177 |
| Kuruparan et al. 2003 | 480 | 1354 |
| Tränkler et al. 2005 | 500 | 1000 |
| 2nd rainy | 458.5 | 592 |
| Kuruparan et al. 2003 | 517 | 584 |
| Tränkler et al. 2005 | 400 | 600 |
| 3rd dry | 464 | 724 |
| Kuruparan et al. 2003 | 578 | 748 |
| Tränkler et al. 2005 | 350 | 700 |
| 3rd rainy | 499 | 404 |
| Kuruparan et al. 2003 | 648 | 358 |
| Tränkler et al. 2005 | 350 | 450 |
| **Average** | **612.3** | **3331** |

A second finding from theses tables is – as mentioned above – that pollutant concentrations are higher during the dry seasons than during the rainy seasons with nitrogen behaving not always according to this assumption. COD values are more regular. And finally, a relatively surprising finding: the values for nitrogen and COD are much lower for the open dump simulation than for the sanitary landfill. In most cases the calculated average per season is almost half or lower than the values from the sanitary landfill. To explain this, one should take a closer look at the seasonal variations again: they stated that when less leachate flows – in the dry season – the pollutant concentrations are higher than when more water flows – in the rainy season. As has been shown before, open dump landfills (lysimeter) produce a much higher leachate flow than sanitary landfills[5]. Due to their reduced flow, concentrations of nitrogen and COD are naturally higher in the lower quantity of water than those from open dump leachates, where a much greater quantity of leachate is produced to dilute the contaminating substances. Visvanathan, et al.

[5] Also, there might be aerobe conditions in the lysimeter, inducing different results than from real dump sites or landfills.

(2003) support this finding by their own calculations: Their open dump simulation produced 330% more leachate than the other lysimeters and 20% total cumulative COD and 180% higher cumulative TKN. To acquire a complete analysis of the differences between the divers types of landfills available it would, therefore, be necessary to include a study about the cumulative contaminant levels and not just the concentration in the leachate at a specific point in time. (Visvanathan, Tränkler, et al. 2003)

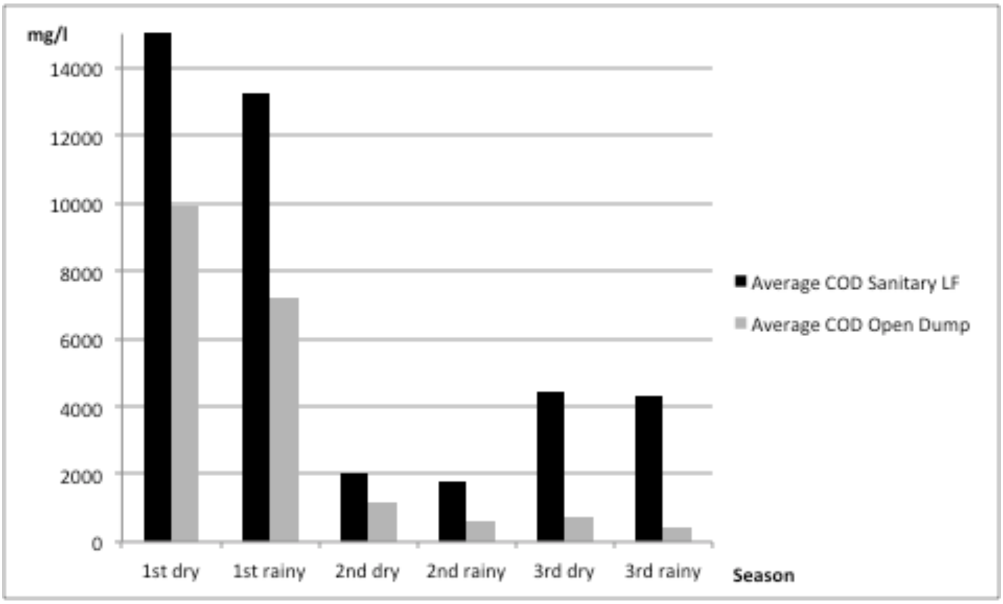



**Figure 30: Average total nitrogen from sanitary landfills and open dumps (Kuruparan, et al. 2003, Tränkler, Visvanathan, et al. 2005)**

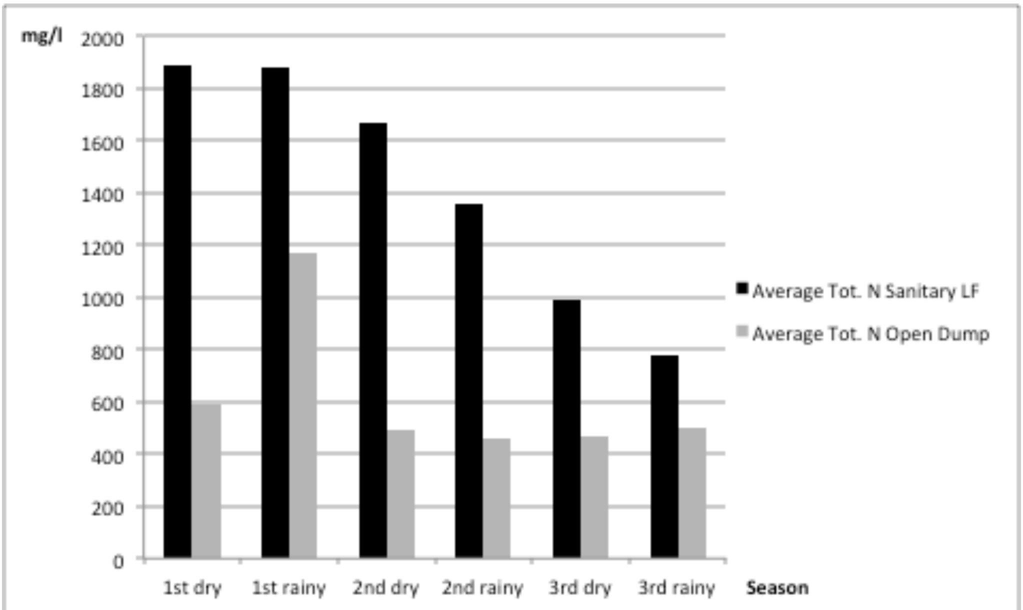



**Figure 31: Average COD from sanitary landfills and open dumps (Kuruparan, et al. 2003, Tränkler, Visvanathan, et al. 2005)**

The findings from the tables have been depicted in Figure 30 and Figure 31. Now it is easy to see that the values from the sanitary landfills are higher than from the open dumps. The general reduction of leachate pollution concentrations is observable as well as the fact that rainy seasons usually spot lower values. It is to be noted that in the graph of COD, the value for the sanitary landfill is in fact 36,344mg/l. The graph was cut at 15,000 to ensure better readability.

Visvanathan, et al. (2003) found similar results: The lysimeter that simulated a sanitary landfill was much worse in leachate emission characteristics than the two simulating open dumps or a pre-treated waste. This could indicate that the traditionally used cover layers and barriers are not the best option when it comes to tropical countries. The authors proposed the open cover system as an alternative option for landfilling if it is combined with leachate recirculation. By means of evaporation and the enhanced degradation (due to the leachate recirculation) the waste is pre-treated and compacted in the open system naturally. Or, in a later study, Visvanathan, et al. (2010) researched different cover layers or barriers that were constructed with low cost, locally available natural materials used. Their durability was found to be good in pollutants under tropical conditions. Any solutions should therefore always include local material (Visvanathan, Karthikeyan und Park 2010).

### 4.5.2. Landfill gas

#### *a. Gas generation*

##### General

The second main emission of landfills after leachate is landfill gas. It consists to 50-54% of methane ($CH_4$) and to 40-46% of carbon dioxide ($CO_2$) and some minor components like hydrogen sulphide, ammonia or volatile organic compounds. It is generated by the decomposition of organic matter. As mentioned above, the MSW undergoes anaerobic biodegradation in three stages in the landfill: The hydrolysis stage in which bacteria hydrolyse organic compounds into soluble products such as glucose; the acidogenic phase in which the glucose is turned into simple organic acids, CO2 and hydrogen:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (3.)$$

Methane, a greenhouse gas that is 25 times as climate-active as $CO_2$, is produced in the third/ methanogenic phase according to one of the following reactions:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (4.)$$

From acetic or ethanoic acid, methane and carbon dioxide are produced.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (5.)$$

From carbon dioxide and hydrogen, methane and water are produced. The production of methane gives a clear indication of strong reducing conditions in a landfill up to a redox potential of around 400mV (Taylor und Allen 2006). To calculate the maximum amount of landfill gas produced, the following equation can be used.

$$C_6H_{12}O_6 + 1{,}5H_2O \rightarrow 3{,}25CH_4 + 2{,}75CO_2 \quad (6.)$$

Methane is the second largest GHG after $CO_2$ but as mentioned above, much more important when it comes to actually influencing the climate. 16% of the global GHG emissions are methane and of these, 21% come from waste dumps as can be seen in Figure 32. Other sources (Wang-Yao, Towprayoon, et al. 2006) state that only 7 to 8% of total methane emissions originate from landfill. Of the annual global emissions of CH4 of around 500Tg, this would then account to 40Tg CH4 that are released from waste dumps per year. Methane from waste dumps is the third biggest anthropogenic emission of methane on a global level, right after rice paddies and ruminants (Wang-Yao, Towprayoon, et al. 2006).

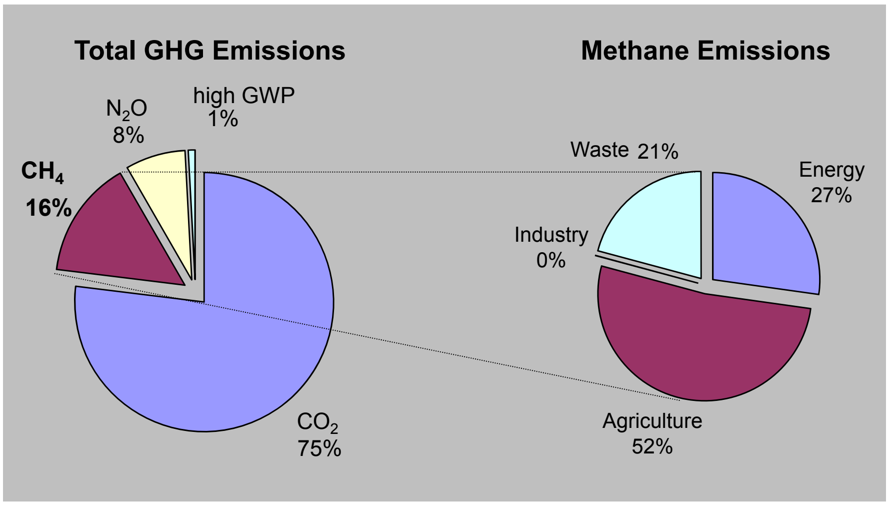



**Figure 32: Methane emissions (%) from landfills (Fellner 2011)**

The quantity and quality of landfill gas produced depends – as was mentioned for leachate generation – on a large number of factors. Listed in Table 21 (Maciel und Jucá 2003), these factors include the depth of the landfill since this co-defines the oxygen content in the waste. It further depends on the waste composition, the way the landfill is managed, including the waste density. The moisture content and the pH of the waste, as well as its temperature are similarly decisive. The age of the deposited waste, its decomposition stage, and finally, the milieu conditions for microorganisms that degrade the organic waste are equally an issue. These include the moisture content, the temperature, the pH-value of the waste and the redistribution of nutrients in it.

**Table 21: Factors controlling LFG generation (Maciel und Jucá 2003)**

| | |
|---|---|
| Landfill depth | Anaerobic processes normally dominate in depth greater than 5 m. |
| Waste type | Waste composition affects the rate, quality, and quantity of gas. |
| Site operations | Waste compaction and rapid infilling will shorten aerobic degradation. |
| Waste density | Production of gas is proportional to waste density. |
| Moisture content | Moisture content increase by recirculation (40-60%), accelerates gas generation |
| Waste mass pH | Optimum pH for anaerobic process ranges between 6.8 and 7.4. |
| Waste temperature | Optimum temperature ranges from 35°C to 45ºC. |
| Ingress of oxygen | Oxygen presence during anaerobic phase delays LFG generation. |

The generation of landfill gas can also be calculated by using the following equation (Tabasaran und Rettenberger 1987)

$$G = 1{,}868 * TOC_b * (0.014 * T + 0.28) * m_w \quad (7.)$$

$$G(t) = G * (1 - 10^{-(t*k)}) \quad (8.)$$

where:

G total amount of landfill gas [$m^3$]

G(t) landfill gas produced [$m^3$/ a]

$TOC_b$ biodegradable organic carbon content of the waste [kg C/ t]

T temperature inside the landfill [°C]

$m_w$ deposited waste mass [t]

t time [a]

k degradation rate [$a^{-1}$]

This equation takes into account the factors mentioned above that influence LFG generation. Some of these will differ depending on the climate or the state of development of a country. Starting off, the amount of waste deposited in a landfill depends on the degree of economic prosperity: The amounts of waste dumped in landfills [t] is constantly increasing in Asian countries while the amount reaching landfills in Europe is kept at a rather constant level (Ableidinger, et al. 2007) due to increased waste pre-treatment methods (incineration, compostion, recycling). Most important in the equation and of greatest relevance when discussing landfilling in tropical climates is certainly the temperature inside the landfill [T]: Although these temperatures can climb to relatively high levels in landfills in temperate climates, they tend to decrease during the cold/ winter season. In tropical countries with an annual minimum temperature of 25°C, temperatures within the landfill never have a chance to cool off. As mentioned in the chapter about waste characterization, the fraction of organic waste content is relatively bigger in a developing country than in an industrialized country [kg C/t]. These factors all lead to higher levels of methane occurring at a faster rate.

### Gas generation in tropical countries

The differences in landfill gas generation in a tropical country can be reduced to a few elements. First of all, the waste is made up of different fractions in developing countries than in industrialized countries. Second, the tropical climate signifies that the total amount of precipitation is much higher on an annual basis. Finally, a strong separation into a dry and a wet season exists that has non-negligible influences on LFG generation.

Since the operation and managing of waste is deficient in a lot of tropical countries, methane from most of the landfills is simply released into the atmosphere and thus – for some countries – even amounts to their biggest contribution to greenhouse gas emissions (Visvanathan, Tubtimthai und Kuruparan 2004).

Starting with the impact of waste characterization on landfill gas generation, it can be said that from one ton of MSW in developed countries (containing 60% dry biomass), 108 $m^3$ to 250$m^3$ or 0.149 tonnes of methane can be generated (Ahmed, et al. 2011, Wang-Yao, Towprayoon, et al. 2006). In developing countries the organic fraction in MSW is more prominent and, therefore, larger amounts could be generated and released to the environment. Also the higher moisture content of the waste leads to increased biodegradation processes, to stronger leachates and to a higher methane production rate (Hernández-Berriel, et al. 2008). Other authors (Ishigaki, Chung, et al. 2008, Chiemchaisri und Srisukphun 2003, Sanphoti, et al. 2006) found that the higher moisture content of tropical soils and wastes can lead to a stimulation of anaerobic degradation and could produce more landfill gas in a shorter time, provided the moisture levels are kept high enough.

Most important for the generation of landfill gas is the time it takes for a waste dump to reach the methanogenic state. In temperate landfills in more temperate countries it normally can require a period of up to 3 years for the transition to the methanogenic phase of a landfill. In tropical climates, with higher precipitation and temperatures, this transition might only take 12 to 18 months (Robinson 2005). In fact, Sanphoti, et al. (2006) found in a lysimeter study in Thailand that this transition can occur even within 180 days (6 months) in the case that not only leachate is recirculated but also additional water is added during the dry phase. If only leachate circulation was applied, the phase was reached on day 290, so after almost 10 months. The control reactor took about the same time (Sanphoti, et al. 2006). In a study by Hernández-Berriel, et al. (2008), the methanogenic phase was reached after only 70 days in two small lysimeters. Tränkler, et al. (2001) oppose such findings by stating that the usual low compaction levels in tropical country landfills would lead to aerobic or anoxic situations in the waste pile, slowing down degradation. Consequently, the methanogenic phase might only be reached after 3 years of operation. They also mention, though, that the higher temperatures of tropical countries might still lead to a very fast degradation.

Of interest is, furthermore, the amount of methane that is produced during the methanogenic phase in a waste dump in a tropical climate. Studies measuring net methane emissions on the field provide results between below 0.0004 and higher than 4000 g/$m^2$/day (Wang-Yao, Towprayoon, et al. 2006). This does not really give valuable data with which to work with. Further research has been done, providing interesting results for tropical climates and also taking into account seasonal variations.

Hernández-Berriel, et al. (2008) found that between 0.76 and 0.79 mL CH4/g dry matter per day were produced depending on the moisture level of the waste. Higher values were produced at 70% moisture and slightly lower values at 80% moisture. Sanphoti, et al. (2006) found rather lower amounts ranging from 9.02 l/ kg dry weight at a rate of 0.10 l/kg dry weight per day from their control reactor to 17.04 l/kg dry weight at a rate of 0.14 l/kg dry weight per day from their reactor that utilized leachate recirculation and up to 54.87 l/kg dry weight at an average rate of 0.58 l/kg dry weight per day from the reactor that used leachate recirculation plus supplemental water addition. They also realised that when increasing the organic loading rate (the amount of COD applied per m3 per day) after the waste reached the stabile methanogenic phase, the gas would consist of a greater methane fraction. More gas would be generated and the COD removal in the leachate would be greater. At the maximum organic loading rate of 5 kg COD/m3/d, the reactor with the leachate recirculation and supplemental water addition still was the most efficient, producing 1.56 l methane per kg dry weight per day; the leachate recirculation reactor produced 0.69 l/kg dry weight per day and the control reactor only 0.43 l/kg dry weight per day. (Sanphoti, et al. 2006)

**Table 22: Methane emissions at 7 disposal sites in wet season and dry season (all values given in g/m2/d, except ratios) (Wang-Yao, Towprayoon, et al. 2006)**

| Site | $CH_4$ emissions in wet season | | | $CH_4$ emissions in dry season | | | Emission ratio (wet season/dry season) |
|---|---|---|---|---|---|---|---|
| | Range | Number of test points | Average spatial emissions ($g/m^2/d$) | Range | Number of test points | Average spatial emissions ($g/m^2/d$) | |
| Pattaya | 0.38 – 697.85 | 40 | 129.79 | 0.00 – 686.93 | 41 | 23.40 | 5.55 |
| Cha-Am | 0.00 – 58.24 | 30 | 5.45 | 0.00 – 8.45 | 31 | 1.00 | 5.45 |
| Hua-Hin | 0.00 – 295.82 | 30 | 51.79 | 0.00 – 117.00 | 40 | 10.31 | 5.02 |
| Nakhon Pathom | 0.00 – 825.79 | 30 | 7.89 | 0.00 – 38.09 | 32 | 4.17 | 1.89 |
| Nonthaburi | 0.00 – 358.22 | 20 | 3.94 | 0.00 – 19.94 | 20 | 1.64 | 2.40 |
| Rayong | 0.00 – 22.79 | 22 | 2.44 | 0.00 – 2.89 | 20 | 1.00 | 2.44 |
| Samutprakan | 0.00 – 724.09 | 16 | 12.21 | 0.00 – 14.28 | 16 | 4.82 | 2.53 |

The generation of landfill gas is not insignificantly linked to seasonal variations. Since higher moisture levels in the waste increase the degradation processes, it can be expected that during the dry season in tropical climates, less methane will be produced. This hypothesis is supported by Chiemchairsri, et al. (2003) who noticed an increase in the methane generation until about ten days after the start of the dry season. Then, methane levels started to decrease slowly (Chiemchaisri, Chiemchaisri, et al. 2003). Also Wang-Yao, et al. (2006) when researching seven landfills in central Thailand found that the spatial variations between the different landfill gas sampling points were comparatively high during the rainy season, ranging from 0 to 825.79 $g/m^2$ per day. This means an average emission of 30.5 $g/m^2$ per day. During the dry season, the spatial variation was lower and also the total values were lower. They ranged from 0 – 686.93 $g/ m^2$ per day but the average value was only 6.62 $g/ m^2$ per day, signalling a reduced methane production during the dry season (Wang-Yao, Towprayoon, et al. 2006).

Similar results were found by Wang-Yao, et al. (2010) when researching models to estimate the landfill gas production rate and the duration of the gas generation phase. Here the Intergovernmental Panel on Climate Change (IPCC) recommends the first order decay model. The authors state that this model should have different parameters according to the climate. Nevertheless, a fixed value might be assumed for a country or whole region. They found that, not only the methane generation rate constant differs between temperate and tropical climates but also due to seasonal variations. The rates for temperate and boreal climates were all lower than those calculated for tropical climates. Also the rates for dry seasons were lower than those for the wet seasons, be it in the temperate or in the tropical climates. The rates showed this diversity throughout all the possible types of waste and not, as might be assumed, only for the rapidly degrading waste that is so predominant in tropical countries. These results are summarized in Table 23 (Wang-Yao, Yamada, et al. 2010).

**Table 23: Recommended default methane generation rate constant values ($a^{-1}$) from IPCC (MAT being mean average temperature; MAP being mean annual precipitation, given in mm; PET being potential evapotranspiration, equally given in mm) (Wang-Yao, Yamada, et al. 2010)**

| Type of Waste | | Climate Zone | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Boreal and Temperate (MAT ≤ 20°C) | | | | Tropical (MAT > 20°C) | | | |
| | | Dry (MAP/PET < 1) | | Wet (MAP/PET > 1) | | Dry (MAP < 1000 mm) | | Moist and Wet (MAP ≥ 1000 mm) | |
| | | Default | Range | Default | Range | Default | Range | Default | Range |
| Slowly degrading waste | Paper/textiles waste | 0.04 | 0.03 –0.05 | 0.06 | 0.05 – 0.07 | 0.045 | 0.04 – 0.06 | 0.07 | 0.06 – 0.085 |
| | Wood/ straw waste | 0.02 | 0.01 –0.03 | 0.03 | 0.02 – 0.04 | 0.025 | 0.02 – 0.04 | 0.035 | 0.03 – 0.05 |
| Moderately degrading waste | Other (non – food) organic putrescible/ Garden and park waste | 0.05 | 0.04–0.06 | 0.1 | 0.06 – 0.1 | 0.065 | 0.05 – 0.08 | 0.17 | 0.15 – 0.2 |
| Rapidly degrading waste | Food waste/Sewage sludge | 0.06 | 0.05–0.08 | 0.185 | 0.1 – 0.2 | 0.085 | 0.07 – 0.1 | 0.4 | 0.17 – 0.7 |
| Bulk Waste | | 0.05 | 0.04–0.05 | 0.09 | 0.08 - 0.1 | 0.065 | 0.05 – 0.07 | 0.17 | 0.15 – 0.2 |

MAP: the mean annual precipitation
PET: potential evapotranspiration

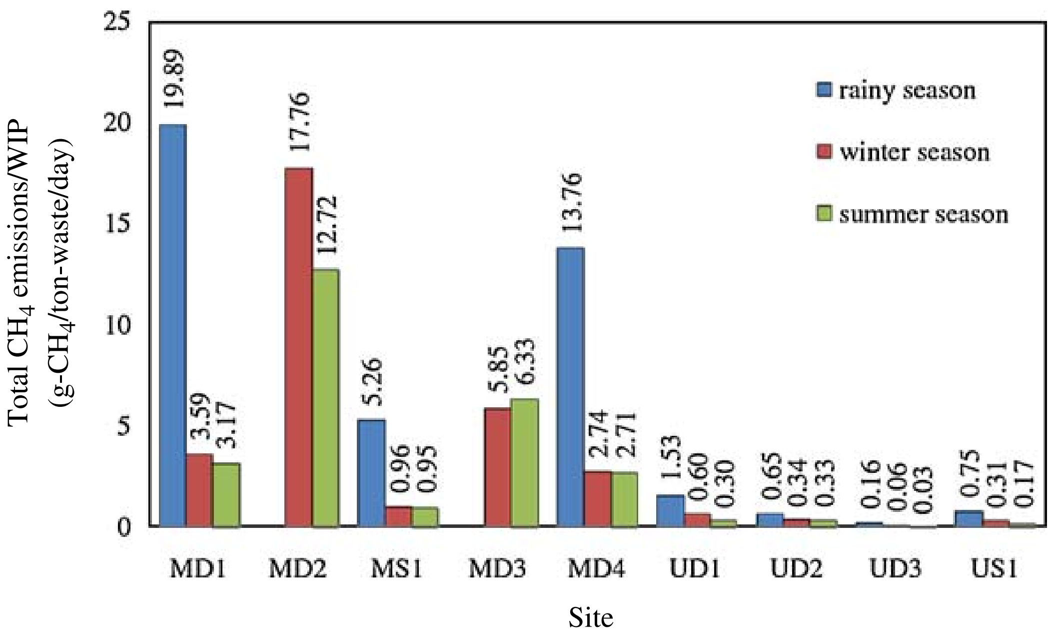



**Figure 33: Emissions of methane per ton of waste in place (WIP) per day from the different landfill sites (called MD1, MD2, …) during rainy, winter, and summer seasons (Wang-Yao, Towprayoon, et al. 2010)**

Finally, Figure 33 (Wang-Yao, Towprayoon, et al. 2010) shows the same findings once again but from a different study. Methane generation was measured at different landfill sites in Malaysia, named MD1, MD2, … for managed landfills and UD1, UD2,… for uncontrolled dumpsites; "D" stands for deep dumpsites and "S" for shallow locations. Methane production was the greatest during the rainy season and less pronounced in the other seasons. They ranged from as low as 0.17g/ton of waste/ day up to 20g/ton of waste/ day. Similar results were found by Börjesson and Svensson (1997) for a Swedish landfill. (Börjesson und Svensson 1997)

### b. *Gas composition*

Gas composition is first and foremost depending on the degradation stage of the landfill. Once the methanogenic phase is reached, the typical composition of landfill gas follows the composition as depicted in Table 24 (Maciel und Jucá 2003).

**Table 24: LFG typical composition and gas properties (units given in the first column) (Maciel und Jucá 2003)**

| Component: | $CH_4$ | $CO_2$ | $N_2$ | $O_2$ | CO | $H_2S$ |
|---|---|---|---|---|---|---|
| Typical concent. (% vol.) | 45-60 | 35-50 | 0-10 | 0-4 | <0,1 | 0-70 ppm |
| Density (kg/m$^3$) | 0.717 | 1.977 | 1.250 | 1.429 | 1.250 | 1.539 |
| Calorific potential (kJ/m$^3$) | 35,600 | --- | --- | --- | 12,640 | |
| Explosive Limit (% vol.) | 5-15 | --- | --- | --- | 12.5/74 | 4.3/45.5 |
| Water solubility (g/l) | 0.0645 | 1.688 | 0.019 | 0.043 | 0.028 | 3.846 |
| General properties* | O, C, NT, A, F | O, C, A | O, C | O, C | O, C, T, F | C, T |

* - O = odorless, C = colorless, NT = non-toxic, T = toxic, F = flammable, A = asphyxiant

The methane fraction varies between 45 and 60%, the rest is almost completely made up of $CO_2$, fluctuating between 35 and 50%. Other gaseous components are nitrogen ($N_2$) with 0 to 10%, oxygen ($O_2$) with 0 to 4%. Carbon monoxide (CO) is represented with less than 0.1% and $H_2S$ only with 0 to 70ppm. As is also specified by the table, only methane and carbon monoxide present a valuable form of LFG, measured by their calorific potential. The calorific potential of CO is 12.640 kJ/m$^3$, that of $CH_4$ higher: 35.600 kJ/m$^3$. Further information can be gained by evaluating the water solubility of the different gases. Neither methane nor nitrogen, oxygen or carbon monoxide are very water soluble, they escape to the atmosphere via the LFG emissions. Carbon dioxide and hydrogen sulphide are relatively water soluble, indicating that a lower amount of those gases is emitted in the LFG but some is dissolved in the leachate and play a role in mobilizing materials and substances from the waste. Finally, the general properties give a hint about which gases feature what kind of properties. On a first glance it is visible that hydrogen sulphide is responsible for bad odours from landfills is the. Like CO it is toxic to humans, and $CO_2$ is not beneficial for human health. Finally, as mentioned above, CO and $CH_4$ are flammable due to their high calorific values.

The overall trend of gaseous emissions from landfills can be seen in Figure 34 after Christensen et al. (1989). Oxygen is present only in the first phase until it is used up in the hydrolysis process and the waste pile or landfill becomes anaerobic. Also the odorous hydrogen sulphide is only emitted during the transition from the acidogenic to the methanogenic phase of the landfill. Nitrogen gas is vented out of the landfill at the beginning of the degradation phases when the oxygen of the air molecules inside the waste is used for biodegradation. All superfluous nitrogen is emitted. Carbon dioxide is produced almost from the start in large quantities originating from the degradation process. It only decreases once the methanogenic phase is reached and methane emissions become more important. After a very long time, waste stabilization is achieved and the processes within the landfill come to a halt. Then no more methane or $CO_2$ is emitted and nitrogen and oxygen from the ambient air will intrude into the landfill.

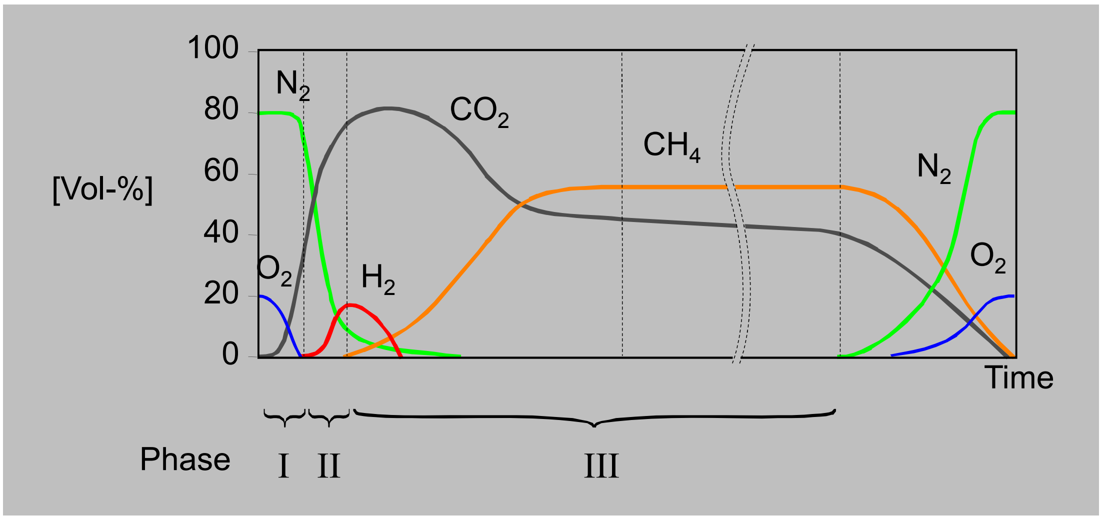



**Figure 34: Trend of gaseous emissions from landfills (Christensen, Cossu und Stegmann 1989)**

### c. *Effects of landfill gas on the environment*

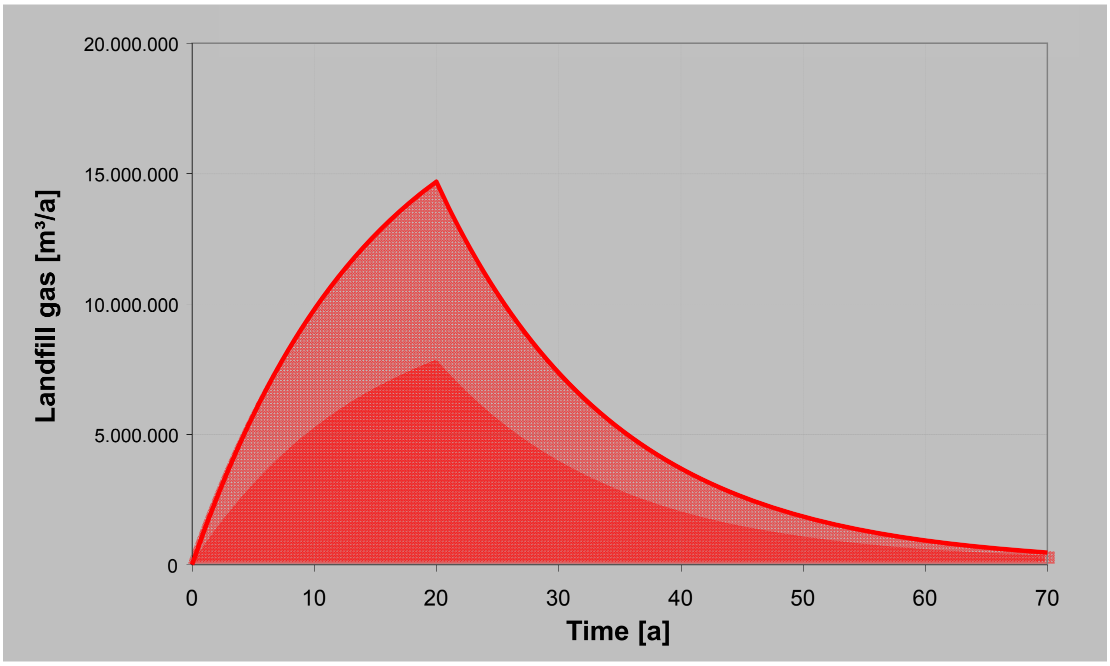



**Figure 35: Trend of emissions from landfills (Fellner 2011)**

A considerable issue – when it comes to effects of landfill gas emissions on the environment – is the time frame of landfill emissions: While the quantity of emissions is slowly increasing until the peak is reached at the closing point of the landfill, the amount that is collectable is much lower until the landfill is finally closed and then also rarely exceeds 50% of what is emitted (compare findings by (Kumar, et al. 2004). In Figure 35 (Fellner 2011), the total amount of LFG is shown in a lighter grey while the amount of LFG collected is depicted in the darker shade.

Maybe the most important impact that landfill gas has on the environment is its climate-warming factor. Methane is 25-times more climate-active than CO2, meaning it traps heat in our atmosphere instead of letting it escape into the universe. These global impacts can only be mitigated by reducing the amount of uncontrolled waste dumps that exist on the Earth. There are, however, also local impacts on the environment. These comprise mainly LFG migration. Migration means that the landfill gases, instead of escaping the landfill in a vertical way, search a horizontal way through the surrounding ground into areas where it is easier for these gases to escape to the atmosphere. This occurs when the surrounding subsurface shows a higher permeability than the waste pile.

Negative impacts on the environment from migrating LFG can include explosion hazards, health risks or a threat to human lives, vegetation damage, groundwater contamination and odour nuisances (Wang-Yao, Towprayoon, et al. 2006).

### *d. Treatment of landfill gas*

Measures to treat landfill gas include the collection of the LFG and then to either flare it, or to use it in a gas turbine and produce energy from it.

For gas utilization, the effects of a recirculation have been studied by Chiemchaisri, et al. (2003). They found that in all their landfill lysimeter experiments, the percentage of methane produced was increasing slowly in the beginning of the experiment. When entering the dry period, methane content in LFG was at about 30% and started to decrease except in lysimeter 3 which was the one that utilised leachate recirculation as well as leachate storage. By keeping up the moisture levels in the landfill, not only methane levels were kept from shrinking but they actually increased. (Chiemchaisri, Chiemchaisri, et al. 2003)

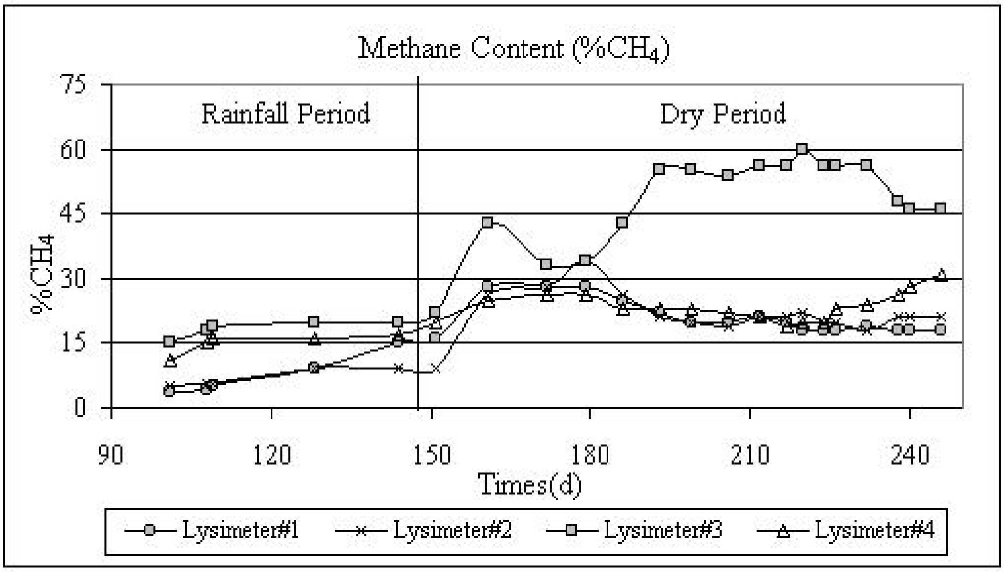



**Figure 36: Methane content in gas from each lysimeter (% of $CH_4$ in landfill gas) (Chiemchaisri, Chiemchaisri, et al.)**

Consequently, storing the generated leachate during the wet season and recirculating it during the dry season can keep moisture levels at the required level and even make the landfill reach the methanogenic phase faster (Ishigaki, Chung, et al. 2008, Chiemchaisri, Chiemchaisri, et al. 2003, Sanphoti, et al. 2006).

Kumar, et al. (2004) provided a contrary finding. While their estimation of methane generation for one year (2001) was 14.2 kilotons or 7.7 kilotons depending on the operation method, the actually collected amounts were much lower, namely 1.7 kilotons per year. This demonstrates that the gas cannot be collected in an efficient and economic way in a lot of (existing) tropical landfills. (Kumar, et al. 2004)

Finally, it was found that in tropical climates, care has to be taken to not build the gas collection pipes too low, since leachate might be clogging it, leading to unacceptable landfill gas qualities and quantities (for utilising the gas). Eam-o-pas, et al. (2000) found that during the rainy season the moisture level in the landfill can mount to almost 2 metres under the cover layer of the landfill. Consequently gas collection might be more difficult during the rainy season (Eam-o-pas, Wetherill und Panpradist 2000). Ishigaki, et al. (2011) added that in tropical countries, horizontal gas extraction pipes might bring bigger success than vertical wells. The reason for this is again the high leachate level in tropical landfills.

Given that in most cases in developing countries it is not economically feasible to collect the generated gas from open dump landfills, most of the publications, therefore, focus on ways to oxidize methane from landfills to $CO_2$. Oxidizing methane is not only relatively inexpensive, also there is no important technology required to achieve it.

The first way to “treat” landfill gas is to actually change it into a different compound. When methane is oxidized it becomes CO2, which still is an important gas when it comes to climate protection but its impacts are relatively lower than those of CH4. Moreover, CO2 from landfills is considered as climate neutral since it originates from biogenic matter.

Whalen, et al. (1990) found that methane oxidation rates for the topsoil of old landfills are the highest compared to any other environment. The optimum temperature for $CH_4$ oxidation is at 31°C and moisture conditions should be at about 11% $H_2O$ (Whalen, Reeburgh und Sandbeck 1990). Similarly, Visvanathan, et al. (1999) observed that the optimal moisture content for methane oxidation actually lies between 15-20% and the optimal temperatures around 30°C. From this, they conclude that methane oxidation is highest right after the rainy season and lowest during the dry season. Furthermore, as soon as water was reintroduced to the dry lysimeter, oxidation recommenced immediately, demonstrating that the methanotrophs were able to survive under the extreme conditions of a very low-moisture soil (Visvanathan, Pokhrel, et al. 1999).

Visvanathan, et al. (2004) found a top cover design that could completely oxidise methane into $CO_2$: a 0.6m thick mixture of sandy loam and market waste compost. The soil was able to keep the optimum moisture content and temperature conditions both in the rainy and in the dry season. The mixture holds moisture even during the extreme dry season and drains additional moisture during the rainy season (Visvanathan, Tubtimthai und Kuruparan 2004). Other ways to achieve oxidation of methane include planting vegetation on top of a landfill. Chiemchaisri, et al. (2003) found that planting the tropical grass *cynodon dactylon* provides best results for such an undertaking. The grass was able to withstand relatively high leachate concentrations, increased methane oxidation and as such, lowered emissions. The authors confess that it can take some time to find the appropriate (local) plant and the perfect leachate concentration level with which the plants are feed until the optimal level of methane oxidation is found (Chiemchaisri, Chiemchaisri, et al. 2003). The need to include a methane oxidative layer for such operations stands in contrast to current practices to design landfills with a hydraulic barrier. It introduces a trade-off between the wish to keep leachate emissions low (local impacts) and gas emissions low (global impact).

## 4.6. Mechanical stability

Waste disposal is not only a health or environmental issue but already the basic design can lead to problems. Piling wastes on top of each other with no pre-treatment or compaction can lead to serious stability issues. Over the years, a number of landfill slides have occurred, not only in developing countries. The first one to be reported by scientific literature happened 1977 in Sarajevo, in the former Yugoslavia. In this incident, 200,000m$^3$ of waste “liquefied”[6] and flowed more than one kilometre down a slope. It was a translational wedge failure and it has been reported that before the slide a lot of leachate of very little concentration came flowing out of the landfill, indicating a high amount of water in the landfill. Second, the landfill was smouldering in some places (G. Blight 2008). The second main landfill slide reported in the literature is the one from the year 1991 in Bandeirantes, Brazil. In June, after a period of continued rainfall, 65,000 m$^3$ of waste slid down from its original place, covering an area of 45,000m$^2$ (Bauer, Kölsch und Borgatto 2008). The next landfill slide happened 1993 in Istanbul, Turkey. In this accident, 12,000m$^3$ of waste liquefied and slid down 60 metres, destroying 11 houses and killing at least 39 people. There was no cover on the landfill and the waste was not compacted. This lead to big quantities of leachate and the landfill was burning in a few places (G. Blight 2008). The next big slide happened in the United States, Ohio. In 1996, on the Rumpke landfill of Colerain Township close to Cincinnati, 1.1 million m$^3$ of MSW slid down the landfill slope. Being among the biggest landfills in the US, the main reason for the slide was that the problematic natural colluvial soil under the first waste layer was not excavated prior to the commencement of the

[6] Waste liquefying means that the solid waste started to flow in a way liquid materials would. This changes the sliding behaviour and speed.

landfilling activity. These types of soil are rather unstable and are constantly close to failure due to the gravity pulling them downwards. This type of soil is very common in the US states of Ohio, Kentucky and Indiana and, thus, the case of the Rumpke landfill might be used as an exemplary warning for other landfills in the area (Stark, Evans und Sherry 1997). Following, there was the landfill slide of the Dona Juana landfill in Bogota, Colombia in 1997. Although it was officially an engineered landfill, 1.5 million tons of waste slid down over a distance of 500 metres. The landfill used leachate recirculation and had a rather bad storm-water run-off system leading to a very wet landfill. There were no injuries during the slide but the river was clogged for a few days to come. Also the failure of the engineered landfill in Durban, South Africa was related to the moisture of the landfill: the landfill was qualified as one in which medium hazardous liquid wastes where allowed to be co-disposed with the normal MSW. This is done by digging trenches in older parts of the landfill that have reached their stabile phase, disposing of the liquid hazardous waste, then closing the trench again. At Durban, the regulations were neglected and only one trench was used continuously. In September 1997, 150 to 180,000 $m^3$ started to slide down into another area of the landfill that had already been prepared for further landfilling purposes. Already prior to the landslide, the water balance showed an increasing amount of liquid in the landfill that was not to be explained by either rainfall, evaporation, leachate outflow or the waste moisture (G. Blight 2008). In this year a third landfill disaster occurred: The Hiriya waste dump in Tel-Aviv, Israel, experienced an important slope failure in the winter 1997-1998. The landfill already showed signs of minor instability problems before due to its steep slopes, a lack of vegetation and drainage issues. (Huvaj-Sarihan und Stark 2008, Stark, Evans und Sherry 1997)

The two landfill disasters that are most discussed in the literature and that caused the greatest negative consequences were the landslides in the Payatas landfill in Manila, Philippines and in the Leuwigajah landfill in Bandung, Indonesia. In 2000 when the landfill in Manila failed, there were ten days of heavy rainfall before the event (in total 750mm of precipitation). This generated a lake on top of the (flattened) landfill, while the landfill was also burning in other spaces. The landslide consisted of 12,000$m^3$ of waste sliding for only 40 metres but it buried all the houses built by scavengers on the foot of the landfill and killed between 300 and 600 people. In this case, a liquefaction of the waste was not observed (G. Blight 2008, Huvaj-Sarihan und Stark 2008, Stark, Evans und Sherry 1997). The final major dump side disaster was the one in Bandung, Indonesia in 2005. As was the case in the Philippines, heavy rainfall events preceded the landslide (a minimum of three days) and as is well known, in the tropics, in a rainfall that lasts for 3 days almost 20% of the annual rainfall of 1500 to 2000mm can precipitate (Tränkler, Manandhari, et al. 2001). Moreover, the dumpsite was placed over a former river stream – further increasing the moisture level in the waste. In February 2005, with loud thunder-like cracking sounds[7] the waste pile failed, liquefied and 500 to 750,000 $m^3$ of waste flowed down the canyon for almost one kilometre, covering scavengers' houses and people under it. 147 bodies were found but many more were missing and the valley floor was covered in waste. The main reasons for the sliding were the water pressure in the subsoil and a fire that had been burning for several months all of the reinforcement material such as plastic fibres and foils. (G. Blight 2008, Kölsch 2009, Bauer, Kölsch und Borgatto 2008)

These catastrophes did not only cause huge amounts of financial losses but also cost human lives and created additional environmental pollution (Machado, et al. 2010). To prevent similar disasters from happening, the underlying causes for the waste slides have to be understood. There are natural causes and anthropogenic causes for landslides in general. Natural causes include groundwater pressuring against the slope, unstable soil structures, no vegetation on the slopes, the toe of the slope getting eroded by water, the slope soil being saturated by snow/glacier melting or rains, and finally, earthquakes and volcanoes. Anthropogenic causes for landslides are deforestation or the general removal of deep-rooted vegetation, (mono-) cultivation, construction or the changing of the landscape. On the one hand, these human activities make the soil and the slopes more fragile and prone to slides; on the other hand, they lead to a bigger infiltration of water into the soil.

Issues when it comes to waste slides include the remaining unknown behaviour of waste as a material, the lacking compaction before landfilling waste, the changing

[7] Sounds resembling thunder, explosion, etc. accompanied most of the landfill disasters.

behaviour of a waste dump in case of fires or in case of heavy rain, and the problems of not bearing in mind the significance of waste management.

The discussion on the mechanical behaviour of waste is advancing only slowly since the calculation methods have been simply transferred from soil mechanics. Mechanical behaviour is mainly analysed through the shear strength. The shear strength is the resistance a solid body opposes to tangential shear forces. It specifies the maximum shear stress a body can receive before shearing, i.e., the tangential force related to the fracture surface. Shear strength is a combination of friction forces and tensile forces. The tensile forces are mainly made up of cohesion between fibres, foils and sheets in the MSW. They bring reinforcement to the waste and are also called fibrous cohesion. Moreover, there are friction forces that keep a certain stability in a waste pile (Bauer, Kölsch und Borgatto 2008, Kölsch 2009). There is a lot of research discussing shear strength (Bauer, Münnich und Fricke 2007, Bauer, Kölsch und Borgatto 2008, Kölsch 2009), yet it is not clear how this force might be influenced by tropical conditions or the different waste composition in developing countries.

Waste composition might have an influence on the stability of a landfill, since in the landslide disasters in Istanbul, Manila, Bandung, Bogota and Durban the waste fractions were relatively similar, indicating a possible correlation between the waste composition and an increased risk of landfill slides (G. Blight 2008).

The influence that waste compaction has on landfill stability is that the denser the waste, the higher the normal stress which results in a higher shear resistance of the waste pile. Furthermore, if the waste is more compacted, less water can percolate through it and more runs off and evaporates. In average, a more equilibrated water balance is achieved within the waste dump (Kölsch 2009). In Bogota, Colombia, the fact that the waste was not compacted was one of the main reasons why the recirculated leachate couldn't percolate effectively through the waste, and as a result, lead to the landslide (G. Blight 2008).

The amount of water in a landfill is definitely greatly influenced by the climate of the country. Many authors argue that a higher amount of water in a waste dump has a definite impact on the material strength. Bauer et al (2007) proved that at a water content of 44%[8], the waste showed significantly different stress-deformation behaviour when exposed to external pressure. At lower moisture levels, by and large, higher shear strength values were reached in the waste pile. Moreover, internal friction values are lower for wastes with higher moisture levels (Bauer, Münnich und Fricke 2007). To reiterate, the first problem with water in the landfill is that it causes the material strength to be reduced. The second problem is that the saturation of the waste material leads to a higher pore water pressure. As can be seen in Table 25, pore pressure was the cause for the main landfill disasters discussed above.

**Table 25: Reasons for landfill disasters and the respective amount of waste that was displaced ($m^3$) (Bauer, Kölsch und Borgatto 2008)**

| Year | Location | Cause of failure | Volume displaced |
|---|---|---|---|
| 1997 | Bogota, Colombia | Pore pressure caused by leachate recirculation | $800 * 10^3 m^3$ |
| 1997 | Durban, South Africa | Pore pressure caused by co-disposal of liquid waste | $160 * 10^3 m^3$ |
| 2000 | Manila, Philippines | Shear failure following heavy rainfall | 13–16 * $10^3 m^3$ |
| 2005 | Bandung, Indonesia | Mechanical failure caused by fire and heavy rainfall | 2,700 * $10^3 m^3$ |

In several tests it has been proofed that the discussed landfill slides have most likely been caused by water pressure in the soil underlying the landfill, such as in the US and Indonesia. Kölsch (2005) who investigated the landfill slide at Bandung, Indonesia in person determined that the waste, in fact, was not excessively moist. The waste that had slid down into the valley had a moisture level of medium values (around 30 to 40%) and the waste that still remained on its original place showed even lower values and would have been able to take up even more water (even after the three days of continued rainfall that occurred prior to the slide). The shear

[8] Their experiment started with a moisture content of 28%. 44% was the highest water content.

strength, thus, could not have been affected strongly by the water pressure in the waste. However, the groundwater (the landfill being "built" on a riverbed) and the infiltration built up water pressure in the soil underneath the waste, so although the internal shear strength was high enough, the shear strength between the waste and the underlying soil layer (external) had strongly decreased. This situation is one of the least favourable since not only small parts of the slope slide down, on the contrary, the whole pile might slide on the slippery ground. Kölsch (2005) found that in combination with this tricky situation, there had also been frequent and continuous landfill fires in Bandung. These keep themselves alive in the inside of a waste pile by feeding on the material that brings the most strength to a landfill: plastics, foils and fibres. By continuously burning over months, the fires reduce these materials and consequently, reduce shear strength of the waste pile. (Kölsch 2009, Kölsch, Fricke, et al. 2005)

Finally, Huvaj-Sarihan and Stark (2008) and Machado et al. (2010) discuss whether the strength of a landfill decreases or increases with its age due to biochemical degradation of the materials. While Huvaj-Sarihan and Stark (2008) report that current research states that the shear strength decreases with time, Machado et al. (2010) found that the high amount of readily degradable organic waste leads to lower shear strength. The further the landfill is in its degradation stages, the higher the fibre content in the MSW and, hence, the higher the shear strength of a landfill. The authors all agree on the fact, that more case studies are needed to give a definite recommendation and that better reporting including data for all the relevant parameter will ease further research. Only high quality reporting of landfill case history will be of help for future work on the subject of mechanical stability of MSW landfills. (Huvaj-Sarihan und Stark 2008, Machado, et al. 2010)

Of the parameters discussed above, the behaviour of the waste in a landfill is related closely to developing countries since its stability and shear strength are principally determined by the amount of plastics or fibres in the MSW. With the different waste composition in developing countries and the higher organic content, this general strength of the MSW to hold its position when exposed to external pressure might be lower than in developed countries. Another issue of the open dumps in developing countries is that no (or rarely) pre-treatment or compaction of the waste exists. The waste simply is collected, scavenged and then pushed over a cliff. The general attention paid to waste management is low which explains why disasters like the dump slide disasters in Manila and Bandung can cause so high impacts.

Issues such as the changing behaviour of waste in a dumpsite after landfill fires or heavy rainfall events are related to the fact whether a country lies in a tropical climate or not. Fires break out more often in dry seasons, which then burn the material responsible for strength of the waste dump and possible causing instability (Kölsch, Fricke, et al. 2005). Nevertheless, fires in landfills are more frequent in developing countries on a general level. They are started by the scavengers who want to collect the valuable, un-burnt metals to resell them. Instability of the waste dump can also be caused by intensive saturation owing to the intensive rainfall events, as they are common in the tropical wet season.

# 5. Discussion

This chapter shall discuss the results from the literature study. The issues researched in this thesis that showed significant differences between tropical and temperate landfills were the leachate quantity, its concentration and composition. Furthermore, landfill gas quantity and its composition differed and it takes the landfill a shorter time to reach the methanogenic phase in which the LFG is produced. Finally, mechanical stability is influenced differently in a tropical climate zone than in a temperate one. Nevertheless, a lot of the issues apparently influenced by the tropical climate are also – at least, partially – affected by the developing status of a country. To assess the different influences Table 26 gives an overview of the findings of this thesis differentiating between the influences of the economic development (measured in GDP) and of the climate zone. As has been shown in subchapters 4.3 and 4.4, the GDP of a country influences, on the one hand, the operation and management of waste and, on the other hand, the waste composition. In the following, these two facts will be considered when discussing the influence of the GDP of a country.

**Table 26: Characteristics of tropical landfills depending on the economic development or the tropical climate**

| | Influence: Economic development | Influence: Tropical climate |
|---|---|---|
| Leachate quantity | ++ | +++ |
| Leachate concentration | + | +++ |
| Leachate composition | +++ | 0 |
| Landfill gas generation rate | ++ | +++ |
| Landfill gas composition | + | 0 |
| Methanogenic phase reached faster | 0 | +++ |
| Mechanical stability | ++ | +++ |
| Faster stabilization of waste | 0 | +++ |

The leachate quantity in landfills in tropical climates is highly influenced by climatic characteristics, as is the leachate concentration. The concentration is further influenced – to a very low level – by the GDP, due to the higher content of biodegradable matter in the waste. The leachate composition is not influenced by the tropical climate since additional water or higher temperatures have no effect on the composition. Solely the level of development (the operation and management, and the waste composition) of a country affects the composition of leachates. For the landfill gas, the experience shows that the quantity – as for the leachate – is highly influenced by the climate zone and also – but to a lesser extent – by the GDP of a country. Since the MSW contains a higher organic fraction in poorer countries, this leads to an increased methane production in landfills. When it comes to LFG composition, a small influence is assumed from the GDP of a country, yet no real indication that the tropical climate stimulates different LFG composition could be given. The fact that landfills in tropical climates reach the methanogenic phase faster, is solely determined by the amount of water in the waste pile. Therefore, only the climate zone has an impact on this parameter, not the GDP of a country. Furthermore, mechanical stability is greatly influenced by the tropical climate given that the higher water percolation and the possible saturation of the waste might lead to greater instability. Also, higher temperatures can increase the chance of landfill fires, which have proven to be a great threat to the mechanical stability of a landfill. Yet, the shear strength of a landfill is also greatly determined by the type of landfilled waste. Here, the GDP of a country comes into play: Lesser-developed countries have a greater organics fraction – which is said to lead to instability, and a lower content of plastics and similar, strength-enhancing materials. Finally, the waste pile stabilizes faster under tropical conditions. Waste stabilisation is influenced highly by the amount of water available for biodegradation, but not at all by the economic development of a country.

Up to now, a lot of research only focuses on issues related to waste management in developing countries, not tropical ones. Table 27 by Idris et al (2004), for example, reports on problems encountered with waste management in developing countries. While being extremely elaborate, this table barely mentions the issues that have been discovered in this thesis. The mentioned topics focus only on the development status of a country and not on the fact that most of the developing countries lie, in fact, in the tropical climate zone[9].

Only, the overlooking of this correlation between development status and climate zone, could result in some misinterpretations of data. Moreover, the risk associated with landfilling in a developing country might be underestimated when omitting the tropical climate and, in consequence, the non-dismissively higher emissions of landfills and increased instability of landfill slopes.

[9] Especially since Idris et al. (2004) focus on landfilling in Asian countries.

**Table 27: Problems in the management of solid waste services in developing countries (Idris, Inanc und Nassir Hassan 2004)**

| Type of problem | Comments |
|---|---|
| External | Population explosion, uncontrolled or unplanned urbanization, squatter area proliferation<br>Socioeconomic crisis<br>Huge external debt<br>Economic austerities<br>Prolonged recession<br>High inflation<br>High unemployment<br>Social disorders, including wars<br>Insufficient public education and limited communal participation |
| External and internal | Accelerated and uncontrolled generation of municipal wastes and industrial hazardous wastes<br>Negligence of, and lack of interest in, solid waste management shown by national and local authorities<br>Lack of intersectoral, interinstitutional, and intermunicipal coordination for sanitary education; lack of interinstitutional coordination between private and public collection services; lack of intermunicipal coordination for intermunicipal landfill<br>Uncontrolled and uncoordinated scavenger activities<br>Inadequately trained human resources<br>High turnover rate of trained professionals<br>Lack of personnel management program<br>Productivity of human resources is low owing to:<br>Untrained staff<br>Poor pay scales<br>Fixed working hours<br>No incentive payment for good performance<br>Inefficient working practices<br>Labor conflicts, such as strikes by syndicated municipal garbage workers<br>Incomplete and obsolete legislation and insufficient enforcement<br>Lack of funds<br>Low assessment rates, or rates that have not increased for many years<br>Poor budgeting: no separate accounting kept for solid waste management, therefore budgeting for this area does not reflect the true expenditure involved<br>The increase in population/generation of waste is not reflected in the assessment charges being levied<br>No enforcement of debtors, resulting in poor collection of funds from the public<br>No proper charging: tipping fees are low and do not reflect the actual cost of upkeep of landfills<br>The rationale for privatisation is economic; public provision is more costly, as evidence seems to show; often public provision is unsatisfactory owing to the inefficiency and rigidity of public bodies; lack of standard financial reporting structure<br>Lack of independent budget administration (in many cases, revenue raised through user fees or taxes become part of the general city treasury, and unexpected demands from other sectors are given higher priority to draw funds initially allocated for solid waste management)<br>Poor monitoring of budget on solid waste management due to lack of basic data and untimely reports<br>No benchmarking to assess efficiency of services<br>No proper financial planning<br>Budgets set are not based on levels of service to be provided<br>Lack of exact cost determination (lack of independent accounting system for municipal solid waste management); it is not possible to monitor all of the costs of service provision; official figures may underestimate the true costs by as much as 50%<br>No proper evaluation of capital expenditure |
| Internal | Structural and institutional weaknesses of municipal solid waste management system:<br>Secondary priority in municipal administration<br>Insufficient and deficiency of allocated resources<br>Fragmented responsibilities borne by various departments<br>Political pressures<br>Lack of short-, medium-, and longterm solid waste management planning<br>Lack of garbage collection route design<br>Lack of supervision, with typical ratios of one supervisor per 10–30 vehicles<br>Lack of equipment maintenance: maintenance is often reactive, that is, repairing vehicles after they have broken down rather than preventive maintenance with regular servicing and routine maintenance, owing to lack of training for maintenance staff, inadequate funds for vehicle repair, and lack of spare parts<br>Technical problems<br>Storage Problems. The present situation in respect of on-site storage varies from one area to another. However, in most cases on-site storage is not satisfactory; storage is not secure and does not allow for effective collection, resulting in health and environmental problems. Some of the common problems of storage are:<br>Lost or damaged trash can lids are often not replaced, leaving waste exposed, emitting odor and attracting flies, rodents, and stray animals<br>Residents with no proper waste storage facilities often hang waste packed in plastic bags outside the house, on fences, trees, or left at the roadsides. Apart from the aesthetic problems, this contributes to the inefficiency of collection<br>Insufficient supply of communal trash cans results in the storage area becoming a dump site<br>Scavenging by rodents and stray animals eventually leaves the waste scattered all around the site, and this is unhygienic<br>Collection.<br>Littering around communal trash cans contributes to inefficiency of collection<br>Different sizes and weight of trash cans makes collection difficult<br>Disposal.<br>Crude dumping is widely practiced<br>Poor control of the site results in haphazard tipping<br>Shortage of suitable land for disposal |

Further research should focus on establishing a similar database for the effects that tropical climate conditions have on the management and operation of landfills as well as their emissions into the environment.

Subsequently, a classification system can be established on a global level, arranging landfills into different categories according to which recommendations and guidelines concerning their operation and management can be given. These recommendations have to take into account the limited financial resources in developing tropical countries and support the aim to achieve maximum efficiency with minimum design and operation costs. This can be done, on the one hand, by relaxing some of the landfill standards and, on the other hand, by establishing a system that ranks the impacts of landfills and takes into account how likely they are to occur. Mavropoulos (2001) drafted a risk assessment tool that describes which control measures a landfill needs. These requirements are derived from the risk calculated that the landfill emissions negatively affect the environment. One important finding was that the risk of groundwater pollution is more sensitive to the size of a landfill than to the climatic water balance (Mavropoulos 2001). The mega-landfills planned in Asian countries could, therefore, affect the environment even stronger in the future. Even more so it is necessary to control the emissions from these landfills. Another tool to help decide what issues to tackle first is provided by Ayomoh, et al. (2008). They determined a solution to ranking environmental and health impacts of MSW disposal. By using a hybrid structural interaction matrix, the authors assess the interdependencies between the different impacts related to waste management. By prioritizing, the problems can be solved at their roots instead of wasting time and money by addressing effects of the original problems. The study discovered that the primary impacts are "air pollution", "water pollution", and "soil pollution". In the second priority the following impacts are found: "places impediment on breathing", "induces body irritation", "exposure to pathogens". Following are the "catalysis of high blood pressure" or "ailment" and lastly a "deteriorating health" and "death". (Ayomoh, et al. 2008)

From these discoveries, certain conclusions can be drawn. Air, water and soil pollution are the issues that have to be handled first. The most important design features that a landfill should have – after having established its class and the risk of it polluting the environment – are first and foremost, a base liner with a leachate collection system and a methane oxidation layer. Compression of the waste and a leachate treatment system are next in the rank of important landfill management and operation tools. Moreover, in many countries, a lot can still be done by raising awareness on a household level and increasing the separation and recycling rate. As such, less waste would go to the landfill, requiring less space in it, the waste that is recyclable would not be contaminated with other materials, and composting the biodegradable waste would provide a clean, natural and cheap fertilizer. Together with the awareness raising, the (official) recycling rate could be improved, by officialising scavengers' work and establishing a neighbourhood-based waste management system as proposed by Pasang, et al. (2007). The authors also provide a table describing the problems of MSW management in Jakarta. (Pasang, Moore und Sitorus 2007)

# 6. Conclusion

With rising population numbers, growing waste quantities and space that is becoming scarcer and more valuable, landfills need to be managed at a more efficient level. It should not further be accepted that open waste dumps and unmanaged mega landfills pollute the environment as well as threaten human health with their risky emissions. To prevent such practices in the future, guidelines and recommendations need to be given for developing tropical countries, taking into account not only their limited financial resources, but also the different waste management needs that exist for tropical climates.

Based on the results of our literature study the following characteristics of landfills in tropical climates can be summarized:

- Large quantities of leachate (often more than 1000 mm/a) as well as strong variations in seasonal generation rates represent a major challenge for landfill operators in tropical countries.
- Leachate generated during the rainy season is characterized by lower pollution and hence would require less intensive treatment as leachate generated during the dry season.
- During the dry season waste decomposition rates are reduced, a problem which could be tackled by leachate recirculation.

- Appropriate design of landfill covers is instrumental for minimizing leachate emissions as well as landfill gas emissions.
- In general, decomposition rates at tropical landfills tend to be higher in comparison to landfills in temperate climates, a fact which is beneficial regarding the stabilization of landfills.
- Although large quantities of landfill gas are generated (due to high contents of biodegradable matter in MSW and optimal conditions for microbial decomposition of organic matter), landfill gas is usually not utilized in tropical climates (mainly due to financial constraints).
- Landfill gas generation is highly influenced by the seasons and is produced in large quantities during the rainy season in tropical climates. Furthermore, methane production in tropical landfills occurs faster, since the methanogenic phase is reached in a shorter period of time. Due to the higher moisture content in the landfills, larger quantities are produced and during a shorter time than in temperate climate zones.
- The mechanical stability of landfills is another issue that is influenced by the increased moisture level of a landfill in a tropical climate. Almost all dump slide disasters occurred after periods of extreme precipitation.
- Financial constraints are probably the most important factor responsible for inappropriate operation and construction of landfills in tropical climates.
- Existing regulations (legal requirements) of waste management and landfill operation are often not obeyed, either due to insufficient financial resources or due to limited knowledge of stakeholders (landfill operators). Hence, training of landfill operators is important for improving the current situation of landfilling, as wells as the development of strategies for earning additional income by landfill operation (e.g. Joint Implementation (JI) /Clean Development Mechanism (CDM) projects for mitigating landfill gas emissions, composting, or recycling).

A tool that would definitely facilitate future research is a classification system like the one introduced in Table 26 in part 5. This could help with the engineering and design process for landfills as well as provide a basis for the establishment of international and national guidelines that could be applied to waste sites all over the globe. This landfill classification system should consider the climate, the development level of the country, as well as the type of waste that is deposited. Moreover, by enforcing certain quality levels for future research, such as that experiments should be conducted for more than one season in tropical countries and that comprehensive data is provided on the landfill/ experiment (For example, the pH-value alone is not interesting if no information is given about the decomposition phase in which it was measured.), more information of a higher value can be obtained and applied. According to the landfill classification system and relevant research results, new guidelines could be designed that fit for every country of any climate zone.

As the final word, it can be concluded that landfills in tropical climates face different problems and challenges in comparison to landfills in temperate climate zones. Hence they require also different solutions, which can only be found by problem oriented research efforts considering local (climatic and economic) conditions.

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# Annex

| Author | Type | Season | Total nitrogen | Ammonia-N | Nitrate | Nitrite | Total phosphorus | BOD5 | COD | BOD5/COD ratio | pH | Conductivity in mycroS/cm | Turbidity | Colour | Total Solids | Total iron | Zink | Total coliform |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluko et al. 2003 | | dry | | 1316 | 0,58 | | 2,07 | 675,6 | 2802 | | 8 | 4807 | 139 FTU | 434,7 HU | 3883 | 122 | 1,4 | |
| Aluko et al. 2003 | | wet | | 633 | 0,47 | | 2,31 | 990,6 | 3066 | | 8,3 | 5662 | 83,4 FTU | 423,6 HU | 4819 | 180 | 2,3 | |
| Ariyawansha et al. 2010 | | | | | | | | 9781,5 | | | | | | | | | | |
| Aziz et al. 2010 | unaerated | | 483 | 542 | 2200 | 91 | 21 | 86 | 935 | 0,096 | 8,2 | 12,17 | 1546 | 3334Pt/Co | 6271 | 7,9 | 0,6 | |
| Aziz et al. 2010 | intermittently | | 1200 | 1568 | 5233 | 49 | 17 | 243 | 2345 | 0,124 | 8,3 | 22,1 | 180 | 3347 | 9925 | 3,4 | 0,5 | <50 |
| Aziz et al. 2010 | anaerobic | | 300 | 538 | 1283 | 52 | 19 | 326 | 1892 | 0,2 | 7,8 | 8,55 | 1936 | 4041 | 6336 | 5,3 | 0,2 | 8100 |
| Blight 2006 | not relevant | | | | | | | | | | | | | | | | | |
| Calabro et al. 2010 | non-tropical | | | | | | | | | | | | | | | | | |
| Chiemchaisri, Srisukphun 2003 | | dry (50mm/d) | 189,1 | 82,8 | | | | 4990 | 20000 | | 5,3 | | | 186,4Pt/Co | | | | |
| Chiemchaisri, Srisukphun 2003 | | rainy (100mm/d) | 64,8 | 51,8 | | | | 3040 | 10000 | | 5,3 | | | 138,2Pt/Co | | | | |
| Hernandez-Berriel et al. 2008 | | 70% MR | | | | | | 23,38g/l | 31,73g/l | 0,735 | 6,3 | 21,65 | | | | | 6,64 | |
| Hernandez-Berriel et al. 2008 | | 80% MR | | | | | | 17,12g/l | 23,08g/l | 0,74 | 6,3 | 20,25 | | | | | 2,21 | |
| Kjeldsen et al. 2002 | non-tropical | | | | | | | | | | | | | | | | | |
| Kuruparan et al. 2003 | open dump | 1st dry | 587 | | | | | | 9812 | 0,48 | | | | | | | | |
| Kuruparan et al. 2003 | open dump | 1st rainy | 1138 | | | | | | 6366 | 0,48 | | | | | | | | |
| Kuruparan et al. 2003 | open dump | 2nd dry | 480 | | | | | | 1354 | / | | | | | | | | |
| Kuruparan et al. 2003 | open dump | 2nd rainy | 517 | | | | | | 584 | / | | | | | | | | |
| Kuruparan et al. 2003 | open dump | 3rd dry | 578 | | | | | | 748 | 0,25 | | | | | | | | |
| Kuruparan et al. 2003 | open dump | 3rd rainy | 648 | | | | | | 358 | 0,25 | | | | | | | | |
| Kuruparan et al. 2003 | engineered landfill | 1st dry | 1779 | | | | | | 35188 | 0,88 | | | | | | | | |
| Kuruparan et al. 2003 | engineered landfill | 1st rainy | 1861 | | | | | | 16525 | 0,88 | | | | | | | | |
| Kuruparan et al. 2003 | engineered landfill | 2nd dry | 1733 | | | | | | 2074 | / | | | | | | | | |
| Kuruparan et al. 2003 | engineered landfill | 2nd rainy | 1509 | | | | | | 2542 | / | | | | | | | | |
| Kuruparan et al. 2003 | engineered landfill | 3rd dry | 1523 | | | | | | 1422 | 0,3 | | | | | | | | |
| Kuruparan et al. 2003 | engineered landfill | 3rd rainy | 899 | | | | | | 1182 | 0,3 | | | | | | | | |
| Machado et al. 2010 | no info | | | | | | | | | | | | | | | | | |
| Madera, Valencia-Zuluaga 2009 | only removal | | | | | | | | | | | | | | | | | |
| Mangimbulude et al. 2009 | | wet | | 580 | | | | 303 | 1260 | | 8,2 | 11,7 | | | | 12,5 | | |
| Mangimbulude et al. 2009 | | dry | | 678 | | | | 435 | 1883 | | 8,3 | 12,4 | | | | 15 | | |
| Robinson 2005 | Mauritius | | | 1299 | | | | 1249 | 5683 | | | | | | | | 2,53 | |
| Robinson 2005 | Thailand | | | | <1 | 0,7 | 1,7 | | 2700 | | 7,6 | 28100 | | | | 2770 | 150 | |
| Robinson 2005 | Thailand | | | | <1 | 0,4 | 15 | | | | | | | | | | | |
| Robinson 2005 | Thailand | | | 3032 | <1 | 0,3 | 14 | | | | | | | | | | | |
| Robinson 2005 | Indonesia | | | 2000 | <1 | <1 | 12 | | | | 8,4 | | | | | 6230 | 463 | |
| Sanphoti et al. 2006 | only removal | | | | | | | | | | | | | | | | | |

| Author | Type | Season | Total nitrogen | Ammonia-N | Nitrate | Nitrite | Total phosphorus | BOD5 | COD | BOD5/COD ratio | pH | Conductivity in mycroS/cm | Turbidity | Colour | Total Solids | Total iron | Zink | Total coliform |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sao Mateus et al. 2012 | no info | | | | | | | | | | | | | | | | | |
| Sawaittayothin, Polprasert 2007 | Thailand | | 389 | | | | 24,7 | 775 | 2950 | | 8,7 | 6,61 | | 642 ADMI | | | | 2236 |
| Tatsi, Zouboulis 2002 | non-tropical | | | | | | | | | | | | | | | | | |
| Tayler, Allen 2006 | non-tropical | | | | | | | | | | | | | | | | | |
| Tränkler et al. 2001 | Thailand | | 800 | 667,5 | | | | 9350 | 13360 | 0,54 | | | | | 12350 | | | |
| Tränkler et al. 2005 | open cell | 1st dry | 600 | | | | | | 10000 | 0,5 | 7,5 | | | | | | | |
| Tränkler et al. 2005 | open cell | 1st rainy | 1200 | | | | | | 8000 | 0,5 | | | | | | | | |
| Tränkler et al. 2005 | open cell | 2nd dry | 500 | | | | | | 1000 | / | | | | | | | | |
| Tränkler et al. 2005 | open cell | 2nd rainy | 400 | | | | | | 600 | / | | | | | | | | |
| Tränkler et al. 2005 | open cell | 3rd dry | 350 | | | | | | 700 | 0,2 | | | | | | | | |
| Tränkler et al. 2005 | open cell | 3rd rainy | 350 | | | | | | 450 | 0,2 | | | | | | | | |
| Tränkler et al. 2005 | sanitary landfill | 1st dry | 2000 | | | | | | 37500 | 0,9 | | | | | | | | |
| Tränkler et al. 2005 | sanitary landfill | 1st rainy | 1900 | | | | | | 10000 | 0,9 | | | | | | | | |
| Tränkler et al. 2005 | sanitary landfill | 2nd dry | 1600 | | | | | | 2000 | / | | | | | | | | |
| Tränkler et al. 2005 | sanitary landfill | 2nd rainy | 1200 | | | | | | 1000 | / | | | | | | | | |
| Tränkler et al. 2005 | sanitary landfill | 3rd dry | 450 | | | | | | 7500 | 0,2 | | | | | | | | |
| Tränkler et al. 2005 | sanitary landfill | 3rd rainy | 650 | | | | | | 7500 | 0,2 | | | | | | | | |
| Umar et al. 2010 | Malaysia 1 | | 1685 | 1380 | | | | 358 | 1788 | | 8,3 | | | | 9693 | 3,6 | 0,3 | 50 |
| Umar et al. 2010 | Malaysia 2 | | 612 | 503 | | | | 515 | 1593 | | 7,8 | | | | 6900 | 6 | 0,3 | 8100 |
| Umar et al. 2010 | Malaysia 3 | | 822 | 566 | | | | 48 | 599 | | 7,5 | | | | 2543 | 3 | 0,01 | 6600 |
| Umar et al. 2010 | Malaysia 4 | | 1176 | 996 | | | | 85 | 990 | | 8,1 | | | | 12568 | 5 | 0,2 | 1600 |
| Visvanathan et al. 2002 | open cell | dry | | | | | | | | | | | | | | | | |
| Visvanathan et al. 2002 | open cell | wet | | | | | | | | | | | | | | | | |
| Visvanathan et al. 2002 | reference cell | dry | | | | | | | | | | | | | | | | |
| Visvanathan et al. 2002 | reference cell | wet | | | | | | | | | | | | | | | | |
| Visvanathan et al. 2003 | repeats Tränkler et al. 2005 | | | | | | | | | | | | | | | | | |
| Visvanathan et al. 2010 | open cell | loads: | 0,13g/kg | | | | | | 32,5g/kg | | 5,6 then 7 | | | | | | 0,297 | |
| Visvanathan et al. 2010 | closed cell | loads: | 0,4g/kg | | | | | | 8g/kg | | 5,6 then 7 | | | | | | 0,185 | |
| Ziyang et al. 2011 | 2xsame intermediate layer | | 280.2 | 146.5 | | | 5,9 | | 106258 | | 6,1 | | | | | | 1,98 | |
| Ziyang et al. 2011 | 2 different interm. Layers | | 277.6 | 113.6 | | | 2,36 | | 105465 | | 7,5 | | | | | | 1,6 | |

| Author | Total nitrogen | Ammonia-N | Total phosphorus | BOD5 | COD | BOD5/COD ratio | pH | Electrical Conductivity in mycroS/cm | Total Solids | Total iron | Zink |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluko et al. 2003 | | 1316 | 2,07 | 675,6 | 2802 | | 8 | 4807 | 3883 | 122 | 1,4 |
| Aluko et al. 2003 | | 633 | 2,31 | 990,6 | 3066 | | 8,3 | 5662 | 4819 | 180 | 2,3 |
| Ariyawansha et al. 2010 | | | | 9781,5 | | | | | | | |
| Aziz et al. 2010 | 483 | 542 | 21 | 86 | 935 | 0,096 | 8,2 | 12,17 | 6271 | 7,9 | 0,6 |
| Aziz et al. 2010 | 1200 | 1568 | 17 | 243 | 2345 | 0,124 | 8,3 | 22,1 | 9925 | 3,4 | 0,5 |
| Aziz et al. 2010 | 300 | 538 | 19 | 326 | 1892 | 0,2 | 7,8 | 8,55 | 6336 | 5,3 | 0,2 |
| Chiemchaisri, Srisukphun 2003 | 189,1 | 82,8 | | 4990 | 20000 | | 5,3 | | | | |
| Chiemchaisri, Srisukphun 2003 | 64,8 | 51,8 | | 3040 | 10000 | | 5,3 | | | | |
| Hernandez-Berriel et al. 2008 | | | | 23380 | 31730 | 0,735 | 6,3 | 21,65 | | | 6,64 |
| Hernandez-Berriel et al. 2008 | | | | 17120 | 23080 | 0,74 | 6,3 | 20,25 | | | 2,21 |
| Kuruparan et al. 2003 | 587 | | | | 9812 | 0,48 | | | | | |
| Kuruparan et al. 2003 | 1138 | | | | 6366 | 0,48 | | | | | |
| Kuruparan et al. 2003 | 480 | | | | 1354 | / | | | | | |
| Kuruparan et al. 2003 | 517 | | | | 584 | / | | | | | |
| Kuruparan et al. 2003 | 578 | | | | 748 | 0,25 | | | | | |
| Kuruparan et al. 2003 | 648 | | | | 358 | 0,25 | | | | | |
| Kuruparan et al. 2003 | 1779 | | | | 35188 | 0,88 | | | | | |
| Kuruparan et al. 2003 | 1861 | | | | 16525 | 0,88 | | | | | |
| Kuruparan et al. 2003 | 1733 | | | | 2074 | / | | | | | |
| Kuruparan et al. 2003 | 1509 | | | | 2542 | / | | | | | |
| Kuruparan et al. 2003 | 1523 | | | | 1422 | 0,3 | | | | | |
| Kuruparan et al. 2003 | 899 | | | | 1182 | 0,3 | | | | | |
| Mangimbulude et al. 2009 | | 580 | | 303 | 1260 | | 8,2 | 11,7 | | 12,5 | |
| Mangimbulude et al. 2009 | | 678 | | 435 | 1883 | | 8,3 | 12,4 | | 15 | |
| Robinson 2005 | | 1299 | | 1249 | 5683 | | | | | | 2,53 |
| Robinson 2005 | | | 1,7 | | 2700 | | 7,6 | 28100 | | 2770 | 150 |
| Robinson 2005 | | | 15 | | | | | | | | |
| Robinson 2005 | | 3032 | 14 | | | | | | | | |
| Robinson 2005 | | 2000 | 12 | | | | 8,4 | | | 6230 | 463 |
| Sawaittayothin, Polprasert 2007 | 389 | | 24,7 | 775 | 2950 | | 8,7 | 6,61 | | | |
| Tränkler et al. 2001 | 800 | 667,5 | | 9350 | 13360 | 0,54 | | | 12350 | | |
| Tränkler et al. 2005 | 600 | | | | 10000 | 0,5 | 7,5 | | | | |
| Tränkler et al. 2005 | 1200 | | | | 8000 | 0,5 | | | | | |
| Tränkler et al. 2005 | 500 | | | | 1000 | / | | | | | |
| Tränkler et al. 2005 | 400 | | | | 600 | / | | | | | |
| Tränkler et al. 2005 | 350 | | | | 700 | 0,2 | | | | | |
| Tränkler et al. 2005 | 350 | | | | 450 | 0,2 | | | | | |
| Tränkler et al. 2005 | 2000 | | | | 37500 | 0,9 | | | | | |
| Tränkler et al. 2005 | 1900 | | | | 10000 | 0,9 | | | | | |
| Tränkler et al. 2005 | 1600 | | | | 2000 | / | | | | | |
| Tränkler et al. 2005 | 1200 | | | | 1000 | / | | | | | |
| Tränkler et al. 2005 | 450 | | | | 7500 | 0,2 | | | | | |
| Tränkler et al. 2005 | 650 | | | | 7500 | 0,2 | | | | | |
| Umar et al. 2010 | 1685 | 1380 | | 358 | 1788 | | 8,3 | | 9693 | 3,6 | 0,3 |
| Umar et al. 2010 | 612 | 503 | | 515 | 1593 | | 7,8 | | 6900 | 6 | 0,3 |
| Umar et al. 2010 | 822 | 566 | | 48 | 599 | | 7,5 | | 2543 | 3 | 0,01 |
| Umar et al. 2010 | 1176 | 996 | | 85 | 990 | | 8,1 | | 12568 | 5 | 0,2 |
| Visvanathan et al. 2003 | | | | | | | | | | | |
| Visvanathan et al. 2010 | | | | | | | 6,3 | | | | 0,297 |
| Visvanathan et al. 2010 | | | | | | | 6,3 | | | | 0,185 |
| Ziyang et al. 2011 | 280.2 | 146.5 | 5,9 | | 106258 | | 6,1 | | | | 1,98 |
| Ziyang et al. 2011 | 277.6 | 113.6 | 2,36 | | 105465 | | 7,5 | | | | 1,6 |
| **AVERAGE** | **919,23** | **966,65** | **11,42** | **3881,62** | **11217,42** | **0,45** | **7,41** | **3516,77** | **7528,80** | **720,28** | **35,24** |