An Environmental Evaluation of Landfill Systems
Case Study from Two Landfills in South Sweden

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ABSTRACT

With the increasing environmental concerns, the demand of waste management is switching from a problem solution to an integrated system of technical, ecological and economical cooperation. The present landfill technologies are the modern landfills, the biocell landfills, and the bioreactor landfills. Though the use of bioreactors techniques, a landfill site is regarded as a biological treatment and therefore is considered to be an alternative for the landfill management.

In this study, two landfill sites in south Sweden is addressed for a better understanding of the landfill technologies. The landfill site owned by Sysav Company in Malmö with the modern landfill technology is compared to the other landfill site in Filborna, owned by the Nordvästra Skånes Renhållnings Company, with a bioreactor technology. For a comparison study of the environmental performance by different landfill techniques in each case, an evaluation system is developed. The environmental performance of each case is evaluated with an index consisting of four impact categories, namely air emission, water contamination, ecological impacts and human health risks. A further environmental evaluation is made accordingly.

The result of the study shows that both technologies can reach a rather good gas production for energy recovery at present while the bioreactor technology has a better environmental performance compare to the modern landfill technology in a long-term perspective. Moreover, the design of future waste management should not be tied to a single technological solution. Further recommendations on technical development and tax-free policies are stated for a better waste management system than it is today.
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1. INTRODUCTION

1.1 Purpose

With the growing population and an increasing concern for sustainability, the previous ways of handling waste through landfill is facing its limitation and problems. Dramatically changes on waste treatment to switch focus from short-term needs to global environment calls have been emphasized during the last decade. At a system level, different treatment systems have been examined in order to bring out the most environmental and economic efficiency on prevention, recovery and reduction of waste. A Council Directive on the landfill of waste across the European Union has been introduced to minimise impacts to environment and the risks to human health. At a technology level, design and operating criteria essentials are provided for practical alternatives to the problem. Further study of different technological applications may also improve the overall condition of waste management.

Biological approaches for landfill controls as bioreactors are considered to be an option to mitigate costs, shorten the time needed to process solid waste, and reduce the typical ecological impacts. From an ecological perspective, a biological treatment resembles natural process in the ecosystem would stop the one-way flows of waste in society from consumption of goods to landfilling of waste. Therefore, the main objective of this study is to evaluate the environmental performance between different landfill technologies. The sustainability of each landfill site will be examined via comparison of the impact from different landfill operation. In a short-term, the outcome of the study aims to provide a clear picture for an appropriate waste management to decrease impacts on the environment and raise the efficiency of waste treatment. In a long-term, it could be seen as basic work for developing more comprehensive and holistic strategies rather than viewing the waste problem as a single entity.

1.2 Method

Environmental problems constitute a new kind of complex and systemic problem that require new type of methods both for scientific analysis and problem solving. In this study, the waste problem is approached in an interdisciplinary way incorporating natural and social sciences for a holistic evaluation. The evaluation of key factors related to the environmental, economic and scientific effects in the case study would provide knowledge for future scenarios in implementing the landfill system to other potential areas. Data is collected and reorganised from both literature research expertise by scientists and from experiences of the companies. Holistic views are taken on different systems such as water, air, policy and economics for orientation in the planning and decision making process to provide the examination of two landfilling sites in Helsingborg and Malmö.

An overview of the approach in this study is shown in figure 1. Firstly, the overall concept of the study is from an ecological perspective. With this concept, the paper will commence by describing the existing landfill system followed by introducing landfill technologies and the impacts of a landfill operation. In the subsequent section of environmental evaluation, the conditions and restrictions of different landfill systems, namely the bioreactor landfill and modern landfill in each case of the study would be examined for further analyse. Evaluation for this case
study is done in two steps. First of all, environmental performance criteria are developed according to four essential impact sectors due to landfill operation. Indicators for each sector of water, air, ecology and human health would be weighed and combined for an overall environmental impact index for each landfill site. Secondly, data from each landfill site are collected for evaluation. Further analyse and discussion would be given in the final part of the paper as a result of the evaluation. Moreover, recommendations for landfill systems are suggested as future scenarios.

1.3 Scope

The ecological comparison used in this study include different procedures for landfill treatments that could minimise the impacts on ecosystem and towards an environmentally sound decision making to promote sustainable waste treatment technologies and practices. Combining ecosystem function with human needs is the emphasis of ecological perspective.

Particular attention will be given to the Swedish experiences due to its pioneer position and data availability. For this reason, two landfill sites of different municipalities in South Sweden were chosen for case study. The focus of the study is on the regional state whereas the outcome is expected to apply to the globe level.

2 BASIC OVERVIEW OF WASTE MANAGEMENT

2.1 Conceptual Model for Waste Stream

Disposal waste can be treated in different ways. Mostly follows the procedure of collection, recycling, waste to energy, biological treatment, and landfill as a final storage. Examine the existing waste management system with a conceptual model could offer a clear view for the overall situation for further improvement. The general waste flow is stated in figure 2. Firstly, waste input from human society by different sources such as farms, industries, public service and household, etc are collected. Secondly, those materials are transported to the treatment plants. Meanwhile emissions are realised as environmental impacts. There are also parts of the waste directly goes to the landfill site for deposit, which should be decrease as much as possible. At the stage of waste treatment, various strategies are used according to their suitable treatments. Properly sorting to make good use of recyclable material has always been putting in the priority. Thus hazardous waste is to be sent to special
hazardous waste collection sites, and recyclable waste to recycling centres, while the treatment fraction is to be sorted into food and other organic waste, waste to be incinerated, and waste requiring landflling. Afterwards, with energy added along to various treatment activities, outputs of the waste flow are transported as emissions are produced. Although landfill is also a way of waste treatment, it mainly contains materials which either cannot be treated by the other methods or residues from other treatments. Therefore it is considered as part of the final stage in the flow. A certain amount of energy could be recovered during waste treatment in terms of electricity or heat which could be utilised back in the human society. Other emissions causing environmental impacts are emerged as a result of the flow.

![Conceptual model of waste flow](image)

**Figure 2. Conceptual model of waste flow.**

### 2.2 Waste Statistic in Sweden

In Sweden, the municipalities are responsible for collecting household waste and comparable waste as well as ensuring properly sorted before final treatment. Collected wastes are transported to the disposal site by refuse trucks or compaction vehicles equipped with identification systems or weighing apparatus. At the waste treatment stage, collected waste will be sorted again for proper treatment. The most commonly used treatment for household waste in Sweden is incineration, namely the waste to energy system. However, emissions to water and air such as hydrogen chloride, mercury, cadmium, lead, and dust have always been an issue. After incineration there remains slag and ashes from flue gas purification is deposited as landfill.

Total waste deposit in Sweden amounted to approximately 12 million tons in year 1999 (RVF, 2001). Among all waste income, households generate about 30% (around 3.8 million) tons of municipal waste in Sweden. On a per capita basis, this amounts to 360 kg per person and per year. Estimates made by the Swedish Environmental Protection Agency showed households are responsible for almost 50%
of environmentally harmful emissions. Figure 3 shows the household waste flow in Sweden at present. About 24.3% of the waste from households goes to landfill, thirty-eight percentage is combusted in incinerations for energy recovery and approximately 28.8% is recycled and 8.4% for biological treatment. Incineration is used for 1,440,000 tons along with 700,000 tons of other fractions including industrial waste. Compare to the previous year of 1998, incineration of waste to energy is at approximately the same level, and the percentage of biological treatment of waste is increasing while landfilling is decreasing. Nevertheless the total quantity of landfill increased slightly in 1999, amounting to 4.9 million tons due to the rising waste quantity as the whole.

![Diagram showing the waste flow of household waste in 1999.](image)

Figure 3. The waste flow of household waste in 1999.
Source: The Swedish Association of Waste Management (RVF).

### 2.3 Ecological Perspective

It is essential to reconsider and reanalyse the current waste management in Sweden, as described in the previous paragraph, with an ecological perspective. Closing the non-cyclic material flows and reducing the environmental impacts are key factors for a sustainable management by this viewpoint.

Ecological perspective is examining the treatment technologies not only for solving the current environmental problems but also for creating feedback loops back to human society as reusable resources by the way of waste recovery. Using this perspective, biological waste treatment could be the optimise technology of our interest for further application. Biological treatment or stabilisation can be used for most types of wastes containing hydrocarbons. Residual municipal and industrial waste remaining after recycling and other treatment is also suitable for biological treatment (Bramryd, 1996). It includes aerobic composting, anaerobic digestion and
landfill bioreactor. Biological decomposition in a landfill takes place in aerobic composting, anaerobic digestion which covers. The process in biological treatment at a bioreactor landfill consists of the stage of acetogenic and anaerobic (Tammemagi, 1999) By a proper biological treatment, residues from digestion either in a solid form as compost or in a liquid form of leachate from landfill biocell reactor could be used as fertilizer for gardens, agriculture to place the artificial fertilizer. The recovered nutrient can accordingly be return to human society. It would resemble the natural ecological process and thus reduce the environmental impacts. The biogas produced during the biocell reactor process could also be used in the form of electricity or heat to reduce the pollution and harmful effects of relying on non-renewable energy from coal and nuclear power.

Before going further to the bioreactor landfill techniques, the scope of the system will be defined first. Figure 4 shows the waste management system. Waste sources from commercial, industrial, garden, household and hazardous waste goes into different treatments. Waste primarily falls into two categories: hazardous waste, and nonhazardous waste. The waste definitions in detail are shown in appendix 1. In the study waste resource are specifically defined as primarily biodegradable waste mostly from household waste but also with a part of industrial and commercial waste as input. Different treatments in the figure are placed in circle mark including recycling, incineration, composting and digestion. The most environmentally sound approaches are implemented according to EU’s preferred order: source reduction first, recycling,
biological treatment as well as energy from waste incineration then disposal in landfills last. The waste stream also depends on the character of the waste. Biodegradable waste usually goes to anaerobic digestion, which is included in the biocell reactor landfill sites as a pre-treatment. Although source reduction, reuse, recycling, and composting can divert large portions of waste from disposal, some waste still remains and will be placed in landfills since no disposal alternatives are currently in use. In recent year, biocell reactor landfills have gained recognition as a possible innovation in solid waste management. By the improving techniques, the state-of-art landfill biocell reactor as part of the ecological method of waste treatment might be an option.

The scope of the study will focus on the biological treatment in landfill biocell reactor to compliance with the stringent Landfill Directive for reducing requirement of landfill capacity as final disposal. To achieve the target of reducing half of the waste amount goes to landfill by 2005 while searching for an advanced technique to handle the huge amount of waste is necessary. Through the use of the bioreactor technique modern landfilling can be regarded as a biological treatment for waste and therefore free from landfill tax. The biocell reactor landfill distinct from other types of landfills is the large amount of biodegradable materials and the following decomposition and stabilization of these materials. Other important characteristics are listed below:

- Premixing municipal solid waste, mainly commercial waste and industrial waste.
- Mixing with leachate.
- Construction in small well controlled units.

Pros and Cons of the biocell reactor landfills will be brought up and discussed in this study to see their potential of being relevant as the future landfills. Therefore the system, shadowed in the figure, is limited in the scope of mainly biodegradable waste which goes under digestion in a landfill biocell reactor, which, in short, will be called bioreactor landfill in the following sections.

3. PRESENT TECHNOLOGY

3.1 Classifications of Landfills

The landfill body is, in essence, a reactor that enhances the decomposition process. Landfills are roughly categorized according to different technologies in operation of the landfill. Bioreactor and biocell landfills are studies in this paper to show their differentiation to the old ones.

3.1.1 Landfills with Conventional Technology

A major environmental problem is presented by previous landfills that were constructed without liners and leachate collection systems. Evolution of landfill development evolved as response to problems and is driven by regulatory requirements. In 1970s, control sanitary landfills were built in response to the problem of odours, windblown refuses and open fires by installing the cover system in formal dumpsites. Liner system was developed in the 1980s as major components of a landfill in response to the groundwater contamination. Siting consideration and new
technologies such as biocell technology were spotlights later on as response to ever raising environmental awareness. However, landfills with conventional technology are still in operation as a majority in the world.

Table 1. Landfill techniques developing history.

<table>
<thead>
<tr>
<th>Date</th>
<th>1970s</th>
<th>1980s</th>
<th>1990s---</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
<td>Control sanitary landfill</td>
<td>Modern landfills</td>
<td>Biocell landfills</td>
</tr>
<tr>
<td>Solved problems</td>
<td>Odours, Open fires</td>
<td>Groundwater contamination, Global warming</td>
<td></td>
</tr>
<tr>
<td>Improvements</td>
<td>Cover system</td>
<td>Liner system Gas collection</td>
<td>Optimised system for gas collection</td>
</tr>
</tbody>
</table>

3.1.2 Biocell

Landfill biocell are special designed cells for rapid methane recovery by undergoing an accelerated digestion. These cells are called biocells, biofills or digestion cells. It is introduced to Sweden by the end of the 1980s. They are designed to aim a landfill treatment with minimum of water percolating the waste and a minimum air emission to the environment. Biocells could be characterised as a landfill designed for landfill gas production and involves in an optimized operation for gas collection by means of installation of horizontal gas extraction systems and an effective leachate collect system.

3.1.3 Bioreactor

Bioreactor landfills are constructed in a manner similar to most modern sanitary landfills equipped with liners system and landfill gas collection systems but operate additionally leachate recirculation and alternative cover designs. It is an advanced biocell with an additional leachate recirculation system to optimise the overall process. The main purposes of operating bioreactors are to optimise the operation technique and the anaerobic degradation and to ensure functional systems for gas extraction and leachate collection (NSR, 2001). The fundamental process used for waste treatment in a bioreactor landfill is leachate recirculation which could speed up microbial decomposition of the biodegradable solid waste therefore accelerate the biological stabilization of the landfilled waste rapidly. In general, The bioreactor landfill is generally defined as a landfill operated to transform and stabilize decomposable waste streams by appropriate control to enhance microbiological processes to their optimised condition for maximal bioenergy and nutrient recovery.
3.2 Landfill Equipment, Construction and Operation

3.2.1 Equipment and Construction

Landfills are basically constructed of a number of cells, as the main reactors for treatment, combined with sealing systems, leachate collection systems, gas collection systems as well as monitoring systems to ensure effective operation and accomplishment of the regulations requirements.

3.2.1.1 Sealing System

The purpose of sealing system is to protect the nature from pollution of the hazardous materials produced by landfill process. The landfill sealing system consists of a landfill cover, a lined base liner, and possibly a side liner to surround the entire landfill body. A typical final cover for a landfill is from 0.6 to 2 meters thick (Tammemagi, 1999). During the filling period a daily cover is needed as well to reduce gas emission. Liners should have high stability during treatment as well as being impermeable to gas migration and leachate leakage to prevent contamination of the ground water under the landfill. To meet the demand, liners are usually made of several low-permeability layers of clay, thick plastic, geomembranes and sand. A second impermeable liner is reinforced with clay and plastic on the bottom and sides of landfills.

3.2.1.2 Leachate Collection System

The purpose of a leachate collection system is to reduce the pressure on the impermeable part of the liner system by minimising the depth of leachate above the liner. In the United States, it is limited to the extent of less than 30 cm at any given time (U.S. Environmental Protection Agency, 1988). In European countries the restriction is based on penetration rate of the pollutants into the soil rather than the depth of leachate. Horizontal perforated pipes are inserted in each drainage layer to collect leachate. Collected leachate is pumped from the bottom of the landfill, stored in tanks and sent either to a regular sewage treatment plant or to an on-site treatment plant.

Leachate recirculation is the essence to distinguish bioreactor technology from biocell. The purpose is to optimise the microbial decomposition process via moisture control which could be achieved by leachate recirculation. Through maintaining high moisture content would enhance decomposition in the bioreactor. Sometimes chemicals or microorganisms are added to the recirculating leachate to promote biodegradation (Tammemagi, 1999). Leachate recirculation has been accomplished by various methods including vertical recharge wells, spray irrigation systems, and surface application. Among these techniques, recharge wells are found to be simplest and most affective (Reinhart and Townsend, 1999).

3.2.1.3 Gas Extraction

Landfills are equipped with vent pipes to collect these gases generated inside a landfill during the decomposition process. Gases can be extracted from a landfill by vertical wells connected to an energy generation station. Collected methane can
therefore be burned in plants or in fuel cells for the energy recovery. In a biocell landfill, an optimised system for gas collection is set. Cleaning and updating the collected methane can reach a proper ratio of methane for a higher marketing potential. The collected gas then can either be sold to natural gas companies or to nearby commercial users as heating and electricity.

### 3.2.1.4 Monitoring System

In general the system covers several monitoring parameters such as groundwater, surface water, landfill gas, atmospheric gas and settlement (Tammemagi, 1999). A modern landfill may have from 20 to more than 100 monitoring wells. Probes and wells are placed below the landfill cover to measure gas pressure, temperature and composition. Contents and internal conditions of landfills can be learnt and improved by proper monitoring. In addition, harmful factors due to leakage of leachate and escape of hazardous gas could therefore be avoided by the detecting probes around the site. Closure and post closure care are conducted by monitoring when the landfill is full and close down to provide a long-term care of the closed landfills.

Table 2. Characteristics of different landfill techniques.

<table>
<thead>
<tr>
<th>Character</th>
<th>Modern landfill</th>
<th>Biocell</th>
<th>Biocell reactor (BCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner system</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gas collection</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Leachate collection system</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Monitoring system</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gas production control</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pre-treatment</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Leachate recirculation</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Processing time turnover time</td>
<td>25-40 years</td>
<td>15-20 years</td>
<td>5-10 years</td>
</tr>
</tbody>
</table>

### 3.2.2 Operation

The flowchart in figure 5 shows the overall streams in a landfill site. It is important to study the process chain to find out the main activities in each sector and the sub-components of the overall process chain. Each step of the processes is described in the following for a further impact identification.
1. The waste composition affects both quality and quantity of leachate and gas, the waste degradation rates, and resource recovery potential. Therefore when the trucks carry the MSW to a landfill site, sorting and weighing is the first step. Different wastes are sorted and deposit to different areas in a landfill site. A uniform waste not only improves leachate and gas composition but also simplifies following landfill operations.

2. In the next step, some pre-treatment procedures are done before transferring the waste into the reactor cells. Pre-treatment could include both chemical and physical
treatment. Most large landfill sites operate with some form of composting before further digestion. Physical properties such as compacting and shredding will be optimised for reactor control. Compacted waste make efficient use of space and also reduce requirement for cover materials. Shredding promotes equitable settlement and enhances the biodegradable process for gas production. Biocell optimised gas collection system by working on putting the proper ratio of different types of waste for the right density and size to give a maximum gas production or an optimised gas component.

3. After those physical treatment wastes are place into the main reactor, daily covering of the waste with soil or other inert material will be added help reduce odour; control litter, insects, and rodents. An impermeable cover over the landfill will be placed. Waste is transformed from an aerobic to anaerobic environment. Main reactor parts of the bioreactor landfill are bioreactors where the decomposition processes take place. The bioreactor landfill should be approached as a waste treatment rather than a traditional landfill. The decomposition process in the bioreactor goes through several stages by the microbial conversion of biodegradable organic content.

\* Acid formation phase/ Acidogenic state:
The continuous hydrolysis of solid waste followed, results in the production of intermediate organic acid at high concentrations. A rapid consumption of substrate and nutrients are the predominant features of this phase. Organic acids, hydrogen, carbon dioxide and some heat are produced. The production of carbon dioxide and large amounts of organic acids results in an acidic leachate, with the lowering of pH to about 5.5 to 6.5 creates leachate. The process can be described as follows:
Biodegradable waste $\rightarrow$ CO$_2$+H$_2$O+organic acids + degraded waste

\* Fermentation phase/ methanogenic stage:
This stage may not commence until six months to a few years after the waste emplacement. But this process becomes dominant and remains so until all the available organic materials have been decomposed. Acid are consumed by methanogenic bacteria and converted into methane, water, carbon dioxide and some heat. The methane gas is a particularly important product being extracted and used as an energy source. Gases nitrogen (N$_2$) and toxic hydrogen sulphide (H$_2$S) may also be generated.

4. Leachate produced within the reators can be collected for onsite treatment or taken to nearby sewage treatment plant. About 80 out of 270 sites in Sweden have local leachate purification (RVF, 2001), either as the sole purification method or in combination with a sewage treatment plant. During the leachate purification, heavy metals are removed from the leachate. In a bioreactor landfill, collected leachate is recirculated to the methane producing area as a way of moisture control during decomposition. Recirculating leachate through the landfill maintains high moisture content to promote degradation process. In the contrary, leachate formed in a biocell landfill is collected, removed and treated to reduce the possible groundwater contamination.

5. In the reactor, another product during the waste decomposition is the landfill gas. It is formed during the methanogenic stage in the reactor and the mainly components of the gas are methane and carbon dioxide. Methane is extracted at 35 biocell landfill
sites in Sweden (RVF, 2001) for energy recovery. The methane production can be accomplished under controlled conditions for maximum methane recovery. The gas production rates relate to landfill age, waste components and decomposition condition, etc. Therefore a control system usually works on proper pre-treatment such as mulching wood and lumber debris to increase the surface area and mixing waste by a certain ratio. Once the methane gas is produced, it will be collected as onsite fuel for operator or transferred to the company then back to consumers. In Sweden a total of 435 GWh was extracted in 1999, of which 405 GWh was used for heating and 30 GWh for electrical energy (RVF, 2001).

6. The monitoring system is an essential system in a landfill site to ensure proper operation. Monitoring should be continued after the site is closed. Monitoring is usually done by sampling different parameters through tubes, wells and other monitoring techniques.

4. ENVIRONMENTAL IMPACTS IN LANDFILLS

4.1 Characterisation

The environmental problems that arise in connection with landfill sites largely stem from the hazardous components in the waste are spread via air and water from gas emission and leachate leakage. The flow of landfill is showed for identifying possible environmental impacts of each step.

Before decomposition, at the level of sorting stage, risks come from improperly sorting by mixing materials with different decomposition times. Poorly degradable substances would lead to higher risks of leakage and less energy recovery in the following procedures.

On decomposition, hazardous substances can be formed and leached out into the environment. The biological treatment affects the environment primarily through the treatment process itself and the process gases that are formed during decomposition, as well as possible leakage of nutrients present in water. The water leaches contains a load of heavy metals, dissolved solids, chlorinated organic compounds, and other substances that can harm the groundwater via the releases of leachate. Ground water monitoring is therefore required to check if releases of hazardous pollutants occur.

Landfill gas through the anaerobic degradation biogas consisting mainly of methane (CH₄) and carbon dioxide (CO₂). Landfills give off an estimated 30% of all the methane emissions in Sweden. The emissions of methane from landfills should be reduced by 30% by the year 2000, compared with emissions in 1993 to reduce the greenhouse effect cause by the emissions (Gardner et al., 1993). The main reason for extracting the gas is to prevent it from leaking out into the atmosphere and thus adding to the greenhouse effect. Other pollutants in the gas are particulates, hydrogen chloride, acidifying substances, PAHs (polycyclic aromatic hydrocarbons), dioxins, organochlorines, plus mercury and other metals.

Overall noise, contaminated groundwater and air pollution either by hazardous emissions, dust or traffic emissions by waste transportation will all have possible negative impacts to human health.

4.2 Classification
At the classification stage, different inputs and outputs are assigned to different impact categories. Different impact factors are assigned to different impact categories. Evaluation may start from the factors of process level, and the outcome will then be checked at a level higher than process from an ecological perspective. In this study impacts are classified into four main impact categories, including water contamination impact, air emission impact, ecological impact and human health impact.

4.2.1. Water Contamination

Leachate from landfill is produced from excess precipitation water and contains organic compounds and heavy metals which might cause environmental problems when leakage occurs.

Eutrophication, namely the overfertilization, is the primarily consideration for environmental impact on water section. It is caused by the nutritive salts, mainly nitrogen salts. Organic compounds produced from degradation of organic materials such as volatile fatty acid and alcohols, ketones and aldehydes. Moreover, specific organic compounds which has been added as solvents during landfilling or as additives in the waste source is also the pollutant resources. Sewage treatment plants are also one of the dominant inputs for those growth-stimulating substances.

Heavy metals have an ecotoxicological impacts on both human health sector and ecological system. It would also be discussed in this sector as heavy metals can be emitted in the form of leachate, especially in landfill with incineration waste or industrial waste. During the process of landfilling, heavy metals in the waste are dissolved and transferred to the leachate. The main heavy metals of concern are kalium and cadmium, which cause human health problems by contaminating water and soil and usually is expressed in kg contaminated body weight.

4.2.2 Air Emission

Another significant environmental impacts of landfill sites are emissions to the air such as green house gases, and dust. According to a study done by Baccini et al in 1987, 99% of degraded carbon will appear as CH4 and CO2.

Methane gas emissions produced from degradation of organic material are the main emissions causing the greenhouse effect. Collected methane could be utilised by energy recovery while non-recovered gas will migrate through the soil cover to become a factor for air pollution. Even though in modern landfills most of the gas is collected, the methane emission is still considered the main indicator for air pollution evaluation. The carbon dioxide ratio from the landfill gas depends on different organic materials from waste components. Landfill gases are considered to be global warming potential factors and therefore are suggested as weighing factors for air pollution.

4.2.3 Ecological Impact

The ecological impact may due to the emission of substances that would be enriched in the food chain, such as chlorinated organic compounds and heavy metals that might cause ecological impacts such as changing the biodiversity of birds, species of insects, etc. In the other hand, nutrients can be brought back into the ecological cycling and reduce the ecological impacts if the leachate is used as fertiliser in energy crops.
4.2.4 Human Health

The impact to human health not only means the illness caused directly by the pollutants but also some harmfulness that may influence human by indirect effects. Take odour for example, it may cause health problem by direct disturbance or indirect illness with consequential insect and rodent vectors. Both toxicological aspects such as heavy metals effects and non-toxicological aspects as odour and noise are all included as the disturbing factors for human health. The contribution to human toxicity is usually calculated separately for emissions to air and water.

In general, odour is not noticeable at distance over 500 m (Bilitewski, 1997). Therefore odour problem can be considered as one of the essential factors for landfill siting. Proper operation like organised daily cover in a landfill site could decrease odour and access for birds and rats. Sources of dust and particulate contamination are primarily from the unloading areas and working faces of the landfill site. By wetting landfill road and proper cleaning can decrease the dust to the surrounding areas. Predominant sources of noise are delivery vehicles and landfill equipments. A protective buffer zone would be about 200 m (Bilitewski, 1997) between landfill site and residential area. In the following section of case study, human health impacts would be analysed in terms of proper siting and management.

5. CASE STUDY

5.1 Landfill Description

Two landfill sites in south Sweden are chosen in this case study. The landfill site owned by the Sysav company in Malmö with a modern landfill technology is compared to the landfill site owned by the Nordvästra Skånes Renhållnings company with a bioreactor technology in Filborna. Locations, equipments and the waste statistics of the two cases are described as the basic information for further evaluation and analysis.

5.1.1 Location

The landfill in Filborna serves the six communities of Bjuv, Båstad, Helsingborg, Höganäs, Ästorp and Ängelholm where around 217,000 inhabitants are covered in these areas. The Filborna plant situated nearby the city of Helsingborg is the main operation place for a regional company NSR (Nordvästra Skånes Renhållnings AB) since 1951.

Sysav, the solid waste company owned by the nine municipalities of Burlöv, Kävlinge, Lomma, Lund, Malmö, Staffanstorp, Svedala, Trelleborg and Vellinge where around 500,000 inhabitants live. The main area of treatment is north of Malmö at Sjölunda and the Spillepeng area along the riverside. The biological treatment landfill site covers around 10-15 hectares among the total 55 hectares landfill site at Spillepeng.

5.1.2 Technical Data

In Filborna, the facilities consist of recycling and other different treatment and pre-treatment equipments such as biogas plant, composting and digestion bioreactor
landfill. The bioreactor cell was built and later on has been improved for full-scale operation. It is operated with four to five new bioreactor cells each filled within a period of 2-3 years. The present one is bioreactor cell 600 with the dimension of 60x170x20 m with a capacity of 200,000 m³ (Binder and Bramryd, 2001). The size of the bioreactor cell depends on both the waste amount and the techniques. The site is estimated to operate for more than one hundred year.

The pretreatment includes shredding and premixing different kinds of waste and leachate before digestion. The landfill gas collection system at Filborna was built in 1985. The produced gas is collected both through horizontal plastic drains placed in every second lift 30 - 50 m apart and through vertical drilled gas wells. About 100 drilled wells and several kilometers of horizontal drains are in operation at the Filborna landfill site. Collected gas is then connected to one of the ten regulation stations were control measurements are made regularly to control gas composition, gas flow and gas pressure.

Leachates are collected and connected to five storing basins with a total capacity of 75 000 m³. With the beginning in 1993 a system for local leachate treatment has been built at Filborna.

At Sysav, the facilities mainly consist of the waste to energy incineration plant and other treatments such as composting, madrass composting, slag sorting, and digestion process in a landfill site. Although the landfill built in 1990 has the same technology and the similar quality as a bioreactor landfill as in Filborna, it can merely be classified as the modern landfill due to the lack of optimised condition for gas collection and proper pretreatment. General mixing was done with a compactor but without shredding. Eighty percent of the incoming waste for landfill combines municipal and commercial waste. The landfill site is estimated to have a capacity for around twenty years. Collected gas from the landfill cell is connected and sold to the nearby plant for energy converting. Leachate is directly connected to a sewage treatment plant where the sewage from household in Malmö is treated. The sewage produced by the landfill site is the same amount of the sewage produced by 5,000 people in a year (Bramryd, 2001).

5.1.3 Waste Component

The component of waste collected and sent to the Filborna plant includes a mixture of commercial waste, sorted recycling materials; household as well as industry waste. The waste amount received at Filborna in 1999 was around 400,000 tons, and out of this the anaerobic digestion was around 120,000 tons and counted for around 31% of the total treatment (NSR, 2001).
In Sysav, the main activities are carried out at the waste to energy plant but the company also operates recycling stations and modern landfills with gas recovery. The incineration counts for 45% of the total treatment. Approximately 60,000 out of 450,000 tons of waste received per year goes to biological treatment at the landfill site (Sysav, 2001a). Most of the recycling is done at a recycled building owned together by Sysav and Malmö Community before the waste is sent to the Sysav landfill site. Once the waste have reached the landfill site, only a small amount of 2,000 tons will be recycled and that is an neglectable amount compare to the overall waste quantity.

5.2 Environmental Assessment

The environmental performance is discussed in the following case comparison from both environmental benefits and impacts of different treatment methods. By analysing
the weighing factors of different environmental sectors, an environmental index is shown as a result of the environmental performance in each case. The results would be evaluated not only by the environmental performance but also by the social aspects including the cost, social acceptance and driving policy.

5.2.1 Environmental Benefits

The environmental benefits are mainly from energy recovery and leachate recovery. Related factors will be discussed in the following sections.

5.2.1.1 Energy Recovery

Landfill gas with a high methane concentration can be recovered to energy as electricity or as fuel gas. The energy recovery can be calculated from the heating value for methane. The energy recovery efficiency is illustrated as the total energy recovered from per ton of waste in a period of time.

- Gas Production
  In the bioreactor cell in NSR, the turnover rate of waste decomposition is five to ten years. Methane can be produced during the waste decomposition for around 150-200 m³ by per ton of waste. The methane content is around 65-70% of the landfill gas. In 1999 about 13 million m³ of the landfill gas was collected from the landfill and that counts for 100% of total gas production in NSR in its full-scale operation.

  The modern landfill in Sysav is operating without leachate recirculation and pre-treatment. Due to this, there is less methane among the landfill gas and the methane content is around 55%. The turn over rate will be around 20 years. At Sysav around 5 million m³ of landfill gas is produced and that counts for 5-10% of total energy production in Sysav (Bramryd, 2001).

  In the bioreactors, gas production is reported to be of higher magnitude than in the modern landfills. The production of methane gas is at a rate twice as much as a landfill without leachate recirculation. Therefore, either from a qualitative or a quantitative point of view, the bioreactor landfill has a better performance on gas production.

- Gas Collection Efficiency
  Collected methane could be sent to energy plant and converted into district heating and electricity for recovery while non-collected methane could be a negative impact for environment as greenhouse gas. The previous study (Suflita et al., 1992) shows that the collection efficiency has often been low at around 50%. Both NSR and Sysav claimed they could collect nearly 100% of the produced gas due to its landfill design either from new techniques or from the location advantages of water pressure.

  As mentioned in last paragraph the overall decomposition in the bioreactor landfill will be optimised and there will be a better performance in gas production. Even if the process in the bioreactor would be the same as in the modern landfill, gas collection will still be more efficient to 75-80% of total gas production, and non-collected methane can be oxidised at a higher methane oxidation rate of 50-75% (Sundqvist and Jan-Olov, 1999).

- Energy Recovery
  The collected gas in NSR, corresponded to 61,900 MWh energy, is mainly delivered
to the neighbouring area for heating purpose. Eighty percent of the gas was used at the combined heat and power plant of the energy department in Helsingborg. Nearly 20% is used for heating greenhouses and the rest of the gas is used internal by NSR at landfill gas-fuelled boilers to heat the leachate (NSR, 2001). This is sufficient for heating roughly for 7,000 single-family houses (Bramryd, 2001). 

At Sysav in Malmö, 25,300 MWh energy is retained through landfill gas (Sysav, 2001a). The energy converted from the waste is then used for heating water and incorporated in the district heating network in Malmö and Burlöv. The total energy produced by Sysav is sufficient for heating approximately 60,000 three-room apartments. This means 6,000 three-room apartments are heated from landfill biogas recovery.

In a bioreactor landfill the recovery rate is expected to be higher than in the modern landfill. In average, the methane content of the landfill gas is around 57% in the modern landfill. With the bioreactor technology it could raise as high as 70-80%.

5.2.1.2 Nutrient Recovery

The nutrients can be brought back into the ecological cycling by using leachate as fertilizer. The consumption of leachate will reduce the amount of leachate needed to be treated in the sewage plant and consequently diminish the environmental impacts caused by the hazardous materials in leachate.

In NSR, the leachate is collected with both on-site treatment and leachate recirculation. During the summer the leachate is used as fertilizer for grass and energy forest. Hence, the water and the nutrients in the leachate are consumed by the plants. Meanwhile, leachate recirculation was practiced to maintain optimum moisture content. In Sysav, wastewater is transported through pipelines to the wastewater treatment plants nearby.

Wet approach is applied to the bioreactor landfill in NSR to promote biodegradation in the early stages of the landfill, when the bottom liner has its maximum integrity. Recirculated leachate is used to improve the decomposition process and therefore increase the turnover rate, which gives more gas production and less risk for leakage.

Dry approach has been taken by other landfills in biocell and modern landfill site (Tammemagi, 1999). This is done either by using impermeable cover or pumping out leachate once it is produced. The main idea of dry approaching is to reduce the producing of leachate as much as possible in order to reduce the following environmental impacts caused by leachate.

Both approaches have its pros and cons. Dry approach seems to reduce the impacts from the beginning. However the problem is shifting from landfill site to sewage treatment plant. The dilemma is to promote a better decomposition situation with a higher content of moisture while at the same time reduce the leakages from operation by pumping the leachate out. Leachate recirculation needs higher technology to maintain and is time-consuming during the process. On the other hand, from an ecological perspective it provides an advanced nutrient recovery by reusing the leachate as nutrient sources.

Therefore, to find a better suggestion to the future approach, the characterization of leachate should be studied for proper controls of the landfill functions and for the operation of leachate treatment facilities.
5.2.1.3 Treatment Efficiency

In NSR, pre-treatment of waste mixing and leachate embedment has been done. In Sysav, compact machines have been used for general mixing to meet the density around 0.8 tons/m³ (Bramryd, 2001). Degradation rate is faster in a bioreactor cell landfill due to its optimised parameters controlling digestions, to minimize degradation time, evaluate gas extraction device, investigate processing of residuals and characterize residuals. In the modern landfill the methane stage ends about 50-100 years after the waste has been put into the landfill while in the bioreactor cell it is expected to be 10-20 years.

5.2.2 Environmental Impacts

Environment impacts of landfilling are classified in the former chapter into water contamination, air pollution, human impacts and ecological impacts. In order to understand the interaction between these factors as an overall environmental performance, each category is quantified for further scoring.

The scoring system is based on the previous study (Meijer et al., 1997) of landfill location and the suggested marks of their study exist as a basis in all landfill site. Therefore the scoring system is applied to this case study. It consists of “Magnitude” part and “State” part for the scoring system. “Magnitude” is the impact degree of each proportion as a percentage of the total environmental impact in an overall situation. “State” is the impact significance in specific case according to data of different cases.

Magnitude
The magnitude of each impact is scored as following.

M1: Water contamination 45%
M2: Air pollution 20%
M3: Human health 10%
M4: Ecological impacts 25%
M: Total Impact 100%

State
The state of each impact is represented in a scale of 0 to 1, with 0 as no impacts and 1 as the worst condition. While the magnitude of each impact is an average amount for all landfill sites, the state varies dramatically in each case. In this study, it is assumed that a landfill site is at its worst environmental performance. By introducing a new technology or other environmentally sound factors can reduce the environmental impacts. Those essential factors of four environmental impact categories will be weighed as the state of each impact.

Environmental index
With both magnitude and state of each impact, the scoring system gives a general index of the environmental impacts in each case and that is presented as the equation.

\[ \text{Environmental index (E)} = \text{magnitude} \times \text{state} \]

If an environmentally sound procedure has been taken, it would reduce the worst state and therefore gives a lower index value. In the other words, a higher value for the
index represent a higher impacts from the relative case.

5.2.2.1 Water Contamination

When comparing the two technologies on water contamination, the main difference lies on the treatment of the leachate. One has leachate onsite treatment with recirculation while the other transports it away to sewage treatment plant. Therefore only leachate would be taking into consideration for the comparison of environmental impact. Assumed that the worst condition of water contamination in each case is 1, environmental impacts which could be reduced by leachate recirculation is calculated according to the percentage of leachate being recirculated. In this case, Sysav has no leachate recovery while NSR is with approximately 10% recirculation. (Bramryd, 2001)

\[ E_{\text{water}} = 45\% \times (1 - \text{the percentage of the leachate that has been recirculated}) \]

5.2.2.2 Gas Emission

Landfill gas, CH₄ and CO₂, produced during the landfill process would have a negative impact on the environmental without properly collection. Although the bioreactors in theory should have a relatively higher collecting efficiency compared to other landfill sites, input data for both companies were put as 100% collection as they stated. Dust is not taken into consideration in this case for they have approximately the same effect on both. With some controversy, landfill reactors might be seen as a carbon-accumulating process in human society (Bramryd, 1997). Therefore the ability of balancing CO₂ emission would also be considered as an evaluating factor. The ability of balancing CO₂ emission would be put as 50% for the modern landfill in Sysav and as 30% relatively for the bioreactor in NSR.

\[ E_{\text{air}} = 20\% \times \text{collection efficiency} \times (1 - \text{global CO₂ balance}) \]

5.2.2.3 Human Health

The potential risk to human health could be from either contaminated water or polluted air or other hazardous emissions. These essential factors have been brought up as two separated indicators, thus only odour and noise caused by different treatment technologies will be the input for human health. However, the two case studies are with similar landfill cell construction, hence odour would be the main weighing factor. Odour could be affected by landfill site location and its treatment such as daily cover. In this case, both sites are around 500 m to 1 km from residential areas without much difference between them. Again the daily covers are necessary for both landfill sites. Therefore it is not a distinguished factor for impact evaluation in this case.

\[ E_{\text{human health}} = 10\% \times \text{Noise} \times \text{Odour} \]

5.2.2.4 Ecological Impacts

The higher amount of methane content in the gas, the higher the value would be and therefore contribute to better energy recovery and reduce the impacts by saving fuel as
energy sources. Methane counts for 75-80% in the bioreactor in NSR with a turnover rate of five to ten years while it counts for around 60% in the landfill site in Sysav with a 20-year turnover rate. A higher turnover rate in the landfill site does not only present higher efficiency of gas production but also a more rapidly process. As a result of that, the risk of leakage would be reduced if the processing time were faster. On the other hand, Sysav has an advantage of better siting due to its nature protection from seawater pressure. Hence the risk of leakage at Sysav is estimated to be slightly more corresponding to both its turnover rate and siting priority.

\[ E_{eco} = 25\% \times (1 - \text{gas recovery}) \times \text{the risk of leakage} \]

### 5.3 Result

The results of the case studies are presented in a summary table together with the environmental index to show the environmental performance of each case.

\[ E_{sysav} = 45\% \times 1 + 20\% \times 1 \times (1 - 50\%) + 25\% \times (1 - 60\%) \times 1 + 10\% \times \text{the risk of leakage} = 75\% \]

\[ E_{nsr} = 45\% \times (1 - 10\%) + 20\% \times 1 \times (1 - 30\%) + 25\% \times (1 - 75\%) \times 0.75 + 10\% \times \text{the risk of leakage} = 69\% \]

### Table 3. Summary of landfill investigation

<table>
<thead>
<tr>
<th>Company</th>
<th>NSR</th>
<th>SYSAV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Helsingborg</td>
<td>Malmö</td>
</tr>
<tr>
<td><strong>Covered area</strong></td>
<td>6 municipalities</td>
<td>9 municipalities</td>
</tr>
<tr>
<td><strong>Inhabitants</strong></td>
<td>217,000</td>
<td>520,000</td>
</tr>
<tr>
<td><strong>Waste amount</strong></td>
<td>400,000 tons/year</td>
<td>450,000 tons/year</td>
</tr>
<tr>
<td><strong>Waste capita</strong></td>
<td>1.1 kg per person-year</td>
<td>1.5 kg per person-year</td>
</tr>
<tr>
<td><strong>Waste to biological landfill</strong></td>
<td>120,000 tons</td>
<td>60,000 tons</td>
</tr>
<tr>
<td><strong>Biotreatment percentage</strong></td>
<td>31%</td>
<td>13%</td>
</tr>
<tr>
<td><strong>Landfill type</strong></td>
<td>Biocell reactor</td>
<td>Modern landfill</td>
</tr>
<tr>
<td><strong>Methane production</strong></td>
<td>150-200 m³ / tons of waste</td>
<td>100 m³ / tons of waste</td>
</tr>
<tr>
<td><strong>Methane collected</strong></td>
<td>13 million m³</td>
<td>5 million m³</td>
</tr>
<tr>
<td><strong>Energy produced</strong></td>
<td>61,900 MWh energy</td>
<td>25,300 MWh energy</td>
</tr>
<tr>
<td><strong>Leachate recirculation percentage</strong></td>
<td>10%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Biogas vs. total energy</strong></td>
<td>100%</td>
<td>5-10%</td>
</tr>
<tr>
<td><strong>Turnover rate</strong></td>
<td>5-10 years</td>
<td>20 years</td>
</tr>
<tr>
<td><strong>On-site sewage treatment</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Nutrient recovery</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Tax</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### 6. DISCUSSION

#### 6.1 Experience from the Case Study

Based on the results of performance evaluation for each landfill site, the following discussions are brought up for a sustainable waste management on landfill technologies. Recommendations are given in the end for future environmental strategies.
6.1.1 Technical Discussion

The environmental index shows the environmental impacts caused by each landfill site. By giving a weighing evaluation, the result is more easily interpreted. In a way, the higher value from Sysav means that more risks are caused and this weigh against NSR with their different landfill technologies. In this case it will rather be interpreted as the lower the index shows, the more impacts it could reduce by introducing the new technology.

Even though four sectors of impacts are comprised for an integrated evaluation system, there might still be some lacking factors. If we take 100% of the index as the worst situation, the outcome of the study would merely show the relative impact reduction by improved technologies.

Bioreactor landfill is considered to be an advanced technology on landfill with less environmental impacts due to its optimised function. Not surprisingly the outcomes back up the hypothesis that bioreactor landfill is with superior environmental performance. However the highlight of the study is not only focusing on how much can be improved by technology but rather on how to improve the current situation under the limitations of the present technology. In other words, beside the advantages brought by technologies, what makes the performance better in a condition for the existing management system is discussed.

In general the evaluation is in favour of the bioreactor landfill due to the advantages of the technique. However the input data from different cases also affects the variations among them. Take the two cases for instance; Sysav may be restricted to its technological limitations to match up with NSR, but the variations between two cases are not as much distinguished as expected. In theory, superior technologies should leap ahead of the old ones, especially when they are compared in different countries with different developing level. However in this case study of Sweden, different technologies do not give a significant variation due to its high level of technical standards. Therefore the differences between different cases are not enormous and the overall environmental performance could level up to the ones with superior techniques by improving other factors such as location, waste component, and landfill cell constructions, etc.

In the case of Sysav, they rise up the overall performance by having a well-organised system and an outstanding team when it comes to landfill construction (Bramryd, 2001). Considering the point of post-closure management, Sysav successfully turned the old landfill site into a recreation area with a jogging track, a shooting range, and also well known for its rich bird life with bird hospital there (Sysav, 2001b). In comparison, NSR in the Filborna site has not been started the management of the close down landfills. The weak points of Sysav mainly exist on its lack of optimising condition. Which means without leachate recirculation and pre-treatment of shredding and mixing waste to make the technique they have to its maximum function. To say is one thing, when it comes to practise, there are other factors than merely technologies. Social factors sometimes affect the company policy more than environmental concerns. Policy is an important driving force which is discussed in the next section. Other issue with great attention would be the economical issue.
6.1.2 Social Discussion

When it comes to social aspects, it is important to take political and economical factors into consideration. Tax is representative for both factors of the policy and economic issue, consequently it has been brought up as a method for future management.

6.1.2.1 Economic Consideration

Besides the concern of environmental sustainability, the effect also depends on the economically interesting options in the waste management system and their limitations. Each technique has its pros and cons. There are always controversies on the conclusion of different studies. Even if the techniques are considered to be superior at its environmental performance, the possible relatively higher cost of operation may stop the company changing from its present state. Therefore social factors sometimes weigh up more for the final decision. Take the case of Sysav for example, although they have the ability to increase the landfill performance to a similar level as the bioreactor, the main focus is still on incineration due to its cost. At present, the incineration technology will not be cost effective for a limited amount of waste being treated. Therefore they go for quantity for economic factor instead of environmental ones.

Although some suggestion (Ness and Bramryd, 2001) showed that with the bioreactor as landfill technology can save the cost by reducing leachate. At this moment most of the companies believe that the new technologies are with higher cost if long-term payback sustainability is not taken into calculation. In addition to economics, social acceptability is the other factor to be discussed. In Malmö, permission for incineration system had been argued considering the higher environmental impacts from incineration. However Malmö still has a higher social acceptability for incineration system that they have had for years compare to other regions that have not had an incineration plant before. In other regions it would be more difficult to build a new incineration plant due to the environmental awareness.

Hence to have driving forces for system changing, it is important to start with policy enforcement by the way of tax regulation.

6.1.2.2 Policy Consideration

Sweden is one of the first countries in the world to recognise the growing number of environmental problems and to include these on the political agenda. Stricter requirements on environmental protection should be imposed than is the case today with the aim of improving the standard of the landfills. The Swedish Environmental Protection Agency has issued a general recommendation on landfilling of waste based on Swedish practise and policy as well as the EU’s proposed landfilling directive. Due to policy steering mechanisms, a number of changes in legislation concerning rules on landfill classes, the reception of waste and maintenance has been made in Sweden (United Nations, 1995) in order to prevent landfills from having a harmful environmental impact by means of a variety of protective measures.

The section of the Waste Collection and Disposal Ordinance prohibiting biodegradable waste as landfill will come into force in 2005. Merely under certain circumstances will special permission authorise to landfill site for the extension
(Swedish Parliament, 1997). The Swedish Environmental Protection Agency suggests in its Action Plan for Waste Management that the amount of waste that ends up in landfills can be reduced by at least half by adopting regulations on treatment of different kinds of waste including more stringent environmental requirements for landfills. From January 2000, tax on waste deposited in landfills has been added to reduce landfill. Tax would only be excluded for landfills that fulfil the material recovery as construction by biological treatment, such as bioreactor landfills.

Meanwhile, government is promoting the development of new waste technologies, based on sustainable strategies that waste management and disposal should be done in a way that negative effects on the nature are avoided. This in turn requires greater knowledge of the characteristics of the waste and the establishment of criteria for determining what characteristics waste to different disposal forms should have. Biological treatment, one of the strategies aims to stimulate better resource utilization and to close the waste flow by imitates the nature, is expected to be doubled by 2005. By the time all waste landfills should meet stringent environmental requirements and a higher standard. Further information on political decisions in the coming ten years is listed in appendix 2.

6.2 Scenarios and Recommendation for Future Improvement

There is no definite solution to waste management problems, however. The design of future waste management should not be tied to a single technological solution. Suitable methods for disposing of the waste based on its characteristics must be developed. Therefore different cases are studied to bring possible criteria for waste management improvement both in Sweden and other countries.

6.2.1 Sweden

From year 2000, tax on landfilling has been added as 250 SEK per ton. Other restrictions on landfilling also direct the waste flow to possible alternatives from landfilling. Future development will favour biological treatment as alternative. Some studies (Tärnström, 1996) showed that incineration and landfilling have the same level of energy recovery while incineration will be less sustainable in terms of environmental perspective. For this reason, to direct the waste flow from landfilling to biological treatment rather than merely to incineration, introducing incineration tax is suggested. Incineration tax is added to the slag left by incineration process, which amounts for around 20% of the waste input. Under this condition, incineration cost will increase and both treatments would be examined for decision-making process. It is an alternative to have an integrated treatment by cooperating an improved landfill control system with the incineration and other treatments.

As for the landfill technique itself, although bioreactor landfill apparently creates fewer burdens to the environment, we cannot draw a conclusion saying technical shifting is the essence of sustainable waste management. There is still controversy at the present stage on which is the right way to do it. Bioreactor technology is considered better for its environmental performance but further investigation has to be made. NSR is a pilot plant out of only 3 bioreactor plants in operation in Sweden. Meanwhile, in Malmö, permission for the incineration was given in the end through great arguments. Therefore Sysav choose to be in a safe side since incineration still covers most percentage of treatment in Sweden. However a higher environmental
concern would definitely lower the acceptability. With an increasingly environmental concern, alternatives are in need.

Changes in waste quantity and quality are essential. This includes developing criteria for the types of waste to be received at landfills and incineration plants, among others. Firstly, the ban on biodegradable material into landfilling is one of the major changes at present. Secondly, leachate recirculation can in a way eliminate the need for treatment of leachate before disposal. Although at present the mechanisms still need further investigation for a better control of the process, this is the direction we are heading for. Thirdly, bioreactor landfills have a fast rate of landfill gas production due to the rapid decomposition rate and that allows the waste to be treated in a matter of years instead of presenting as a potential environmental hazard for many decades. Moreover, another important research field will be increasing the energy recovery from bioreactor landfills.

In general, the guiding principle in Sweden lies on more stringent standards applied to new plants while old plants to be brought into line step by step to meet new standards.

6.2.2 Other Countries

When the techniques are the gap, it is easier to start with installing new technology for overall improvement. However it could be limited by lacking of finance, well educated operators and also limited by different region, policy and life styles when it comes to global.

In developing countries there might not be enough knowledge and money to built up modern bioreactor landfill. An option is to integrate new techniques into the original system in operation by handling certain percentage of waste in bioreactor landfill and still keep incineration as the main function as in Sysav.

In Taiwan, landfills are considered to be an unsustainable solution due to its land-scarcity that results in the siting difficulties and therefore raise the potential risks for both environment and human health. Current waste disposal methods have to be improved through the use of new technologies. Different case studies in Sweden may offer new vision for Taiwan for a more sustainable waste management by new landfill technology as an alternative to replace the traditional landfills. Furthermore, biological treatment could be integrated with incineration, which is the major waste treatment in Taiwan. The introduction of bioreactor landfills is possible to improve the efficiency of treatment and also extend the life spans of existing landfills in many countries.

7. CONCLUSION

Pretreatment prior to disposal by 2005 in order to reduce waste volume and enhance its recovery is required separate collection and recovery of organic wastes. As a result, alternatives to meet the restriction on the Landfill Directive are required among EU countries. In Sweden, the strategy is to get the technique accepted as a biological treatment method for non-recyclable materials, with a minimum of environmental impact and maximum energy efficiency.

In this study, the environmental impacts of two landfilling technologies have been evaluated to show how much impacts could be reduced by introducing a new
technology. Different sectors of impacts have been showed, besides an approximately equal impact to human health, other sectors could be reduced for a certain degree by bioreactor landfill such as decreasing the volume of leachate to be treated and prolong the lifespan in landfill site avoiding the possible leakage. From this study we also found that both can reach a rather good gas production for energy recovery at present but from a long-term environmental point of view, it might be better toward a more environmentally sound technique.

With this outcome, conclusions are addressed:

- In terms of technical development, a rapid treatment period to stabilise landfill material and a better environmental performance could be reached with new technology in landfill operation.
- Economic assessment would be in the priority list when it comes to implement bioreactor landfill in the social system. Tax-free policy and subsidies are considered to be a powerful motivation at present.
- Modifying the existing landfills to be more efficient and environmentally sound either by technical upgrading or management improvement is an option, especially for developing countries.

8. REFERENCE


9. APPENDIX

**Appendix 1: Waste definition for the purposes of COUNCIL DIRECTIVE 1999/31/EC of 26 April 1999 on the landfill of waste** (European Union Law, 1999)


2. "Treatment" means the physical, thermal, chemical or biological processes, including sorting, that change the characteristics of the waste in order to reduce its volume or hazardous nature, facilitate its handling or enhance recovery

3. "Biodegradable waste" means any waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste, and paper and paperboard.

4. "Landfill" means a waste disposal site for the deposit of the waste onto or into land (i.e. underground), including:
   - Internal waste disposal sites (i.e. landfill where a producer of waste is carrying out its own waste disposal at the place of production)
   - A permanent site (i.e. more than one year) which is used for temporary storage of waste but excluding:
     - Facilities where waste is unloaded in order to permit its preparation for further transport for recovery, treatment or disposal elsewhere
     - Storage of waste prior to recovery or treatment for a period less than three years as a general rule, or storage of waste prior to disposal for a period less than one year.

5. "Leachate" means any liquid percolating through the deposited waste and emitted from or contained within a landfill.

6. "Landfill gas" means all the gases generated from the landfilled waste.
Appendix 2: Summary table of political decisions of waste management for the coming 10 years.

<table>
<thead>
<tr>
<th>Year</th>
<th>EU</th>
<th>Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>EC directive on landfills adopted</td>
<td>Environmental Code comes into force</td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td>Landfill tax introduced. Industrial waste deregulated</td>
</tr>
</tbody>
</table>
| 2001 | ✷ EC directive on waste incineration adopted (preliminary).  
| 2002 | ✷ Requirement to sort combustible waste. Ban on the deposition of separated combustible waste as landfill.  
✦ Section 26 of the Waste Collection and Disposal Ordinance, concerning combustible waste.  
✦ Section 27, the prohibition on separated combustible waste in landfills come into force. | |
| 2004 | | Planned review of waste tax. |
| 2005 | | Ban on organic waste in landfill. Total amount of landfill at least halved from 1994 level. |
| 2008 | | All landfill sites to have attained a uniform standard according to the EC landfill directive. |

Source: RVF 2001