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Fundamentals of municipal solid waste management (MSWM)

A condensed version of the UNIDO Training Manuals on MSWM, prepared for the project "Cleaner Municipal Solid Waste Management in China"

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Federal Department of Economic Affairs FDEA
State Secretariat for Economic Affairs SECO

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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna, 2007

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Foreword

From 1998 to 2005 the United Nations Industrial Development Organization (UNIDO), supported by the State Secretariat for Economic Affairs (SECO), from Switzerland, assisted the People's Republic of China in improving the country's municipal solid waste management (MSWM) activities. One of the outputs of the assistance provided was the preparation and publication of a Training Manual on MSWM.

The present document is a condensed version of the MSWM Training Manual, published by UNIDO and aiming at contributing to improve solid waste management systems in other developing countries and countries with economies-in-transition around the world.

In the year 2000, the United Nations General Assembly adopted the Millennium Declaration that addressed the urgent needs to respect and protect nature; moreover, the Member States asserted that "the current unsustainable patterns of production and consumption must be changed in the interest of our future welfare and that of our descendants." They agreed that no effort should be spared to free all of humanity, particularly future generations, from the threat of living on a planet irredeemably spoiled by human activities, and whose resources would no longer be sufficient for their needs.

These commitments, codified into "Millennium Development Goal 7 (MDG 7)" which calls on the international community to ensure environmental sustainability, were reiterated in the Plan of Implementation of the World Summit on Sustainable Development in 2002, which stated that fundamental changes in the way societies produce and consume were indispensable for achieving global sustainable development. The countries should promote sustainable consumption and production patterns with programmes addressing the de-linking of economic growth and environmental degradation through improved efficiency and sustainability in the use of resources and production processes, and reduction in resource degradation, reduction in quantity and toxicity of waste/pollution and introduction of environmentally friendly approaches for waste treatment and disposal. This document aims at contributing to creating the necessary capacities in the target countries to facilitate the achievement of the MDGs.

Dmitri Piskounov
Managing Director
Programme Development and Technical Cooperation Division
UNIDO

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Abbreviations

AD	Anaerobic digestion
APC	Activated particles of carbon
ASCP	Association of Swiss Compost Plants
BOD	Biological oxygen demand
BPF	British Plastics Federation
COD	Chemical oxygen demand
E	Evaporation
GE	Gas emission
Gj	Giga joule
HDPE	High density Polyethylene
Kg/kg	Kilogramm
Kj	Kilo joule
kWh	Kilowatt/hour
L	Leachate
LDPE	Low density Polyethylene
LOI	Loss on ignition
MBT	Mechanical/biological treatment
MSW	Municipal solid waste
MSWI plant	Municipal solid waste incineration plant
MSWM	Municipal solid waste management
NF	Nano filtration
P	Precipitation
PE	Polyethylene
PET	Polyethylene Terephtalate
PP	Polypropylene
ppm	Parts per million
PVC	Polyvinyl Chloride
RMSW	Residual municipal solid waste
SBR	Sequence batch reactor
SCR	Selective catalytic reduction
seco	State Secretariat for Economic Affairs (Switzerland)
SNCR	Selective nitrogen catalytic reduction
TCDD	Tetrachlorodibenzodioxin [Dioxin]
TCDF	Tetrachlorodibenzofuran [Furan]
UASB	Up-flow activated sludge blanket
UK	United Kingdom
UNIDO	United Nations Industrial Development Organization
USA	United States of America
UV	Ultra violet
WC	Water from waste
WG	Water gauge
WRAP	Waste Resources Action Programme

Introduction

The present condensed version of the UNIDO Manuals on Municipal Solid Waste Management that was prepared for the project "Cleaner Municipal Solid Waste Management in China" concentrates on the four most important aspects of MSWM: Recycling, composting, land filling and incineration.

As it becomes more difficult to find suitable sites for landfills, a reduction of the quantity of waste to be fed into the landfills becomes imperative. The segregated collection of valuable materials for subsequent **recovery and recycling** could contribute to reduce the amount of waste disposed in the landfills as well as to generate income through commercialization of some recovered/recycled waste fractions.

The building up of a successful system of segregated collection and recycling of waste requires active communication to motivate the citizens. It also requires specific knowledge on the collected materials, their costs, on the characteristics and requirements of the recycling processes, and on logistics to organize the segregated collection of waste.

In the search for alternative waste treatments processes, **composting** is a favourable solution and is, at the same time, a sustainable way of resources utilization. As well, compost could generate income, if properly produced and marketed.

Composting and digestion for waste, however, are complex biological processes and it is important to have good quality input materials – a separate collection of "green waste fraction" is essential - to guarantee the production of good quality compost that will not pollute the soil and water sources. The existing compost production processes are many and varied. It is important to choose a composting process, which is adequate to the amounts of waste to be processed; the chosen process should be the most suitable for the climatic conditions in the location of the composting site and the infrastructure available.

In rural areas, **land filling** will be, still for a long time, the preferred method of MSW treatment and disposal. If not properly designed, however, landfills may be a source of secondary pollution and in the long run become polluted sites. Therefore, it is very important that landfills in poorer areas be well designed and constructed. They must be efficiently and effectively managed for safety and security reasons and for the prevention of epidemics and the presence of rodents and other pests.

Incineration is an adequate treatment method for MSW, also for large cities. However, incineration is a demanding and complex technology. On this topic, as well as on the three previously introduced, the training manual elaborated in detail not only on available technologies, but also on design characteristics, risks, etc., to ensure proper training of the staff involved.

This document offers the basic principles of MSWM, extracted from the above-mentioned Manuals.

1 Introduction to recycling and re-utilization of waste

A condensed version of the Chapter on
‘Utilization of Waste Fractions and Waste Recycling’
from the UNIDO Training Manuals on MSWM
prepared for the project
“Cleaner Municipal Solid Waste Management in China”

1.1 Introduction

Recycling of municipal solid waste material represents the highest level of waste management culture that contributes to reduce land filling and hazardous material flows into the environment, to preserve the landscape and to save financial resources in the long run. Recycling is saving growing amounts of primary materials used in the economy, which further aids the conservation of resources. As labour intensity in preparing recyclable secondary raw materials is generally greater than that for producing primary materials, recycling also creates five to seven times the number of jobs needed for incineration and about ten times more jobs than those needed for land-filling activities[1].

The market-driven recycling model deals mostly with high-grade waste/secondary materials, supplying half of the raw material to steel, non-ferrous metals, paper, and glass industries. Recycling activities for materials like metals, and to a lesser extent, paper, compete at global levels, and are subject to international conventions, regulations, and market fluctuations.

1.2 Packaging waste

One dominating source of municipal solid waste (MSW) in highly industrialized countries is packaging waste. A second source is paper from newspapers, journals, other publications and waste paper from offices. Other sources are organic waste, bulky waste like furniture, electronic equipment, and old cars.

Waste laws in most developed countries require that manufacturers be responsible for recycling a certain amount (according to volume) of the material used in containers and packaging. If necessary, the recycling services are subcontracted to specialized companies wherein related costs are passed on to consumers. The objectives are to minimize waste and to return recyclable packaging materials to the production cycle.

1.2.1 Incentives

Utilization of minimum packaging or easy-to-recycle product components is a good marketing factor, as modern consumers consider such aspects when making product choices.

Special awards and/or recognition for reusable products might also be an incentive for manufacturers/businesses.

A recent implementation plan is the ‘Dual system’, by which retailers of certain packed goods are required to take back the packaging material for subsequent recycling.

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[1] European Commission Draft Final Report of Recycling Forum, 1999-2000.

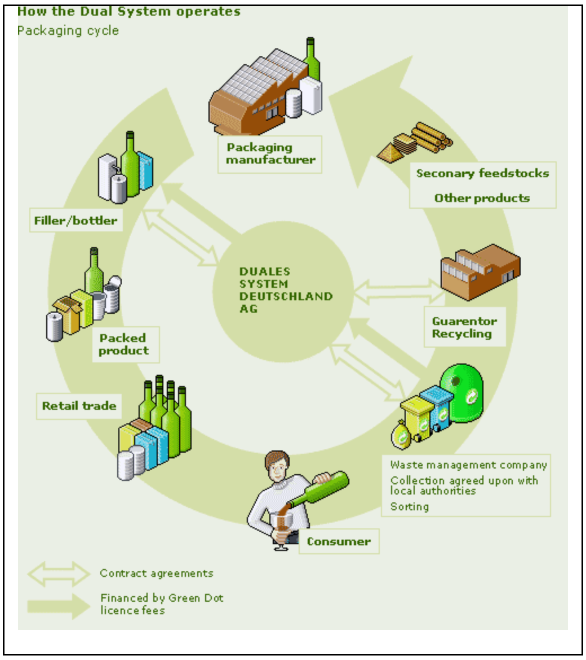

Figure 1: Dual System. Source: www.gruener-punkt.de

1.2.2 The "Green Dot"

In an increasing number of European countries, the Green Dot trademark indicates that the packaging company is participating in a privately organized recycling system with a corresponding financial contribution. As a result, per capita consumption of sales packaging in Germany decreased from 95 to 82 kg between 1991 and 1998, implying that the average family used about one kilogram less packaging in 1998 than in 1991. Sorting and recycling costs remained constant since 1994 and dropped by 9.5% in January 1999.

1.3 Organic waste

Organic waste is the largest fraction of waste that can be recycled. In industrialized countries, this fraction may be as low as 15-20%; while in developing countries it may be 50-60% of the MSW quantity. Organic waste is typically re-used for composting and/or fermentation processes.

1.4 Paper

In industrialized countries, the fraction of paper and cardboard in the MSW may be as high as 30%. All kinds of paper can be produced from waste: recycling paper (grey), packaging paper (brown), newspaper paper, and copy paper (white). The World Watch-Institute attests that the production and use of paper has one of the greatest environmental impacts as almost one-fifth of felled trees are used for the paper industry. For the production of one ton of paper, 2 - 3.5 tons of wood is required. According to the Watch Institute, it is feasible to reduce by half the wood demand for paper production through paper recycling methods.

Only clean waste paper, free from dirt or foreign matter can be recycled. The length of fibre material is an important aspect to guarantee good-quality paper. Therefore, waste paper should not be shredded, as fibres will be shortened. Often a lower quality waste paper can still be used to produce cardboard. Today, a substantial amount of waste paper is being used to produce high quality paper.

1.4.1 Recycling methodology

Paper is bound and placed on the roadside or pick-up point on collection days. This method prevents the inclusion of other waste in the paper collection. (Switzerland, Germany)
Paper is collected in containers.
All sorts of paper and cardboard are collected in one collection container.
Paper and cardboard are collected separately.
Only newspapers and journals are collected.
Office paper is collected separately in containers.
All paper, glass, plastic, and metals are collected as one recyclable fraction.

Any mixed waste paper or paper waste containing impurities is first sorted before further process. Very little equipment is necessary as the largest proportion of the sorting process is done manually. Sorting plants consist of a feeding system with conveyor belts, a sorting and a packaging station and a bale press.

1.4.2 Production process

To obtain high quality paper as final recycling process product, the steps to be followed could represent a set of sophisticated unitary operations. A sample process as used in larger Swiss newspaper recycling plants is described below:

Stage		Process
1	Pulper	Paper is dissolved in water and disintegrated into fibres. Large foreign particles are not disintegrated. Foreign particles are filtered out and are thus separated from the fibres.
2	Centrifugal Separator	Impurities, which are heavier than the fibres are separated (e.g. staples)
3	Strainer	In the three-step strainer separation, pulp (4%) is pumped through strainer baskets with an opening of 1.4 mm. Impurities with a larger surface area such as plastic or aluminium films or tapes are filtered out.
4	Perforation	At low pulp concentrations, air is injected into the pulp and fine air bubbles separate the ink from fibres. The bubbles carry the ink to the surface in a foam-like consistency, where it is collected. The foam is further concentrated and any fibres left in the foam are recovered.

Stage		Process
5	Fine slit sorting	The suspension is passed through a fine slit strainer with a width of 0.15 mm. Cubic impurities like polystyrene and glue particles are separated.
6	Disk filtration	To increase the concentration of the pulp to 10% again, the pulp is pre-dehydrated by filtering off water by disc filters.
7	Continuous filter press	The pulp is further dehydrated to 43% by filtering the mixture through a continuous filter press.
8	Disperser	The fibre is heated using an injection of steam at 85-95°C and then pressed through rotating wheels. The aim is to homogenize the pulp, disintegrate the small impurities and separate ink particles from the fibres.
9	Bleaching	With a concentration of 35-40%, the pulp is bleached for 60 minutes, using hydrogen peroxide. After bleaching, the pulp is again diluted to 4% concentration.
10	Secondary flotation	The secondary flotation works in the same way as the primary flotation aiming at separating the impurities.
11	Disk filtration	With a group of disk filters, the pulp is brought to its final concentration of 12%.
12	Storage tank	The pulp is kept in stock in an elevated storage tank, where it is diluted with the surplus water from paper the production process.
13	Rejecter	All separated impurities are collected. With a press, these materials are dewatered, reduced in volume, fed into a container, and transported to a MSW incineration plant.
14	Sludge thickening	The sludge from the fine separation and the flotation steps is thickened in a two-stage process. The first is a special settling process and the second is achieved using a screw conveyor press. The dewatered sludge reaches a concentration of 60%. This sludge is again dewatered in the incineration plant, and used for energy recovery. The filtrate is led to the mechanical biological wastewater and sewage treatment plant of the paper factory.

1.4.3 Environmental Impact

Chlorine may form organic compounds that are hazardous to health. Thus, chlorinated chemicals are substituted with hydrogen peroxide during the paper production process. The wastewater must be treated in a mechanical/biological water treatment plant. Several wastewater treatment technologies have been developed for the paper industry and these should be utilized optimally. For example, the separated impurities and sludge is collected and dehydrated. The dehydrated material can then be incinerated in plants that run on flue gas treatment.

1.5 Glass

Glass is an environmentally friendly material, but high quantities of energy are required for its production and transportation. The main sources of waste glass are beverage containers (beer, wine, soft drinks, and milk), food containers (for preserved foods), household glass, window panes (flat glass), and custom-made glass (car and railway-train windows).

1.5.1 Acceptable waste quality

Glass is produced in melting ovens at very high temperatures (140°C). At these high temperatures, considerable concentrations of NO_x are formed and emitted with the flue gas. Modern glass factories apply NO_x reduction systems to reduce these emissions.

Waste glass quality differs according to origin. That is: Beverage containers are made from industrial standard glass in the colours of green, white or brown; food containers made from mostly white industrial glass; household glass is made from white or crystal glass (high lead content); window planes (flat glass) are made from industrial standard glass; special glass (car and railway-train windows); cooking glass is made from high-temperature-resistant boron-containing glass; and TV screens contain barium and lead.

Until recently, waste glass was only used for making bottles. The majority of bottles made are green bottles as any colour of waste glass may be used for its manufacture. Brown bottles can only be manufactured using brown or white used bottles, whereas white bottles can only be manufactured using white waste bottles.

1.5.2 Contamination

The majority of waste glass collected is from bottles. However following materials may contaminate the waste: Caps (steel, aluminium, plastic); closing mechanisms (steel, porcelain); and labels (paper, plastic, glue). The collection containers themselves may contain some impurities. The most serious impurity that must be completely removed before the melting process is ceramic material. Ceramic material has a higher melting point than glass and is not dissolved in water. Melted ceramic lumps may cause complications during the further glass manufacturing process.

1.5.3 Collection

Standard unbroken bottles

The best system applied in Europe for recycling bottles is the return of the standardized unbroken bottles to the retailers. These standardized bottles may be used by different producers/suppliers. If a deposit is paid at the time of purchase, a high return rate can be expected. The retailer normally returns the standard bottles with the same truck that delivers new supplies from the manufacturer. The bottles are stocked and washed just before refilling. A standard return-bottle can be returned and refilled up to 30 times. Special -bottles can be returned and refilled almost 80 times.

Non-standard bottles

In Europe, non-standard bottles normally do not have any deposit payment – these are collected by private institutions or by the public service from standard crates of 0.8 x 1.0m at collection points. Using a scanner, up to 100 various types of bottles may be automatically differentiated and classified. Bottles are then stored and washed just before they are sold for refilling.

Broken glass bottles or waste glass
In Europe, broken glass bottles or waste glass "contaminated" with paper, metal or plastic are collected in a special container located at each household or taken to collection points directly. These are then collected by private or public collection companies, which then deliver the collected material to the central purification stations where the glass is sorted by colour and passed on for the removal of impurities.

1.5.4 Separation

To obtain good glass quality from waste material, glass waste must be sorted and separated by colour. Specialized machines, equipped with an optic system are capable of detecting and removing incorrect coloured glass fractions from the total waste bulk.

The collected broken glass usually contains 2-5% of impurities. Therefore, the glass discharged at the central collection point is fed onto a conveyor belt for manual separation before being sent to a crusher. Metals are separated using a magnetic separator whilst non-magnetic impurities are separated with an inductive separator. Light parts, like plastic or paper, are blown from the glass with an air stream whereas non-glass and non-combustible particles are removed. The purified material is then sent to the glass factory. Instead of re-manufacturing bottles, glass can also be ground to a size of 3-6mm and used as absolute inert material for backfilling after laying pipes, such as water pipes.

1.6 Plastic

The wide diversity of plastic compounds and plastic usage makes plastic recycling a difficult task. Plastic is normally a product of high purity, but if it is collected from mixed waste, it is normally contaminated with impurities such as food, residues, chemicals, etc. Such impurities must be washed off consuming large quantities of water. Used plastic is increasingly traded in the world market. Developing countries in Asia import most of recycled plastics. China is currently the largest importer of recycled plastics in the world.

1.6.1 Recycling of mixed plastics

The technology of plastic recycling includes more than 140 automated sorting systems, which can classify plastics into categories by resin type and colour. Robust industrial systems are re-claiming post-consumer plastics as new raw materials. Automatic sorting systems help eliminate contaminants, increase output and lower costs by minimizing manual labour and contribute to the production of high quality, yet reasonably priced, raw materials nearing their original quality.

Plastic waste collected has been used in the production of pig iron in Germany since the end of 1993. Heavy fuel oil is being replaced largely by plastic waste for iron ore reduction. In the past, for every ton of pig iron produced, 100 kg of heavy fuel oil were injected into a blast furnace. 30% of the heavy fuel oil can be replaced by plastic agglomerate. The plastic agglomerate is a granule consisting of a mixture of waste PE and PP. This process makes it suitable to utilize large quantities of waste.

Clean fractions of plastics containing PE, PP Poly-olefins and PET are shredded, crushed and then washed in an intensive process. In a separation process using water, the different qualities of plastic are separated and dried. Extruders to make a new granulate for industrial production can process the cleaned fractions.

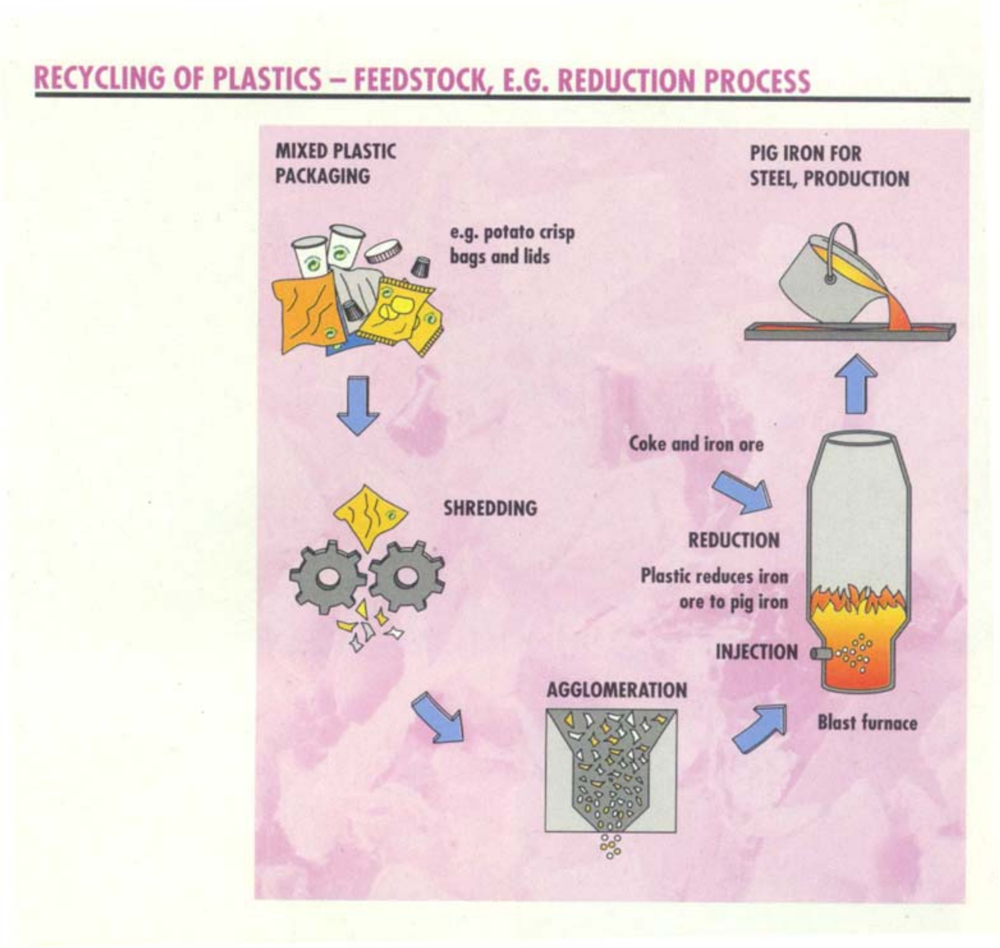

Figure 2: Recycling mixed plastic waste via the iron industry

1.6.2 Recycling of Polyethylene (PE)

Polyethylene is a plastic with little environmental impact since its basic components are carbon and hydrogen. Polyethylene waste can easily be incinerated and the heat produced can be reused. High-density polyethylene (HDPE) is used to make milk jugs and detergent bottles. Most milk jugs are translucent white and do not contain any pigment. Since HDPE retains its natural colour, it is a valuable kind of waste as it can be made into any colour. Low-density polyethylene (LDPE) is less dense and thus more flexible. It can be used to make plastic grocery bags, tubing, agricultural film and plastic lumber. This scrap may be either clear or pigmented.

1.6.3 Polyvinyl Chloride (PVC)

PVC contains chlorine and a variety of other additives. The lack of uniformity in the composition of different PVC products makes PVC less recyclable than other resins. Most post-consumer PVC collected is processed into different, lower-grade items, a process commonly known as "down cycling". Down-cycling process does not contribute to reduce the toxic pollution considerably, since the overall demand for virgin resin is maintained. In addition, most PVC products can be "down cycled" only two or three times before the quality has degenerated too much to make further recycling worthwhile.

The presence of PVC in high-temperature metal recycling processes (e.g. steel reclamation from cars) can also lead to dioxin emissions.

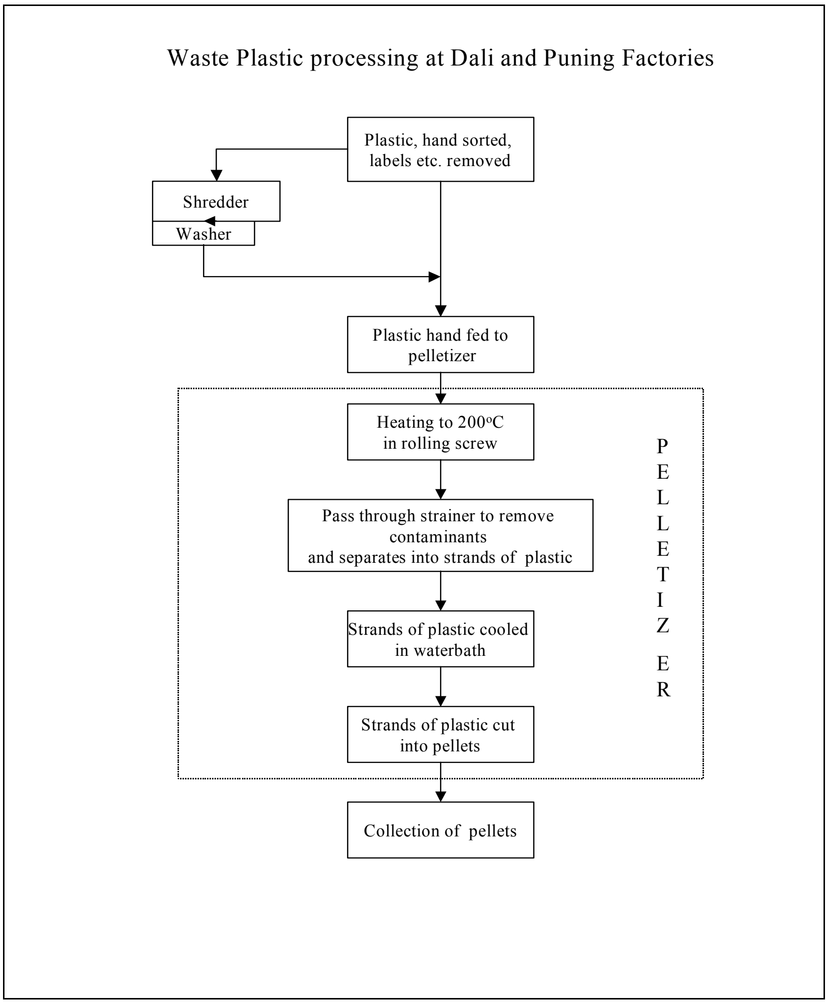

Figure 3: Recycling Process of PE, Applied in China[2]

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[2] Source: UNIDO Publication

1.6.3.1 Recycling methodology of PVC

PVC from floors may be recycled; PVC from windows is difficult to recycle because of the metal frames inside the structure; and PVC from food packaging cannot be easily recycled. It is worth noting that the concept of recycling materials refers to returning the materials for the manufacture of the original products. The greatest potential for the re-use of PVC, is to be found in the construction industry; however, 64% of all PVC products in this industry already have a service life of more than 15 years. A prerequisite for efficient recycling is the identification of large PVC components (such as window frames) before they enter the solid waste stream.

In-house reprocessing

Where in-house re-utilization is not possible, the scrap/cut-offs and other PVC waste materials are sold commercially for further treatment and resale. This so-called fabricator waste and up to 95% of in-house scrap is re-used in this manner. Research carried out by the British Plastics Federation (BPF)-Windows Group on a range of profiles and percentages of reprocessed materials shows that certain properties of the PVC are actually improved by adding measured amounts of pre-processed material. This idea of using pre-processed material is already being carried out to a large degree by extrusion companies to conserve raw materials and reduce production costs. Generally, the amount of material available for this is less than 7% of the total material used in the process.

PVC bottles

PVC bottles are first separated from other plastic bottles, and ground into small pieces. Then they are washed and treated to remove any remaining impurities before being reduced to a fine powder to be reprocessed by one of the various existing forming techniques.

PVC floor covers

Old PVC floor covers are crushed to chips with a maximum size of 30 mm. After passing through a magnetic separator and passed through a hammer mill, cement and glue particles are stripped off. In a screening machine, these impurities are separated. The material is then cooled down to –40 ºC by using liquid nitrogen for fine crushing. At low temperatures, the PVC gets brittle and can be crushed to 0.4 mm size particles.

1.6.3.2 Marketing

PVC waste is mainly recycled into the following materials: Insulation material for electric cables, drain pipes, plastic window frames, plastic floors/floor tiles, shoe stiffeners, fence posts, outdoor furniture and packaging.

1.6.4 Polyethylene Terephtalate (PET)

Consumers separate PET plastic containers and other recyclable materials. Once the PET container is properly prepared (cap removed, rinsed and flattened), it is placed in the consumer's recycling bin and put out at the kerb for collection. Typically, 40 - 60% of recyclables are returned using this method, and contamination is low. Other collection methods include:

Drop-off sites placed at convenient locations. About 10-15% of available recyclables are usually recovered by this method. However, contamination levels can be as high as 10-30%.
Buy-Back Centres can also be set up to purchase PET containers and other recyclables. This method provides an incentive for consumers to separate and return their recyclables. About 15-20% of available recyclables are recovered.
Return Vending Machines, placed in accessible places, by which consumers receive coupons or tokens in return. This method achieves similar return rates as the buy-back method.
Refill and Deposit: Bottles are sold (retail stage) with refundable deposits that are redeemable on return of the bottle to participating retail sites. Deposits may be charged on both refillable and single-use PET bottles. PET deposit programmes are achieving high return rates (90%) and low levels of contamination.

Now most recycled PET bottles are cleaned, flaked and used directly or blended with virgin polymer, before being processed. Purity is essential as mechanical recycling of PET is particularly sensitive to the presence of PVC. The acceptable level of PVC is less than 0.25%.

Marketing
The percentage penetration of recycled PET in Europe was 8.5% in 2000 but increased to a roaring 25% in 2002. Recycled PET is also used to spin smaller diameter fibres. These can be woven into fleece fabrics. Such fabrics can contain over 95% of recycled content. Major outdoor clothing companies already recognize the benefits of these ‘recycled garments’ and are introducing new ranges. A "recycled" fleece jacket uses 25 PET bottles!

1.6.5 Environmental impact

The utilization of plastic as a fuel in waste-to-energy systems as well as the iron industry must follow the same emission control limits as applied to MSW incineration. If these limits can be adhered to, these recycling methods would be environmentally sustainable.

PET containers are 100% recyclable but this does not imply that readily recyclable material is necessarily environmentally sound. Being extremely light, packaging and transport emissions are reduced drastically and thereby save costs.

1.7 Metals recycling

1.7.1 Mixed metals

Large quantities of recycled metals stem from industrial waste and civil construction waste. This scrap consists mainly of large pieces, such as stoves, ovens, cookers, fences and other house or garden installations and bicycles, small pieces such as beverage containers, tin boxes and small household appliances.

Recycling methodology

Iron and steel are separated from other metals by a magnetic separator.

Heavy metals and aluminium are separated from impurities by an inductive whirl power separator.

Manual picking separates copper, stainless steel, aluminium and all other fractions.

1.7.2 Iron and steel

Steel is the world's most versatile material to recycle as well as a powerful energy and resource saver. More than half of all steel has been recycled at least once. It takes at least 60% less energy to produce steel from scrap than it does from iron ore. Once recycled, steel can metamorphose from one product to another without losing its quality. Steel from cans, for instance, can be used in blades for turbines or high capacity suspension cables.

Recycling methodology

While steel recycling mainly refers to post-consumer scrap, scrap re-circulated from within plants and steel processors is also recovered. Melting down one ton of recycled steel cans uses only 25% of the energy needed to melt enough ingredients to produce an equivalent volume of virgin steel. Once the contents of the food cans (including pet food cans) have been used, they just need to be rinsed (not scrubbed) but there is no need to remove labels.

Waste steel is taken to Materials Recovery Facilities where cans are magnetically separated from the other recyclables. The cans are compressed into bales ready for transport to the steelworks. The tin coating used to protect against corrosion is removed in some cases before the steel is re-used. All the steel cans are then combined with other steel scrap and melted in a furnace to produce new steel.

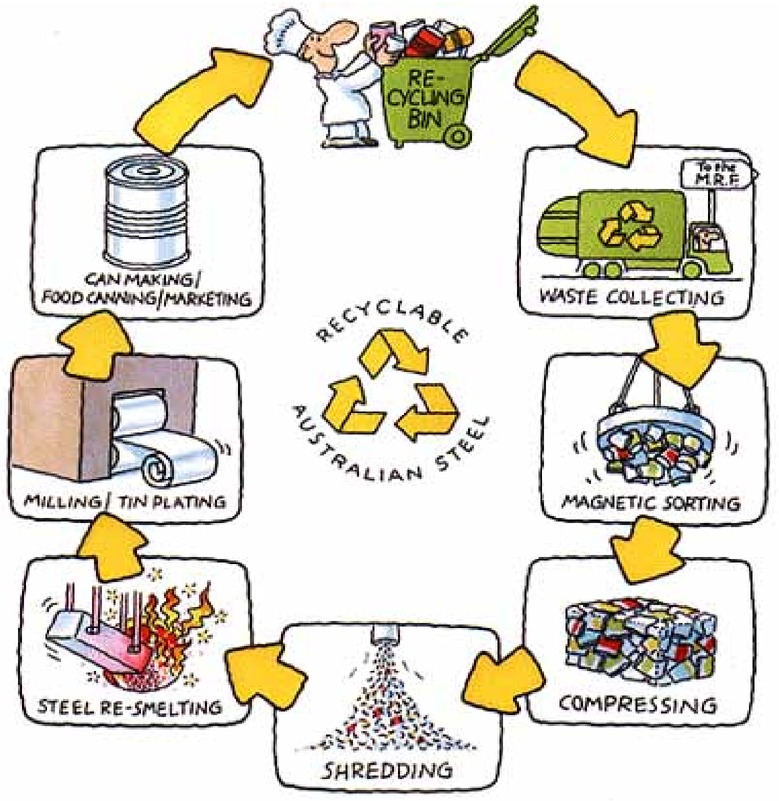


Figure 4: Recycling Steel Cans. Source: Australia Steel Recycling

1.7.3 Aluminium

Aluminium contained in the solid waste comes from different sources such as construction waste, automobiles and household waste, but is 100% recyclable. Recycling one kilogram of aluminium saves about 8kg of bauxite, 4kg of chemical products and 14 kWh of electricity. Thus recycling aluminium saves 95% of the energy needed to produce new metal from raw materials.

Aluminium cans found in MSW are a very important fraction; although they represent less than 1% of solid waste, given their value, efforts should be made to recycle all available aluminium cans. Today's aluminium can requires about 40% less metal than the can made 25 years ago; this implies a reduction in the need for both energy and raw materials per can.

Aluminium recycling applies especially to the automobile industry where more than 80% of parts are recycled in line with growing annual demand for automobiles. A fully recyclable automobile is the goal for the near future. The separate collection rates are at 80 to 90%, which makes this material ecologically attractive. The collected aluminium is pre-treated and re-melted. The recycled product has the same high quality as new aluminium from electrolysis.

Collection

Different means of collection including curb side collection, placing containers of different designs at collection points, individual private collectors and/or aluminium cans with games to motivate collection have been tested and applied throughout the world.

Recycling Processes

Cans from a collection point are crushed and taken to recycling plants.

Used aluminium –which is dirty and covered in coatings – is placed on a conveyor belt, shredded, and passed through large magnets where foreign components are systematically removed.

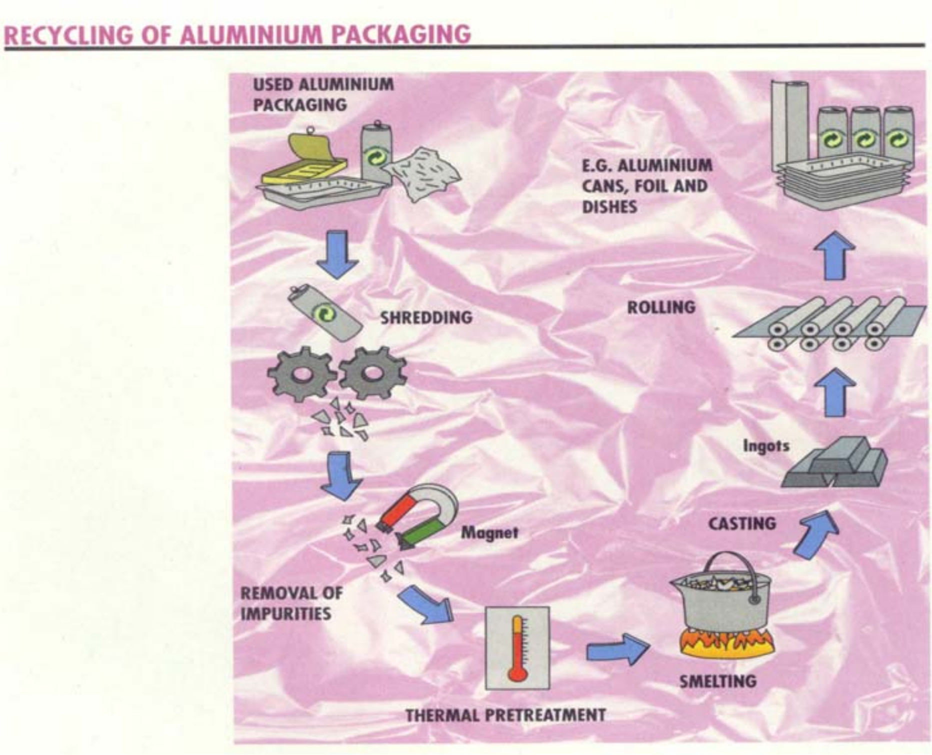
The aluminium is then loaded into an oven and is heated until the paint and coatings melt off. Later powerful fans suck these resins out.

The fragments of aluminium are then placed in a furnace for complete melting and mixed until the right quality for re-utilization is obtained.

Lastly, melted liquid aluminium is poured into large moulds, cooled and resold.

It should be noted that the first and second process are optional, whereas the third and fourth stages can be processed in the furnace.

Figure 5: Aluminium Recycling



Environmental Impact

The salt melt used to cover the melted waste must be replaced for every batch. The used salt should not be dumped. In many cases, it is dissolved and residues containing aluminium can be recovered. The dissolved salt may not be drained into fresh water, as it would cause heavy pollution. There are special evaporation processes available to evaporate the residual water and recover the salt for re-melting.

1.8 Coal ash

In countries where coal is used as a fuel for heating, coal ash is an important solid waste component. The coal ash in the MSW is a problem for different reasons:

MSW may catch fire when mixed with glowing coal ash. This may be a problem in bunkers of incineration plants.
Coal ash is formed as very small particles. Waste screened to separate fine fractions may still contain coal ash.
Compost with a high coal ash content also has a high mineral content, which makes it low quality compost. Heavy metals in coal ash (pressed into compost) will further poison the soil.

Coal ash is utilized in road construction, cement production or directly as a cement component. Sand cement tiles or bricks can also be made of coal ash.

Environmental Impact
Coal ash recycling has no major problems if it is free of heavy metals. If used for brick production or formed into artificial stone, coal ash pollution is less significant than if it were used for road construction.

1.9 Special products

Special attention products such as electric appliances, refrigerators, air-conditioners, fluorescence lamps and batteries contain pollution-producing substances that might cause problems if disposed of in a landfill. Many industrialized countries have already developed strategies to deal with electric and electronic waste and set a model for their feasible replication.

2 Introduction to composting and anaerobic digestion

A condensed version of the chapter on
'Composting and anaerobic digestion'
from the UNIDO Training Manuals on MSWM
prepared for the project
"Cleaner Municipal Solid Waste Management in China"

2.1 Introduction

Composting and anaerobic digestion are recycling methods that transform clean organic waste into valuable and marketable products such as compost and digestate. This chapter addresses the marketing aspects of these products. Similar methods can also be applied to municipal solid waste composting or biological treatment before land filling but these techniques are not discussed, as they do not lead to marketable products. The processes described do not apply to community- or home-composting initiatives, but mainly to facilities treating more than 1000 tons of compost annually. Issues such as process management and control and environmental aspects are discussed briefly as the latter are aspects that are, in most cases, extremely site and process specific.

2.1.1 Aims of composting and anaerobic digestion

The main aim of composting and anaerobic digestion is to generate marketable products from waste materials. To obtain valuable marketable products, only uncontaminated source materials such as bio-waste should be used.

Another important pre-requisite for the manufacture of marketable products from waste is the application of reliable technologies to ensure suitable sanitation. Legal provisions in line with international standards must be formulated in order to:

- Encourage the application of biological treatment methods of biowaste and ensuring the harmonization of the applied management strategies, in order to prevent any negative environmental impact;
- Ensure the soil protection and the optimal use of compost and digestate;
- Ensure that recycled products are of durable and high quality, whereby the connotation of waste would no longer apply.

2.1.2 General principles

Composting is one of the oldest forms of biological recycling roughly used as a waste treatment method. In the past century, the organic fraction of municipal solid waste (MSW) was composted in many places around the world. Over the last few decades, some countries have shifted to separately collected biowaste, so as to ensure a market value of the product. This tendency was particularly practiced in Germany, Holland, Austria and Switzerland. In many other countries, composting is still considered a treatment process for municipal solid waste prior to land filling.

Though composting and anaerobic digestion can both be termed waste treatment processes, they are, more importantly, recycling processes. As such, they are subject to the same basic prerequisites as any recycling process.

Recycling only makes sense, if:

- The resulting products can be commercialized
- The ecological impact of recycling is lower than that of other treatment processes

2.1.3 Key Terms

The listed key terms are based on the 2001 European Commission issue of "BIOLOGICAL TREATMENT OF BIOWASTE 2nd draft".[3] In some cases, particularly regarding the terms *composting*, *compost*, *anaerobic digestion* and *digestate*, a more detailed definition will be provided later in the text.

Biowaste: Waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste;

Green and wood waste: Vegetable waste from gardens and parks, tree cuttings, branches, grass, leaves (except street sweepings), sawdust, wood chips and other wood waste not treated with heavy metals or organic compounds;

Compost: The stable, sanitized and humus-like material rich in organic matter and free from offensive odours resulting from the composting process of separately collected biowaste, and which complies with the legal environmental quality requirements (see also chapter 3);

Digestate: Material resulting from the anaerobic digestion of separately collected biowaste, and which complies with the legal environmental quality requirements (see also chapter 3)

Biogas: Mixture of carbon dioxide, methane and trace gases resulting from the controlled anaerobic digestion of biowaste;

Composting: Autothermic and thermophilic biological decomposition of separately collected biowaste in the presence of oxygen and under controlled conditions by the action of micro- and macro-organisms in order to produce compost (see also chapter 3);

Windrow composting: Composting of biowaste placed in elongated heaps that are periodically turned using mechanical means in order to increase the porosity of the heap and increase the homogeneity of the waste;

In-vessel composting: Composting of biowaste in a closed reactor where the composting process is accelerated by an optimized air exchange, water content and temperature control;

Home composting: Composting of biowaste and the use of compost in a garden belonging to a private household;

On-site composting: Composting of biowaste where it is generated;

Community composting: Composting of biowaste by a group of people in a locality with the aim of composting their own and other people's biowaste and manage it as close as possible to the point at which it is produced;

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[3] Updated EC documents on biowaste treatment, can be found at http://europa.eu.int/comm/environment/waste/.htm

Anaerobic digestion (AD): Biological decomposition of biowaste in the absence of oxygen and under controlled conditions by the action of micro-organisms (including methanogenic bacteria) aiming at producing biogas and digestate (see also chapter 3);

Mechanical/biological treatment (MBT): Treatment of residual municipal waste, unsorted waste or any other biowaste unfit for composting or anaerobic digestion with the objective of stabilizing and reducing the waste volume;

Separate collection: Collection of biowaste separately from other kinds of waste to avoid the different waste fractions or waste components from being mixed, combined or contaminated with other potentially polluting residues, products or materials;

Residual municipal solid waste (RMSW): Fraction of municipal solid waste remaining after the source separation of main municipal solid waste components, such as food and garden waste, paper and paperboard, metals, glass, etc. This fraction is unsuitable for the production of compost because it is mixed, combined or contaminated with potentially polluting products or materials;

Sanitation: Treatment of biowaste during the production of compost and digestate aiming at killing organisms pathogenic to crops, animals and humans, to a level that the risk of carrying disease in connection with further treatment, trade and use is minimized;

Stabilization: Reduction of the decomposition properties of biowaste to such an extent that offensive odours are minimized;

Impurities: Fragments of plastic, glass, metals or similar non-biodegradable materials, with the exclusion of sand, gravel and small stones.

2.2 Fundamental conditions

We present here the fundamental conditions required to produce marketable quality products based on experiences gathered in Switzerland.

2.2.1 Legal conditions based on Swiss framework

In the first two articles of Swiss law regarding the protection of the environment (SR 814.01) two fundamental principles are enounced:

- **The precautionary principle (Art. 1)**: Any effects that could result in damage or nuisance to humans, animals or plants or to the environment must be avoided at source.
- **The polluter pays principle (Art. 2)**: The responsible party violating prescribed environmental protection laws must cover the costs of its action.

As a consequence, limit values have been set in the Swiss Ordinance on substances, regarding the emission of pollutants into the environment (particularly the soil) by the products of biowaste (compost and, by analogy, digestate). These limits pertain to heavy metals and composts, as past data has shown high levels of contamination. Directives exist regarding the content of impurities and sanitation criteria (ASCP, 2001).

Other requirements based on these two principles concern the planning and operation of biowaste treatment plants but are beyond the scope of this document.

Table 1: Limit values for heavy metals in compost

Element	**Limit values in grams per ton of dry weight compost**
Lead (Pb)	120
Cadmium (Cd)	1
Copper (Cu)	100
Nickel (Ni)	30
Mercury (Hg)	1
Zinc (Zn)	400

Impurities level in compost

A distinction is made between stones and other impurities, of which plastic and aluminium foil form a sub-group.

Table 2: Limit values for impurities in compost

Parameter	**Limit values in grams per kg dry weight compost**
Stones > 5mm in diameter	50
Other impurities such as metals, glass, plastics >2mm ø	5
Plastics and aluminium sheeting >2mm ø	1 g p

Sanitation requirements

Properly sanitized compost or digestate should contain only negligible levels of organisms pathogenic to humans, animals or plants.

Table 3: Sanitation requirements for compost

Requirements for compost	Observations
At least 3 weeks over 55°C	Applies to the entire windrow, including the outer layers
Or at least 1 week over 65°C	Used mainly with in-vessel composting
Or another equivalent process which guarantees the same degree of sanitation	Pasteurization, steaming etc.

Legal requirements do not exist concerning the sanitation of digestate, but the ASCP has proposed some criteria, listed in the following table.

Table 4: Proposed sanitation requirements for digestate

Requirements for digestate *	Observations
At least 24 hrs hydraulic retention time at 53°C or higher	Absence of short-circuit flows must be demonstrated
At least 14 days hydraulic retention time below 53°C plus successive heating (post-maturation) to at least 55°C for 10 hrs or at least 60°C for 5.5 hrs	During post-maturation the temperature must be reached in the entire windrow, including the outer layers
Or another equivalent process which guarantees the same sanitation	Such as pasteurization, steaming etc.
** Requirements are based on the Danish (Statutory Order, Ministry of Environment & Energy No.823) and Swedish (RVF-Quality Assurance System) guidelines.*	

2.2.2 Economic conditions

According to the "polluter pays" principle, the cost of preventing or repairing environmental damage must be borne by whoever bears the responsibility for the damage. As a consequence, recycling is only sustainable if the product has market potential and if the environmental impact of the recycling operations is lower than those of new production. These principles likewise apply to the recovery of biowaste, which must therefore aim at manufacturing high-quality products. A certain number of prerequisites should be observed:

Separate collection: Biowaste must be collected separately, to avoid contamination by pollutants and impurities.

Proper treatment: Sound technologies must exist, companies must be financially sound and operational and environmental regulations must be enforced.

User-friendly products: Production must be end-user oriented (quality specifications and fertilizing prescriptions must be defined).

Balanced cost division between waste producers and end-users: The gate fees paid on delivery of the waste must be calculated so as to cover the largest part of the treatment costs, while sale of the products can only be expected to cover 10 to 20% of the expenses.

2.2.3 Requirements of the raw material

In Switzerland, composting of residual MSW was banned in 1986. Since then, the heavy metal content in composts, such as copper, lead and zinc, has decreased 5- to 10-fold. Nickel levels decreased much less as it originates in large part from soil-born material. The difficulty of using MSW is not only its high heavy metal content, but also the small pieces of glass, plastic and other impurities that make the compost unacceptable for the user. This is why the composting of MSW cannot be termed a long-term solution. In Europe, MSW-composting is only used as a pre-treatment before land filling or incineration.

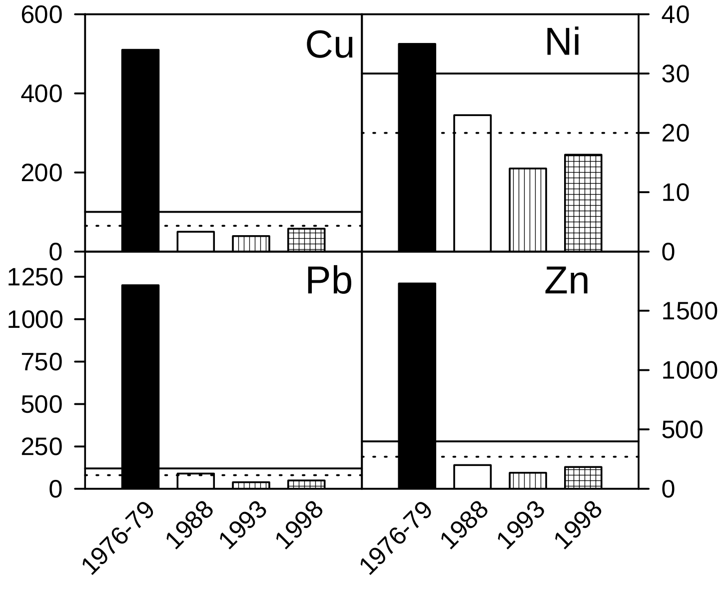


Figure 6: Heavy metal contents in composts produced from MSW (black bars) and from separately collected biowaste (hatched bars). The horizontal lines indicate heavy metal limit values for Copper (Cu - 100 ppm), Lead (Pb - 120 ppm), Nickel (Ni - 30 ppm) and Zinc (Zn - 400 ppm).

In addition to specifying limit values for contaminants in the finished products, it is best to act at source by drawing up a positive list of materials that are acceptable for composting. An example is given below. Such a list is site-specific.

Table 5: Example of a positive list of biowastes that are treatable by composting or AD

Origin	**Material**
Arboriculture, landscaping, horticulture,	Cut grass, lawn trimmings, tree and bush cuttings, leaves Reeds and aquatic plants from ponds and rivers
Households	Vegetable and fruit peel, waste foodstuffs, tea leaves, ground coffee, cut flowers, ornamental plants, litter from household pets
Agriculture	Waste hay and straw, fruit and vegetable waste, manure
Food industry and other industrial sector	Marc Mushroom growth substrates Wastes from the processing of coffee, tea, coca, oil-yielding plants, cotton, wool, flax, coconut fibre, potatoes, rice, Flour mill waste Paper, spice, canning waste, Clean tree bark, sawdust or wood chips that have not undergone any chemical treatment Catering waste

2.3 Basics of composting and anaerobic digestion

2.3.1 The life cycle

Life consists of formation and degradation of biomass. The sun provides the energy for the formation of biomass from carbon dioxide and water by photosynthesis. When it dies, this biomass is once again degraded, for example in the soil or aquatic environments. Many degradation steps are required to transform dead biomass into the mineral CO_2 that is released as the end product of the degradation and is the primary building block for the formation of new biomass.

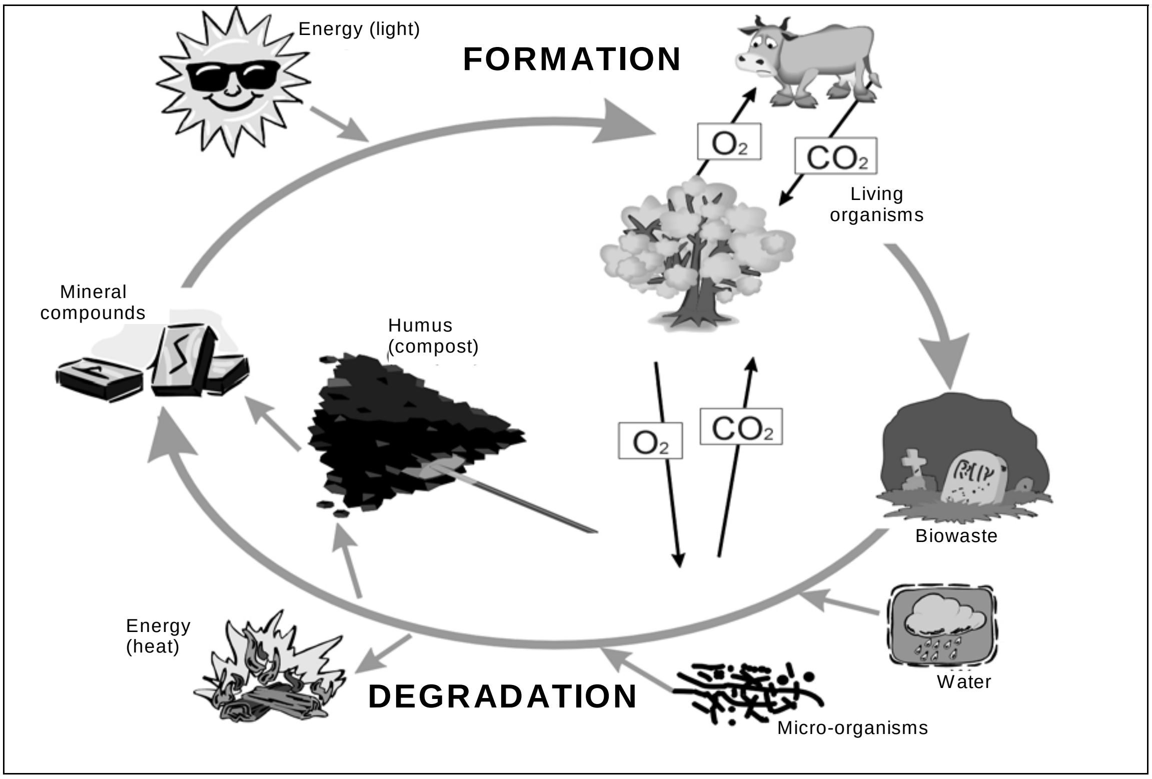


Figure 7: Life Cycle

2.3.1.1 Carbon cycle

Carbon is the main component of living organisms. Present in air as CO_2, it is fixed into bacterial and plant biomass by **photosynthesis**. The organically bound carbon is then consumed by herbivores, which are in turn eaten by carnivores. A large part of the carbon consumed is excreted directly by each successive consumer as CO_2, the product of the **respiratory metabolism** of living organisms. Dead biomass is degraded by a group of organisms called **decomposers**, consisting of macro-organisms (mainly invertebrates) and micro-organisms (bacteria, fungi and actinomycetes), and finally released once more into the atmosphere as CO_2.

In industrial composting, only microorganisms belonging to bacteria, fungi and actinomycetes are involved in the degradation process, as the high temperatures reached are inhibitory to larger organisms.

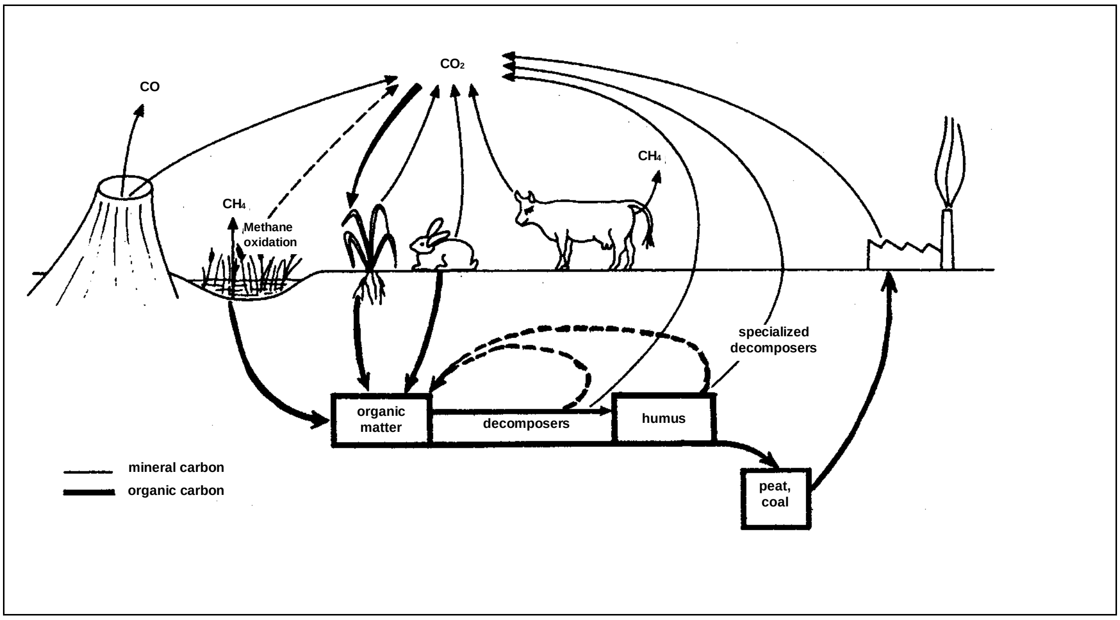


Figure 8: The Carbon Cycle (from P. Davet, 1996: Vie microbienne du sol et production végétale. INRA, Paris).

2.3.1.2 Nitrogen cycle

Nitrogen is an essential component of proteins. The air we breathe contains 80% of nitrogen. However, before gaseous nitrogen (N_2) can be used by living organisms, it must be transformed into an assimilable form, ammonium (NH_4^+) or nitrate (NO_3^-). This **nitrogen fixation** is carried out by specialized microorganisms, either free-living or symbions of plant roots. Plants can then assimilate nitrogen and incorporate it into their proteins, from where it passes on to carnivores. The organic nitrogen of dead organisms is degraded by decomposers into ammonia (**ammonification**). Ammonium is transformed by microorganisms called nitrifies into nitrite and nitrate (**nitrification**), the most soluble form of nitrogen. As nitrate, plants can then easily take up nitrogen with the soil water. It can also be lost by **denitrification**, whereby under certain unfavourable conditions (such as flooding, compaction or O_2 deficiency) microorganisms transform it once more into gaseous nitrogen and return it to the atmosphere.

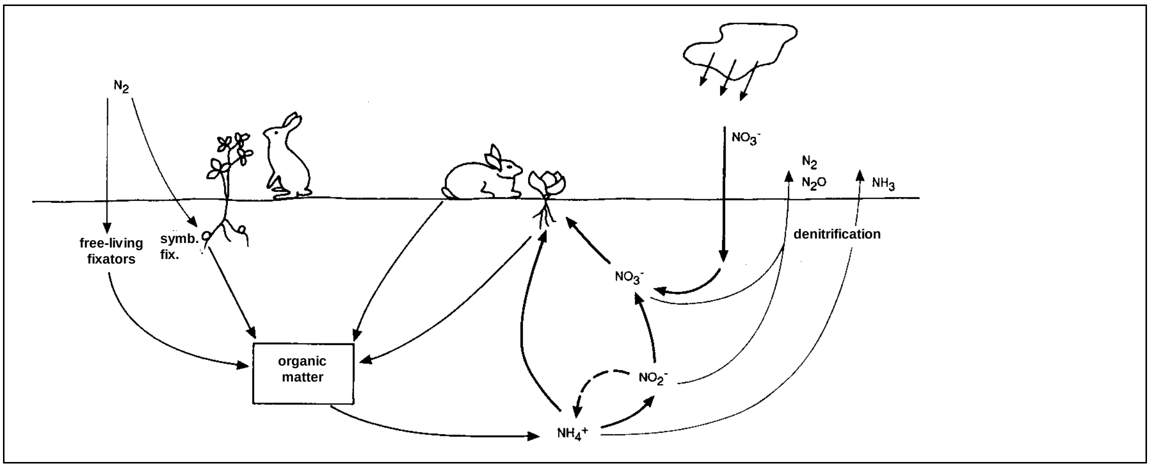


Figure 9: The Nitrogen Cycle

2.3.2 Composting

For **aerobic digestion** oxygen is required throughout the entire process. The end product is called **compost**, while **carbon dioxide** and **water vapour** and **heat** during the degradation process are remaining residues. During composting, degradation is predominant in the early stages. In the later stages of composting, some new formation also occurs (**humus**).

COMPOST

⇨ *Is an organic fertilizer*
⇨ *Contains micro- and macro-fertilizing elements*
⇨ *Improves soil structure and microbial activity*
⇨ *Improves water-retention capacity*
⇨ *Protects against erosion*
⇨ *Is a biological plant guard*

2.3.2.1 Composting stages

A composting mass of organic material evolves through four stages, characterized by the different processes occurring inside it: **Degradation, transformation, neo-formation and stabilization**. The transition between stages is gradual and no clear delimitations can be seen.

In more intensive processes only two stages can generally be distinguished: **Degradation** (degradation and transformation) and **maturation**.

Degradation
This stage is characterized by a sharp increase in temperature, followed by an almost 50% loss of volume of the degrading material. It is during this phase that a phenomenon essential to industrial composting occurs: The natural thermal sanitation of the material (destruction of weeds, pathogens and pests). This is also the most microbiologically active stage, as can be seen by following two parameters: The increase in temperature, due to the waste energy during biological degradation and high microbial oxygen consumption.

Maturation
After the degradation, the organic molecules are reorganized and reformed into stable structures and consequently **mineralization** and **humification** occur. This results in physiologically ripe compost, with an aggregate structure.

Ripe compost is still microbiologically active as degradation and restructuration processes are still occurring, but much more slowly. The final state of degradation of organic matter is complete mineralization, a process that will take years in soil.

2.3.2.2 Physical-chemical parameters

During the composting process physical-chemical characteristics of the decomposing mass evolve. This makes it possible to monitor the development of the process and apply corrective measures, if any deviation from the established parameters is observed. Precise knowledge of these process parameters and the capacity to judge and balance them are fundamental for good quality compost production.

Temperature

This is one of the most important parameters that can be easily measured. Monitoring temperature evolution is essential to assess the sanitation of the fermenting mass. Because of its regularity, temperature evolution is also a good way of following the development of the composting process.

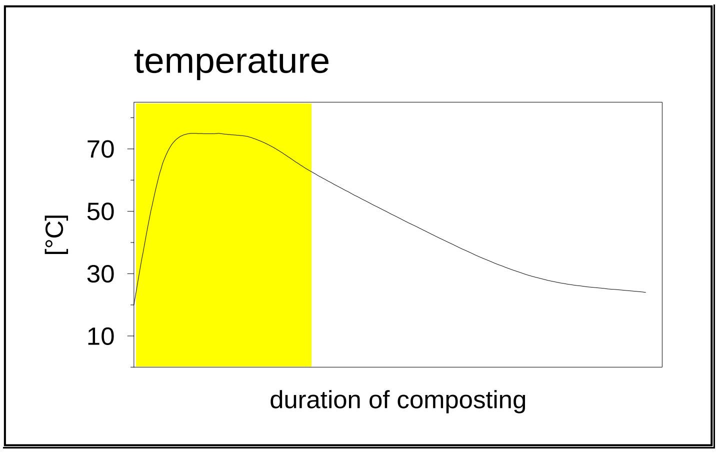


Figure 10: Temperature evolutions during composting

During the degradation phase (yellow), the intense microbiological activity causes the temperature rise to about 70°C. As soon as the easily degradable substrates have been consumed, temperature starts to decrease. Fungi then start attacking the ligneous materials. The maturation phase starts simultaneously. A normal temperature curve should change smoothly. Any abrupt break is a sign of some problem occurring, such as material drying or lack of nitrogen in the composting mass.

Gaseous phase

Normally, the sum concentration of oxygen (O_2) and carbon dioxide (CO_2) should be equal to about 21%, with O_2 remaining higher than zero. During degradation, intense microbial activity corresponds to a high production of CO_2. Thus CO_2 concentrations will decrease gradually as maturation sets in. Conversely, O_2 levels will be near zero at the beginning and gradually rise with time. Ensuring adequate oxygenation of the material during degradation is essential for producing good quality compost.

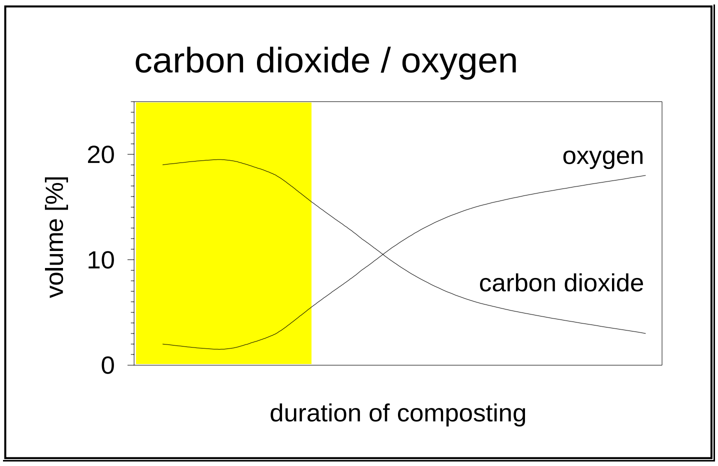


Figure 11: Evolution of carbon dioxide and oxygen content during composting

Organic matter

The organic content in the composting mass decreases very fast in the beginning, when the mass degradation is intense. When degradation slows, the amount of organic matter decreases slowly.

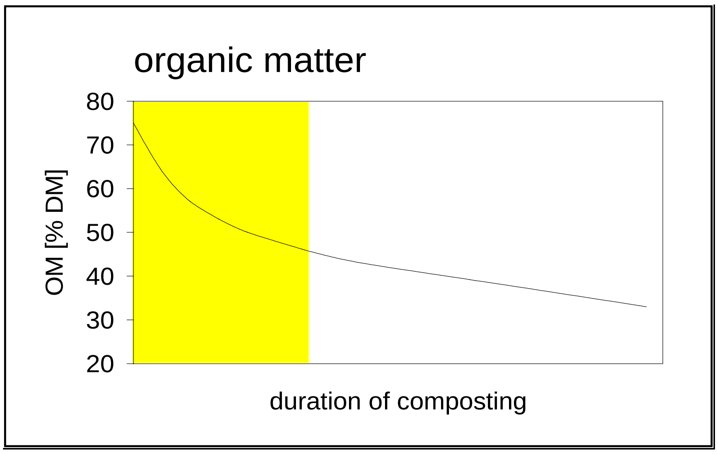


Figure 12: Evolution of organic matter content during composting

Nitrogen: Ammonia, nitrate and nitrite

Most of the nitrogen present in the material to be composted is organically bound. During degradation, nitrogen is released as ammonium (NH_4). Nitrifying microorganisms will then transform it into nitrite (NO_2) and then into nitrate (NO_3) - the form of nitrogen most easily assimilated by plants.

The ratio between the different forms of nitrogen is a good measure of the degree of maturity of the compost. The presence of nitrite in mature compost is a sign of a lack of oxygen during maturation. Nitrite evolution at this stage is negative for the biological quality of the compost, as it may make the compost toxic for plants.

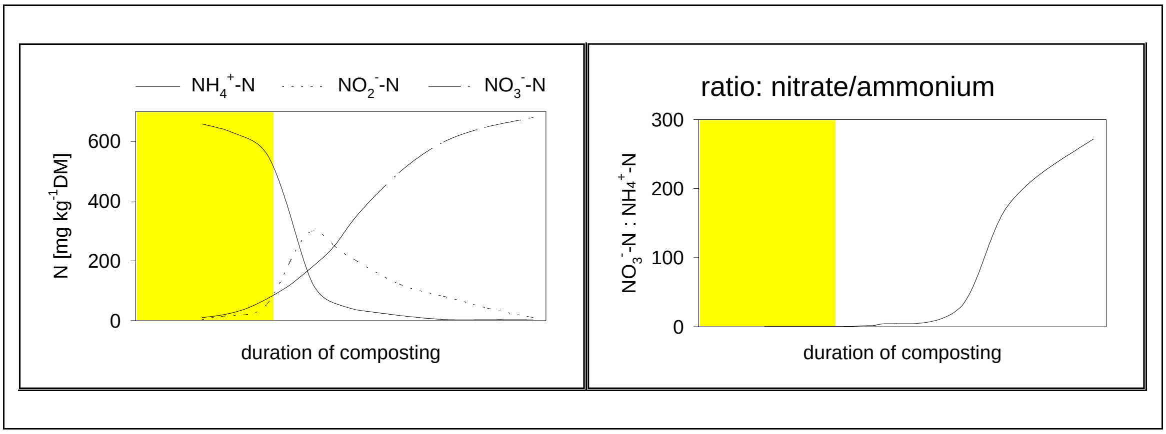


Figure 13: Evolution of nitrogen compounds content during composting

pH evolution

As maturation advances, the decreasing ammonia content and concomitant increase in nitrate will slowly lower the pH.

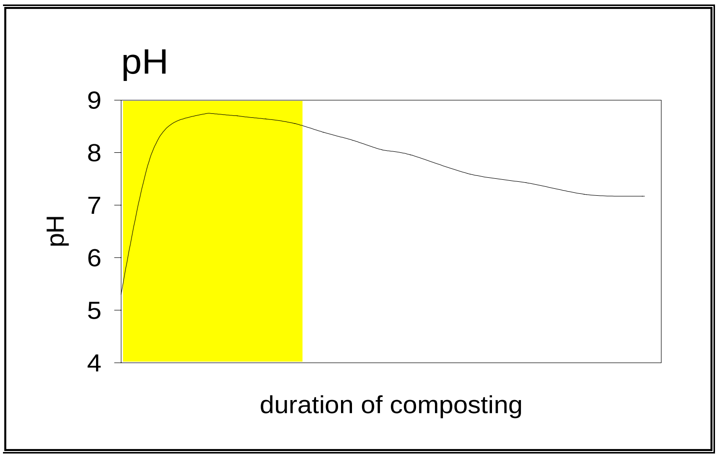


Figure 14: pH evolutions during composting

Extract colour

While aqueous extracts from mature compost are pale, as the stability of the humid acids increases, they become less water-soluble.

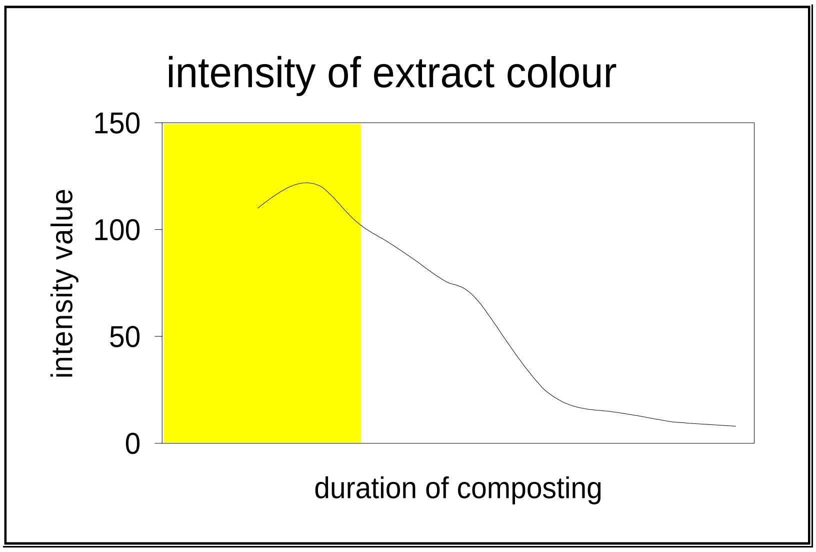


Figure 15: Evolution of extract colour during composting

2.3.3 Anaerobic digestion

Anaerobic digestion occurs in the absence of oxygen. It is typical of wetlands and other aquatic habitats. The process is not only oxygen-dependent, but it is even inhibited by oxygen. Apart from the stabilized organic residue called **digestate**, its other main end product is **biogas**, a mixture of **carbon dioxide**, **methane** and **trace gases**. Very little heat is released during anaerobic digestion and energy released from the biomass is stored as methane.

Digestate is the material resulting from anaerobic digestion, either solid or liquid, depending on the process. In some cases, the solid and liquid phases can be separate. Digestate has a more fibrous structure than compost, as lignin has not been degraded. Mineral nitrogen is present mainly as ammonium. As a rule, digestate is richer in nutrients than compost, since the input materials are generally richer in nutrients.

DIGESTATE

⇨ *Is an organic fertilizer*

⇨ *Contains micro- and macro-fertilizing elements*

⇨ *Contains easily assimilable mineral nitrogen in the form of ammonium*

⇨ *Is better tolerated by plants than liquid manure as most of the acids have been degraded*

⇨ *Has a greater fertilizing effect than compost*

⇨ *Enhances microbial activity in the soil*

Anaerobic digestion (AD) is an isothermal process, contrary to the aerobic composting process, which is highly exothermic. This is why AD requires external heating to accelerate the process.

2.3.3.1 AD steps

While both unicellular and pluricellular organisms (both Procaryotes and Eucaryotes) are able to degrade organic matter aerobically, anaerobic degradation is carried out exclusively by bacteria (**Procaryotes**). It is a **stepwise process** involving **several metabolic groups**, each living on the degradation products of the preceding group. In contrast, aerobic organisms can independently carry out the total degradation of complex substrates into the mineral end products, CO_2 and water.

The metabolic groups of anaerobic degradation are characterized by very **different growth rates** – in part due to the different growth substrates. Therefore, the slowest growing metabolic group will determine the overall rate of degradation.

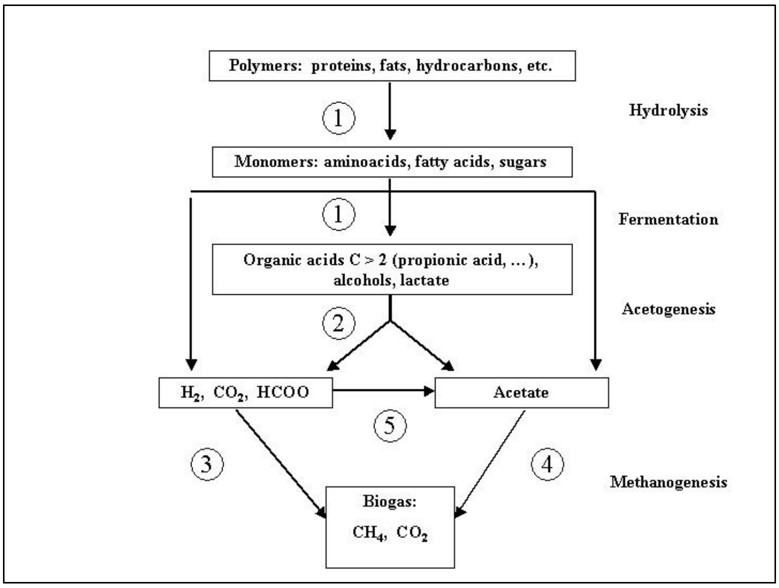


*Figure 16: The AD pathway of complex organic matter into biogas. Metabolic groups of Procaryotes involved: **1** – hydrolytic and fermentative bacteria, **2** – acetate-forming bacteria, **3** – hydrogen-oxidizing methanogens, **4** – acetate-cleaving methanogens, **5** – acetogens*

During **hydrolysis,** the complex polymers are broken into their single units, or monomers (short chain fatty-acids, sugars and amino acids), which are then **fermented** to produce acetate, alcohols and organic acids. The composition of the resulting mixture is influenced by the **hydrogen partial pressure**: If the hydrogen concentration is low, large amounts of acetic acid are produced, while a high concentration will result in the build-up of organic acids, such as propionic acid, butyric acid, lactic acid, and ethanol.

During **acetogenesis**, fermented products will be transformed into the precursors of biogas, acetic acid, CO_2 and hydrogen. The cleavage of organic acids such as propionic acid or butyric acid to acetic acid is thermodynamically favourable only if the concentration of hydrogen remains low.

In the last step of **methanogenesis**, biogas is produced by the methanogenic Procaryotes. About 70% of the biogas originates from the cleavage of acetic acid into CO_2 and CH_4, while 30% is produced by the reaction of hydrogen and CO_2. Methane formation is very dependent on the degradation of propionic acid, as it is the consumption of hydrogen by the hydrogen-oxidizing methanogens that keeps the partial pressure of molecular hydrogen low. All the methanogens can produce methane from H_2 and CO_2. The methane formation pathway by acetate cleavage is thermodynamically less favourable and can only be carried out by a restricted group of methanogens. Acetoclastic methanogenesis is nevertheless accountable for most of the methane production.

All four steps occur simultaneously in a biogas reactor, but at differing rates. **Hydrolysis** is normally the **rate-determining step by biogas formation.** Bacteria, in particular, hydrolyze cellulose and hemicellulose, a main component of many biowaste, slowly. If more easily degradable substrates are dominant, as in a distillery or in kitchen waste, methane formation becomes the rate-limiting step, as the fermentative bacteria multiply relatively rapidly. The feed into the reactor must then be carefully dosed, so as not to cause a too rapid build-up of acids by the hydrolytic bacteria, which would then lower the pH level unfavourable for methanogens. The inhibition of methane formation will lead to a further accumulation of acids, and finally bring the whole process to a standstill. In the event of such a growth inhibition occurring, the feed of fresh substrate must momentarily be halted or at least reduced; this is why a bypass should generally be installed on fermenters for easily degradable substrates.

Lignin, a component of wood, is **not degradable** anaerobically. It is however one of the only organic molecules which anaerobic bacteria cannot degrade.

As AD is mainly a biological degradation process, a post-maturation phase is necessary to produce compost.

2.3.3.2 Physical-chemical parameters

As anaerobic bacteria thrive on very little energy, the anaerobic degradation pathways correspondingly release no heat. Higher temperatures, however, speed up the overall reaction times. Methanogenic communities are divided into three groups: **Psychrophilic** methanogenesis has a maximum of about 25°C, **mesophilic** methanogenesis has its optimum around 35°C and **thermophilic** methanogenesis around 57°C. Though anaerobic degradation processes also occur on the seabed around 4°C, this is never the case in technical systems, as the reactions are too slow at such temperatures. Temperatures around 45°C, between the two optimums of mesophilic and thermophilic methanogenesis are unfavourable for anaerobic degradation.

Technical systems use mainly mesophilic or thermophilic methanogenic communities. As **the process releases no heat**, the substrate must initially be heated to the proper temperature. The optimum temperature also depends on the water content of the substrate. For cold substrates with high water content, thermophilic methanogenesis is generally not a reasonable choice, as most of the biogas produced must then be used as process energy to heat the system. High-temperature processes can, however, be used for solid waste containing relatively little water, in particular since diseases and weeds are destroyed more efficiently at higher temperatures. Thermophilic methanogenesis may also be used to treat liquid waste at high temperature.

The **optimal pH level** for methanogenesis is between 7 and 7.5. Biogas can also be produced just under or just above this range. In one-step processes, the pH level generally stabilizes by itself in the optimal range, as the metabolic groups form a self-regulating system. In two-step processes, the pH level of the hydrolytic stage generally ranges between 5 and 6.5, which is the optimum of the fermentative bacteria. At a pH level of 4.5 the growth of the hydrolytic and fermentative bacteria is inhibited by their own metabolites. In the methanogenic stage, the buffer capacity of the medium generally returns a neutral pH level.

A lowering of the pH level generally results in a **self-inhibiting process**: As the methanogens cannot function under acid conditions, the acids start to build-up and lower the pH level further. The reactor then acidifies completely. As soon as the first signs of acid build-up appear (e.g. signaled by a rise in propionic acid), the substrate feed must be reduced or stopped, to allow the methanogens to degrade the acids already present and so restore more favourable conditions for development.

2.3.4 Contaminants

Heavy metals present a particular environmental problem because they are not degraded and so accumulate over time. This also happens in composting and AD. The loss of volume due to the mineralization of part of the biomass means that the concentration of those pollutants that are not degraded will have increased in the mature product. This one reason is why the quality of the input must have limit values set for heavy metals in materials considered suitable for composting and AD.

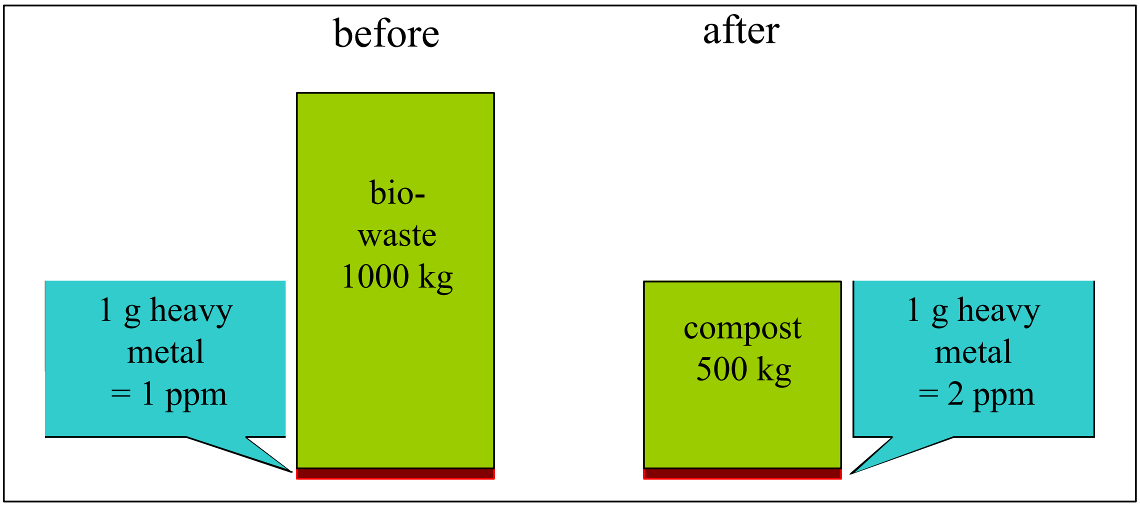


Figure 17: Evolution of heavy metal concentration before and after composting.

2.4 Comparison of composting and AD systems

Composting techniques have evolved from open-air composting, often plagued by odour problems, to cover and in-vessel composting, to anaerobic digestion. Anaerobic digestion, which proceeds in the absence of air, has been shown to be particularly suited to easily degradable waste. It complements aerobic composting, where difficulties were often encountered to aerate poorly structured materials. Anaerobic digestion is an isothermic biological process, so it requires good heating for the thermophilic variant, while aerobic composting is highly exothermic, releasing large amounts of warmth and is therefore a self-heating process.

2.4.1 Types of waste for aerobic and anaerobic processes

The types of waste most adapted to anaerobic digestion or composting are schematically presented in Figure 13. This classification is only valid for the dominant waste-type of a mixture.

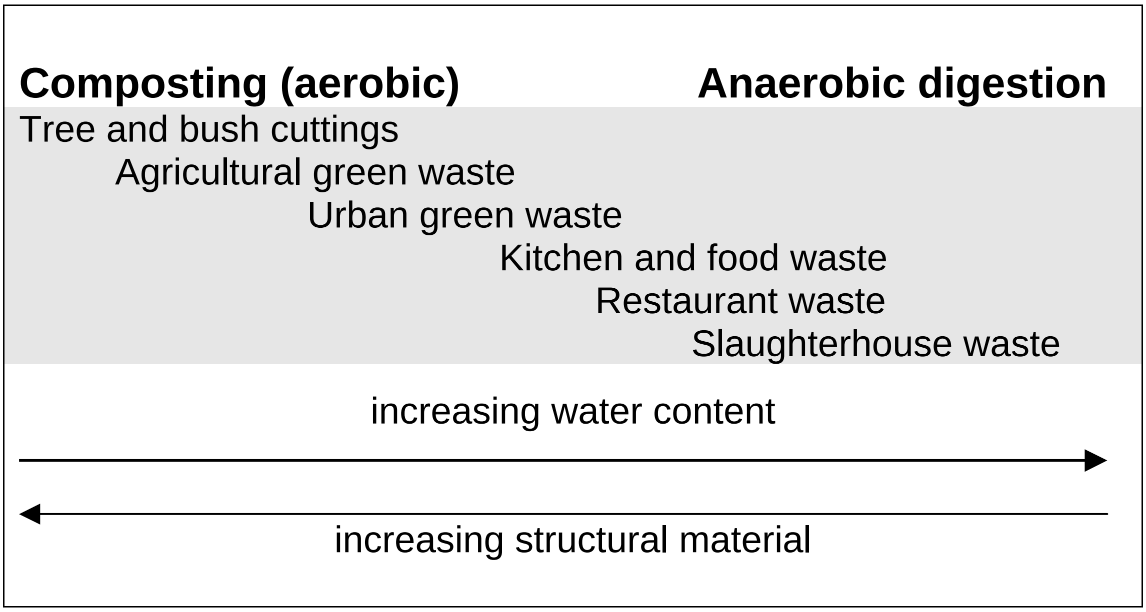


Figure 18: Suitability of various biowaste types for aerobic or anaerobic processes (K. Michael (1994), 5. Hohenheimer Seminar, Stuttgart).

Biowaste processing has three main aims: To favour the biological processes, to improve the quality of the end products and to ensure operational efficiency.

2.4.2 Steps required for composting or anaerobic digestion

Delivery and weighing

This is where the compostability of the waste received is checked. Quality compost requires the removal of larger impurities. Weighing the waste is essential for waste management planning and correct accounting of the amounts received.

Shredding

Shredding is the preparatory step for biological degradation. It must be adapted to the structure of the material, so as to allow for adequate oxygenation: Neither too fine (pulp or powder), nor too coarse (sticks will favour air bypass). Fine shredding is a prerequisite for efficient degradation in anaerobic digestion.

Anaerobic digestion (AD)

AD is optimal for easily degradable materials that produce offensive odours if they are composted. AD is also a source of renewable energy. In general, the material is shredded a second time in a rotary shredder and ground into a pulp. As AD is mainly a biological degradation process, a post-maturation phase is necessary to produce compost.

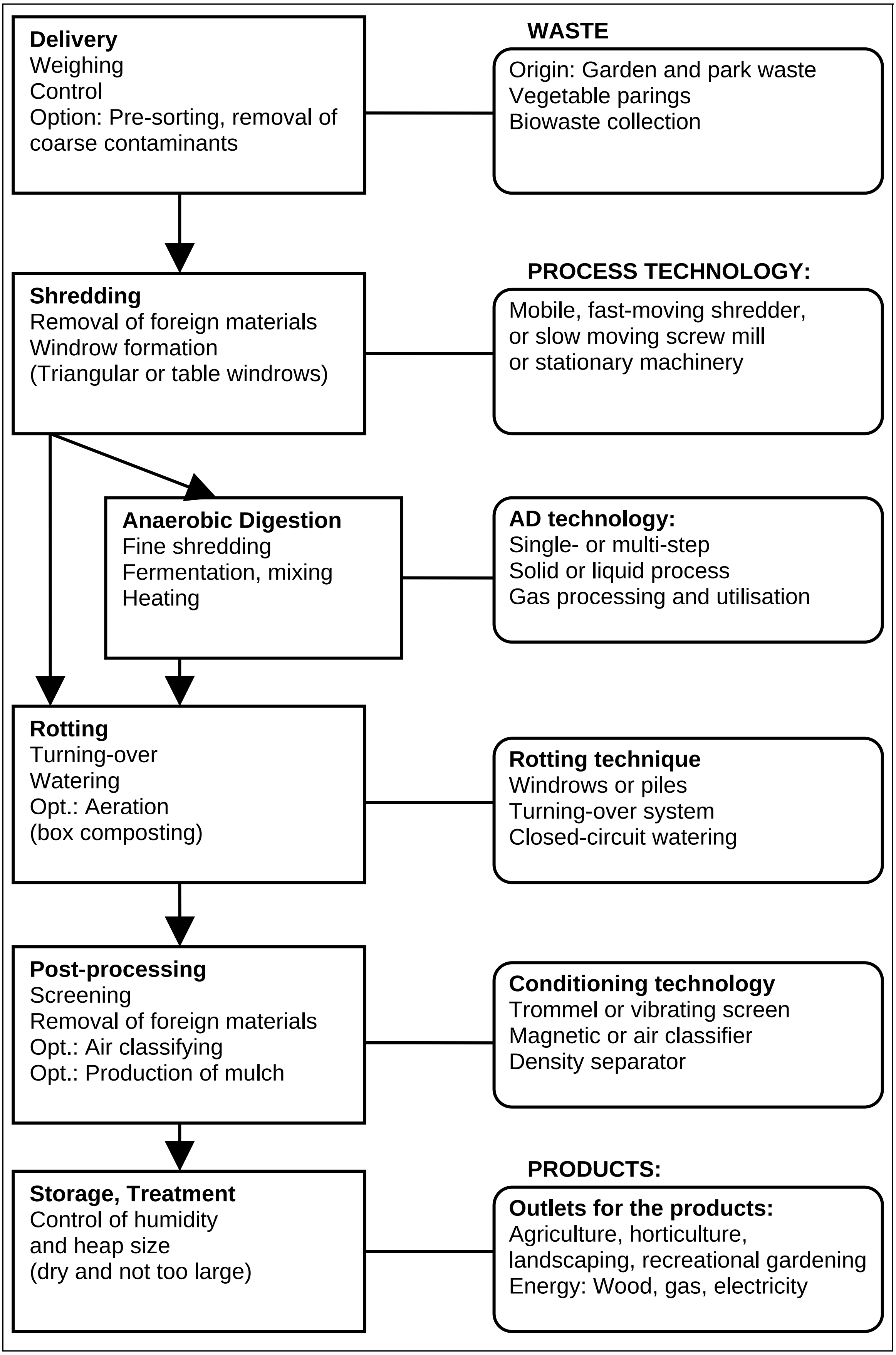


Figure 19: Sequence of operations in a composting or anaerobic digestion facility.

Rotting process, turning-over, aeration and watering
Turning-over affects the biological process most. Its finality is the mixing, aeration, and watering of the substrate, and these must be carefully balanced. Turning-over may be partially replaced by forced aeration, as the turning-over mixes the dry and wet parts, thus optimizing the water balance.

Post-processing and conditioning
This consists mostly of eliminating the foreign materials and calibrating the product to the required particle size. This is generally carried out after the rotting phase is over. Sometimes mature compost is also stored and conditioned shortly before sale. In general, screens are used to remove foreign materials.

2.4.3 Types of processes

2.4.3.1 Overview of various processes

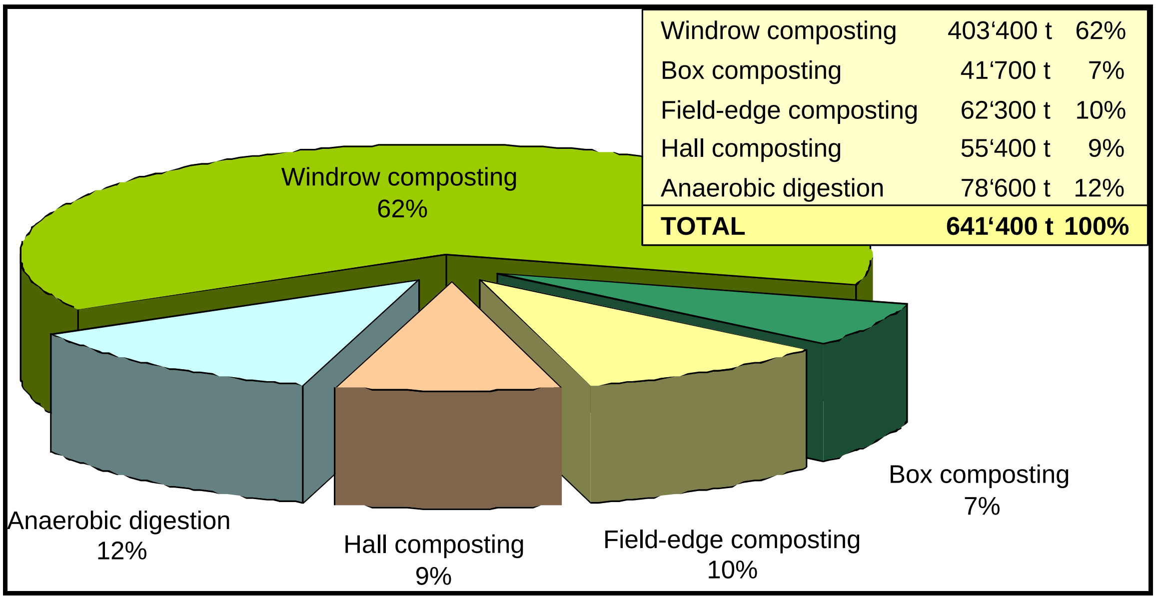
In Switzerland, two-thirds of the biowaste is still composted in traditional **open-air windrows**. This technique is characterized by its relatively low investment costs and a high quality end product. Its drawbacks are the emission of odours, when too many unsuitable materials are processed (kitchen waste) or when the facility exceeds its capacity (5'000 to 10'000 t/yr). **Field-edge composting** counts as windrow composting, since piles are made along fields; though the amounts treated rarely exceed 1'000 t/yr.

Hall- and box composting can be grouped under the heading of **covered systems**. Covering the facility avoids water logging. By completely housing a plant, it becomes possible to treat the exhaust air through a bio filter. In Switzerland, only a few plants are completely housed (**in-vessel**). In Germany, Holland and Austria, this type of plant is more common for larger facilities (> 20'000 t/yr). The energy consumption of fully housed facilities, for the forced aeration of the windrows and the air cleansing system is very high.

In Germany and Switzerland, some 10 to 12% of the total biowaste is processed by anaerobic digestion. In the canton of Zurich, a pioneer in this field, this percentage rises to over 30%. With such a ratio, the energy balance of the total collection and processing is positive: Biogas production is about double the consumption of diesel fuel by the composting facilities.

Liquid digestion is almost exclusively used for co-digestion in agriculture, in wastewater treatment plants and in industrial processes. For **solid-phase digestion** the input biowaste must contain 20 to 40% dry matter, which is usually the case for separately collected biowaste.

For the solid-phase AD, also called dry anaerobic digestion, the **plug-flow reactor** yields the best results and is also most widely used in Europe. The plug-flow reactor is a one-step technique whereby the complete process is generally located in a single room. In other, less common, **two-stage processes**, the hydrolysis stage is carried out in the first reactor, and acids formed are washed out by percolation pumped into a high-performance methanogenic reactor.



Windrow composting	403‘400 t	62%
Box composting	41‘700 t	7%
Field-edge composting	62‘300 t	10%
Hall composting	55‘400 t	9%
Anaerobic digestion	78‘600 t	12%
TOTAL	**641‘400 t**	**100%**

Figure 20: Types of Processes Used in Switzerland in 2000 (SAEFL 2001)

AD-systems also differ by the mixing methods used, some being completely mixed, which is the standard with liquid digestion, others, in particular the plug-flow reactors of solid-phase digestion, having no mixing of the material at all. Batch reactors are used for fully mixed reactors, but there is no mixing between reactors.

The biogas produced consists of about 2/3 methane and 1/3 CO_2. The gas is usually saturated with water vapour and also contains some trace gases (H_2S, H_2). The gas quality obtained will depend on the composition of raw material, the water content during fermentation, the temperature of digestion, the pressure in the digester, the retention time and the quality of the inoculum.

Anaerobic digestion produces on average $100m^3$ biogas per ton of waste, with a composition of 65% (vol) methane, 34% carbon dioxide and 1% trace gases. The energy content amounts to about 6 kWh per m^3 biogas. This gas can be converted into about 130kWh electricity by combined heat and power generation. If all the biogas produced is used as biofuel, 120kWh of electricity is consumed. Optimization is possible with combined heat and power generation.

Table 6: Net energy balance (energy production minus energy consumption) of various biowaste treatment processes

Useful residual energy in kWh per ton	**Electricity (kWh)**	**Heat (kWh)**	**Fuel (kWh)**	**Total (kWh)**
AD (100 % electricity production)	130	320*	0	**450**
AD (100 % fuel production)	-120	-100	600	**380**
AD combined heat and power (50/50)	5	110*	300	**415**
Wood chips heating	0	1000	-25	**975**
Composting, open system	0	0	-30	**-30**
Composting, housed system	-100	0	-20	**-120**

** Often the heat is not used, since most industrial buildings are already equipped with individual heating systems. Other outlets for this energy can rarely be found in the immediate vicinity of the plant. Therefore, the electricity and fuel values here are most significant for comparing the yield of an AD plant.*

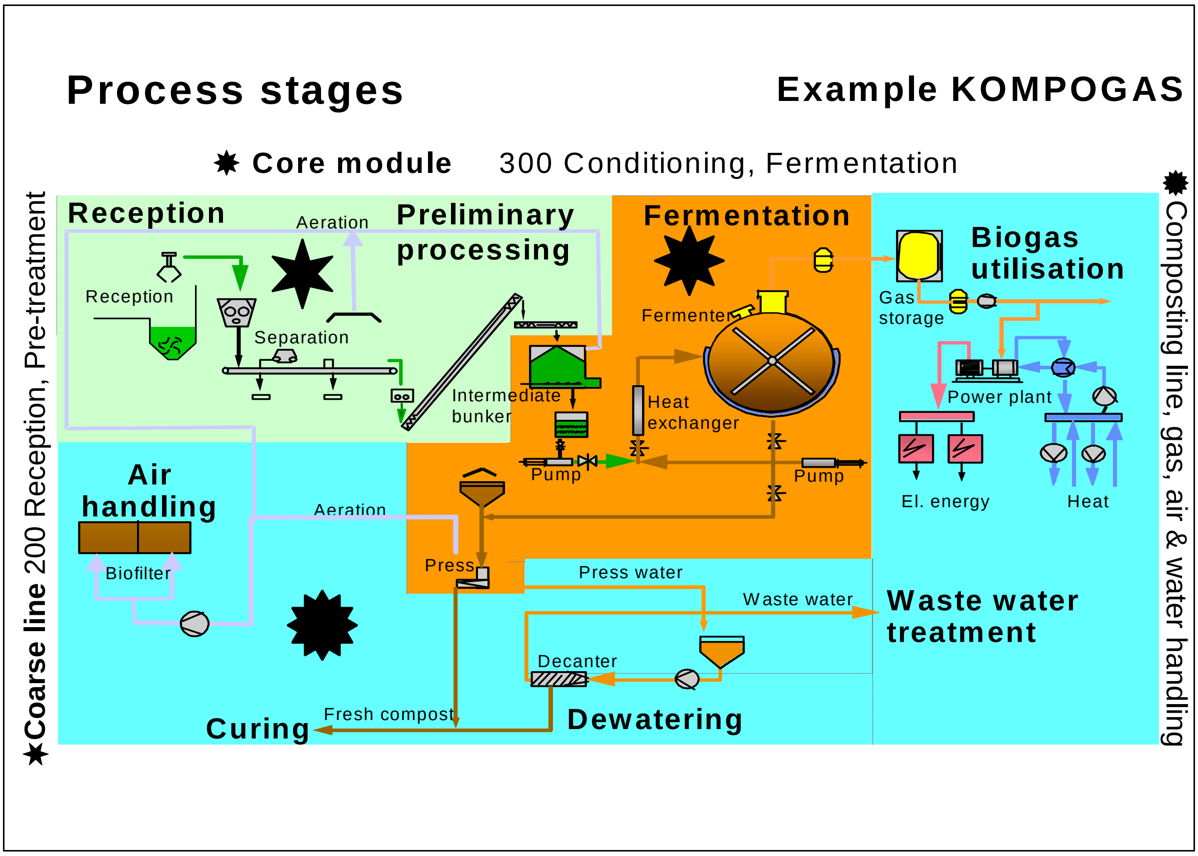


Figure 21: Typical process stages of anaerobic digestion (example KOMPOGAS)

2.4.3.2 Recommended processes and methods

The following processes and methods are particularly recommended:

Open Windrow Composting

Characteristics: Outdoors. Simple technology. Sufficient distance from densely populated areas.

- ✓ Height of the windrow: 1.5m to 2.1m
- ✓ Time required: 25~30 days
- ✓ Turning frequency: 3 times per day, half an hour per time

Recommendation: Suitable for rural regions

Advantage	Disadvantage	Equipment/remarks
• simple, proven (robust) technology • generally applicable • modular extension possible • usable for small quantities • small investment	• Possible problems: • rainfalls > 1000mm/y • windy situations • extremely dry conditions (extreme drought?) • if no paved area is available	• Equipment required: • front-end loader or similar • windrow-turning system for large plants • shredder • sieve • irrigation (depending on the area) • paved area

Closed Composting in Halls

Characteristics: Indoors. Substantially higher expenditure for technical installations.

- ✓ Height of the heap: 2m to 2.5m
- ✓ Time required: 20 days
- ✓ Ventilation frequency: Twice per day, one hour per time

Recommendation: Suitable for urban districts (capacity >10’000t/y).

Advantage	Disadvantage	Equipment/remarks
• few restrictions regarding climate, rainfall etc. • controlled composting possible • no emissions. The plant may be located in urban areas • several proven systems • several bidders on the market	• exhaust air treatment necessary • building necessary • high investment • surface protection	Equipment required: • closed building • ventilation/aeration for heaps and building • bio-filter • front-end loader or similar • converter • shredder • sieve • irrigation • loading/unloading and control device (depending on the process)

Composting in Boxes

Characteristics: Closed system. Substantially higher expenditure for technical installations.

- ✓ Ventilation frequency: Once every two days

Recommendation: Suitable for urban areas (capacity >10’000t/y) and for post composting.

Advantage	Disadvantage	Equipment/remarks
• independent of weather conditions • controlled composting possible • no emissions. The plant may be located in urban areas • no building necessary • several proven systems • several bidders on the market	• exhaust air treatment necessary • high investment • surface protection	• Equipment required: • rotting boxes including ventilation • bio-filter • front-end loader or similar • windrow-turning system • shredder • sieve • irrigation • loading/unloading and control device (depending on the process)

Liquid Anaerobic Digestion

Characteristics: Closed system. Energy production.

- ✓ Hydraulic retention time: 10-20 days
- ✓ Load: 0.6-1.6kg/m^3.d
- ✓ Temperature: 30-38℃(mesophilic), 55-60℃(thermophilic)
- ✓ Gas collected: 0.5-0.75m^3/kg (CH_4 55%， CO_2 45%)

Recommendation: Method for utilization of industrial and agricultural waste (capacity >10’000t/y).

Advantage	Disadvantage	Equipment/remarks
• independent of weather conditions • closed system • energy production with biogas • especially suitable for wet waste from kitchen and industry • water content > 80% • suitable in combination with agricultural waste • no emissions. The plant may be placed in urban areas • several proven systems • several bidders on the market	• not suitable for municipal solid waste • not suitable for wood waste • end-use of the digestate only in liquid form	Equipment required: • reactor • press • gas treatment device • gas utilization device • water treatment or tanks • front-end loader or similar • shredder • sieve

Solid Anaerobic Digestion

Characteristics:	Closed system. Utilization of the organic fraction of municipal solid waste with energy production. ✓ Hydraulic retention time: 20-30 days ✓ Load: 6-7kg/m^3.d ✓ Temperature: 30-38℃(mesophilic), 55-60℃(thermophilic) ✓ Gas collected: 0.625-1.0m^3/kg (CH_4 50% ， CO_2 50%)
Recommendation:	Method for utilization of municipal solid waste (capacity >10’000t/y).

Advantage	**Disadvantage**	**Equipment/remarks**
• independent of weather conditions • closed system • energy production with biogas • suitable for wet and semi-dry waste from gardens, kitchens and industry • water content 60 to 80% • suitable for municipal solid waste in combination with agricultural waste • no emissions. The plant may be placed in urban areas • several methods available	• waste with very high water content (> 80%) can only be processed by addition of structural matter • depending on the compost, post composting is necessary	Equipment required: • reactor • press • gas treatment device • gas utilization device • water treatment or tanks • front-end loader or similar • shredder • sieve

2.4.4 Prospects

Techniques exist for every type of process. However, market prices hinder the application of sustainable processing. An important argument in favour of AD is energy production. However the proceeds from energy can be expected to cover at most 10% of the running costs, since low oil and electricity prices do not allow for a profitable sale.

Advocates of a purely energetic exploitation of biowaste claim that composting is not necessary since the woody fraction could be burnt in wood-chips heating systems and the remainder digested anaerobically. It is in any case questionable whether it is sustainable to anaerobically process biowaste that is rich in wood, if the woody fraction cannot be easily removed mechanically. What remains certain is that digestate will always have to be matured aerobically to be marketable as a value added product.

In biowaste treatment, just as in any other production process, market investigations must be carried out *before* any production is initiated. As long as the waste producers accept to pay for treatment, there appears to be no need for an evaluation of the marketability of the products. However, the logic of this approach is skewed: It often results in inappropriate investments in technologies that produce unmarketable products and unwanted residues. If market prices covered production costs, attaining zero level waste is feasible. Waste treatment fees must cover the difference between the production costs of marketable goods and the market price for such goods.

2.5 Quality standards and marketing

2.5.1 Waste utilization

Separately collected biowaste can be divided into green and wood waste, and household biowaste (vegetable and kitchen waste). Biowaste compost is an organic fertilizer and soil conditioner accepted by markets all over Europe. It can be produced to a good quality without much technical equipment.

Two opposing trends dominate the compost market in Europe: Some composting plants try to minimize their costs by decreasing handling fees. As there is little margin for optimizing costs at the treatment stage, this mostly results in their delivering the compost free of charge to farmers without additional marketing efforts.

A more positive approach, which is being increasingly pursued, is to add value to their compost by producing special mixtures based on customer demands. Quality assurance and professional organizations are encouraging this trend by organizing research projects on compost application and by providing quality standards. Present here as a model are the quality guidelines developed by the Association of Swiss Compost and Methanisation Plants (ASCP, 2001)[4]. A comparison between other international composting standards has been carried out by the UK organization Waste and Resources Action Programme (WRAP) and can be downloaded from their website[5].

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[4] The full text of these guidelines may be downloaded at www.vks-asic.ch, under "DOWNLOAD": ASAC directive 2001 E (http://www.vks-asic.ch/acrobatreader/vks_richtlinie_english.pdf)

[5] www.wrap.org.uk/reports.asp

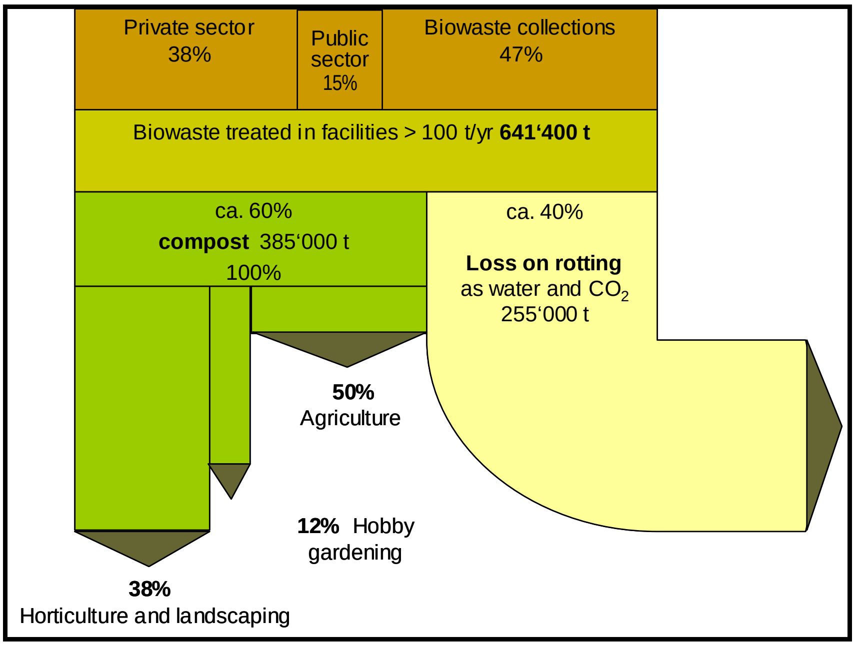


Figure 22: Diagram synthesizing the origin of the biowaste treated in Swiss composting or AD facilities in 2000, and the destination of the products. It shows the increasing need for quality products, since 38% of the compost produced is now used in horticulture and landscaping (SAEFL 2001)

2.5.2 Quality criteria for composts and digestates

The ASCP Guidelines 2001, Quality criteria for composts and digestates produced from biowaste, are presented in detail in this chapter.

2.5.2.1 Aims

The product resulting from anaerobic digestion without successive post-maturation is defined as digestate and must comply with the minimal requirements for composts with regards to impurities, heavy metals and sanitation. If a digestate is composted, either independently or mixed with other compostable wastes, high quality compost may be obtained.

The compost quality levels defined in the ASCP guidelines can be reached in any well-operated treatment plant using updated, but not necessarily highly technological, procedures. To obtain a high quality finished product, not only is state-of-the-art processing required, but also a correct choice of feedstock. This excludes wastes susceptible to being highly contaminated, such as sewage sludge, or waste from street cleansing.

The ASCP directives define limit values for pollutants and contaminants, as the minimal requirements are essentially negative in outlook. However, an important and original part of these quality guidelines is the addition of positive, maturity and plant compatibility criteria that are proposed for the higher qualities. In this, the Swiss guidelines differ markedly from existing European quality standards.

Once a high level of quality has been reached, this must be regularly monitored. While these analyses require specialized methods, most of the proposed maturity and plant compatibility criteria can be checked directly on-site in a simple laboratory.

2.5.2.2 Minimal quality requirements

As stated in Chapter 3 these requirements correspond to the legal prescriptions and are valid for all composts and digestives. They are generally sufficient for most **agricultural uses**, where the products are spread in layers less than 1 cm deep.

For mesophilic digestion, an alternative to the proposed sanitation requirements for digestate (see table 4) would be a pre-treatment of the biowaste at 70°C for one hour instead of post-treatment at 55°C for 10 hours. In fact, liquid digestives cannot reach such temperatures during aerobic post-treatment.

2.5.2.3 Quality criteria for composts used in horticulture, market gardening and landscaping

Besides the minimal quality requirements, composts destined for horticulture, market gardening or landscaping must comply with additional conditions for environmentally sound application.

The older the compost, the more nutrients are bonded into stable humus. These composts are considered important soil improvers characterized by a slow release of nutrients. The stable humic substances and well-developed aggregate structure of composts (prolonged maturation) make them especially adapted for utilization in heavy soils.

Each lot of compost destined for horticulture, market gardening or landscaping must comply individually with the quality guidelines for their physical, chemical and biological parameters.

Table 7: Physical, chemical and biological requirements for composts destined for market gardening, horticulture or landscaping (ASCP guidelines)

Parameter	**Prescribed value (X: value must be specified)**
Dry waste in % of fresh weight	> 50 %
Organic matter in % of dry weight	< 50 %
pH level	< 8.2
Particle size	< 25 mm
Density	X
Colour of extract (humus number)	X*
Salinity	< 4 mS/cm
Total N	> 10 g/kg DW
C/N ratio	X
NH_4-N	< 300 mg/kg FW
NO_3-N	> 40 mg/kg FW
NO_3-N / NH_4-N	> 2
NO_2-N	< 5 mg/kg FW
Weed seed germination test	< 1 per litre of compost
Plant compatibility tests:	
Cress (open)	> 70 % of reference
Cress (closed)	> 25 % of reference
Salad	> 50 % of reference

*A simple determination method still needs to be developed

2.5.2.4 Quality criteria for composts used in covered cultures and private gardening

Composts used in covered cultures must be of excellent quality and highly stable. Besides the minimal quality requirements, they must show perfect plant compatibility (no phytotoxicity). A positive biological activity (measured as disease suppressive potential) is desirable.

Not all plants have the same requirements, thus different composts may be produced depending on their destination. Certain quality criteria must be specified for each lot of compost, even if no limit value has been set for these parameters. In this way the user can correctly select the type of compost required and determine the correct quantities of additives.

Each lot of compost destined for covered cultures and private gardening must comply individually with the quality guidelines for their physical, chemical and biological parameters. Given the very diverse needs of the users, no requirements will be given here for composts intended for the production of potting soils.

Table 8: Physical, chemical and biological requirements for composts destined for covered cultures and private gardening (ASCP guidelines)

Parameter	Prescribed value (X: value must be specified)
DW in % of fresh weight	> 55 %
OM in % of dry weight	< 40 %
pH level	< 7.5
Particle size	< 15 mm
Density	X
Water-holding capacity	X
Colour of extract (humus number)	X*
Salinity	< 2,5 mS/cm
Total N	> 12 g/kg DW
NH_4-N	< 300 mg/kg FW
NO_3-N	> 50 mg/kg FW
NO_3-N / NH_4-N	> 20
NO_2-N	< 2.5 mg/kg FW
SO_2	< 0.5
Weed seed germination test	< 1 per litre of compost
Plant compatibility tests:	
Cress (open)	> 90 % of reference
Cress (closed)	> 50 % of reference
Bean	> 70 % of reference
Ray grass	> 70 % of reference

* Determination method needs to be developed

2.5.3 Training

To produce quality compost every worker in a plant must possess some basic knowledge. In practice, the driver of the front-end loader must not only know how to drive his vehicle, but must also be conscious that by piling up compost without taking the necessary precautions, the resulting compaction will reduce the quality of the product.

Once the biowaste processing branch in any given country has developed sufficiently, one or more professional organizations generally take root. One of the primary duties of such an organization should be to promote high-level training programmes to the staff as established by the ASCP objectives, which has been organizing basic and advanced courses on a regular basis since 2000.

2.5.4 The sale and marketing of compost

2.5.4.1 The concept of "Marketing"

Marketing specialists consider vendors or producers as the industry and buyers or clients as the market. In this report, it is this meaning that is implied by the word "market".

Marketing activities are fundamental to all companies and cannot be considered as separate functions within the companies. Marketing aims to satisfy the needs and desires of clients by producing, offering and exchanging objects of value. In these commercial relations, the concepts of usefulness, costs and satisfaction assume a central importance. The relation between producers and market, respectively between offer and demand, is illustrated in the following diagram.

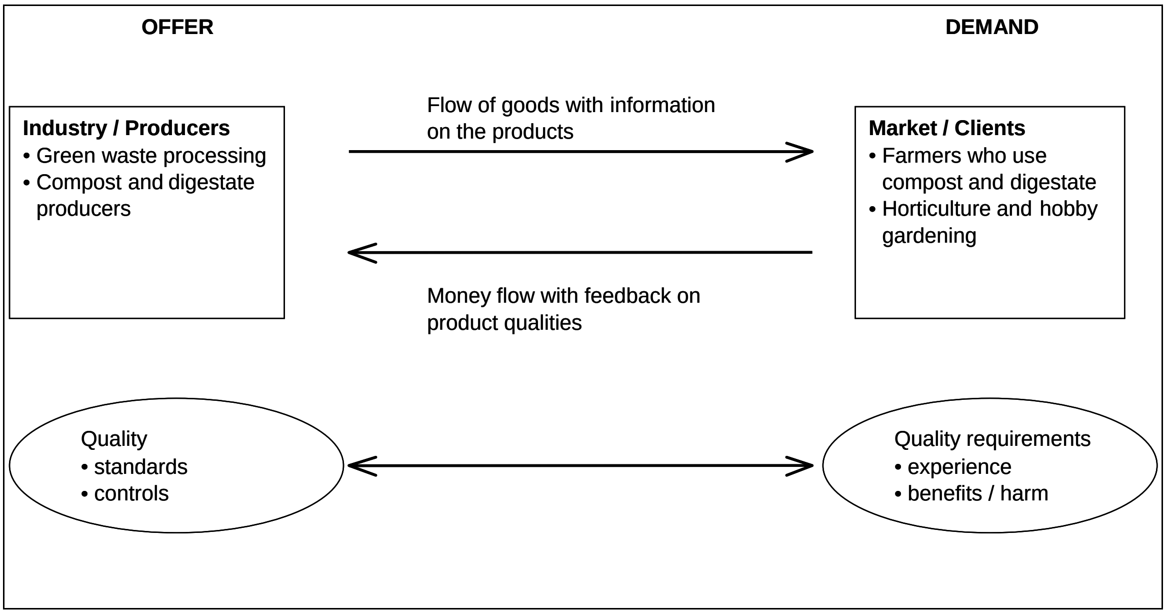


Figure 23: Schematic representation of offer and demand

Consumers prefer to acquire best quality products. Industrial managers in product-oriented businesses concentrate on manufacturing and upgrading good product designs.

Marketing concepts: Determine the needs of the market and aim at satisfying these more efficiently than the competition. Marketing is client-oriented and always depicts clients' image of the company.

The main characteristics of marketing:

- Normative economics, aiming at deducing commercial strategies,
- Involve a target-oriented company management, which not only react to the market, but also try to actively structure the market, in order to acquire market potential,
- Must be understood as a principle of company management, a means of forming buyer preferences, a method of systematic and appropriate analysis techniques and of useful decision-making,
- Requires planned conceptual action.

2.5.4.2 The ‘4 P’ marketing strategy

The measures a company may take to efficiently promote its products are mutually related. They come under the heading "marketing policy instruments". The combination of measures implemented can be termed a marketing mix. In marketing theory, a marketing mix is composed of elements belonging to the 4 Ps (product, price, place, promotion); this is also the case for compost and compost-derived products:

1. Product defines characteristics and specificities. Some elements, such as particle size and packaging, can be modified at short notice by the composting plant. The development of new qualities of products, with the corresponding quality assurance generally takes several years. For marketing in agriculture, emphasis should be placed on its uses as a soil-quality improver and protector against plant diseases. The nutrient content alone does not suffice as a positive characteristic of the product for farmers.

2. Price includes all the pricing elements of a product. This comprises quantity discounts and other discount offers, as well as terms of payment. Until five years ago the price of waste taken from a composting plant per cubic metre was nothing. Now the price is negative, meaning that the cost of delivery has been taken over by the composting plants and losses are incurred.

3. Place describes all aspects related to location, including the terms of delivery. For clients in agriculture, this means having the compost spread on their fields free of charge. Horticulturists know where they can obtain the compost in bulk and where it is conditioned in so-called "big bags". Under this heading comes the storage of the finished product in other locations, closer to the end-users and the sale of compost in garden centres.

4. Promotion includes all the active marketing efforts, such as advertising, individual offers and promotions and public relations. For those clients who pay for the product, this includes all the classical promotional efforts. For clients from agriculture, who have, up until now, received the product free of charge, advertising efforts should include promotion of the product in collaboration with the professional organizations in agriculture, so as to gradually increase the demand over the offer which would make it possible to raise the price in the future.

Table 9: Marketing strategy

Product	- Guaranteed nutrient content - Particle size - Maturity - Mixtures - Packaging
Price	- Discounts - Price structure of each product - Additional discount services - Terms of payment
Place	- Terms of delivery - Sales locations (Agro Centres) - Choice of products
Promotion	- User recommendations - Counseling - Classical advertising - Information brochures - Demonstration plots - Fairs - Sponsoring

2.5.4.3 Recommendations for compost marketing

- Compost marketing should begin during the construction phase of a compost plant, **before** large quantities of compost have had time to accumulate.
- The organization of a well-functioning compost distribution network takes time. Depending on the location and market situation, the time frame is 1-3 years.
- First, buyers with the capacity to purchase large quantities of compost must be found. The primary goal should not be to achieve a profit, but rather to cover about 10-20% of the production costs through the sale of compost (figures based on experience).
- Lobbying and PR activities must be initiated early. Primary targets are agricultural schools and associations, opinion leaders, politicians and potential buyers.
- Carry out a market analysis in the region where the plant will be located. Base distribution and sales efforts on the results of the market analysis.
- Advertising: Provide compost samples and consulting free of charge to potential users. Set up experiments demonstrating the applications for compost and show these to interested groups (the goal here is a snowball effect).
- Maintain regular contact with all potential buyers.

2.6 Conclusion

The most important prerequisite for successful compost production is to collect separately the biowaste that should be processed.

The quality requirements for compost to be commercialized have to be defined. Uniform controls must also ensure that the rules are respected throughout the country.

Minimal requirements include the limits for heavy metals, organic pollutants or contaminant materials and the directives for proper sanitation. They are generally sufficient for agricultural application of compost, while products for use in horticulture and covered cultures must comply with additional specifications.

If the demand for the products is to be sustained, the needs of buyers must be taken into account from the initial stage. Only a user-oriented approach can ensure that what is produced will satisfy the market requirements in the long term. This also implies a communication strategy that emphasizes the cost and resource advantages of products made from recycled materials. At the onset of planning a regional strategy for biowaste composting or digestion, this may seem to demand a very great effort. However, examples where such a strategy has been successful exist and are open for inspection and/or replication.

3 Introduction to land filling technology

A condensed version of the chapter on
‘Land filling technology’
from the UNIDO Training Manuals on MSWM
prepared for the project
“Cleaner Municipal Solid Waste Management in China”

3.1 Introduction

The disposal of all types of waste in landfills was regarded as the simplest and cheapest form of waste treatment. With the growing awareness of the environmental problems generated from old landfills, or dumps, many industrialized countries have set new guidelines for waste treatment, aiming at reducing the overall quantities of municipal solid waste to be land filled. These guidelines imply that before land filling, almost all waste has to be separately collected, sorted, neutralized, decontaminated and immobilized, undergo bioorganic degradation or be burnt.

3.2 Design and construction of a landfill

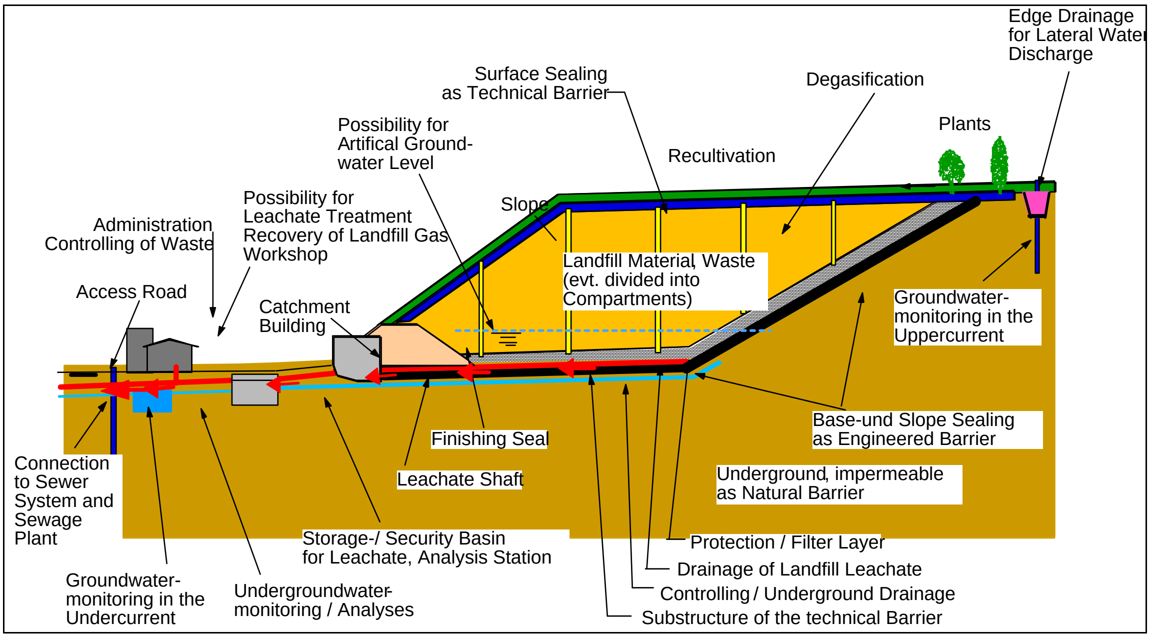


Figure 24: Common landfill features

Errors during construction or operation of the landfill can often only be rectified later at great additional cost. Safety and quality issues should be taken into serious consideration, as they will impact in the performance of future landfill operations. Long term monitoring of landfill activities is important to ensure the sustainable protection of the immediate environment and groundwater supply.

The three-barrier concept applies to landfill management. The natural subsoil, which forms Barrier *1*, should have the following properties:

- Low permeability with sufficient magnitude and homogeneity ($k_f = 1 \times 10^{-7}$ m/s, at layer depth magnitude of 5–10 m).
- Great self-purifying forces – measured by the capacity of adsorption and ion exchange.

- Resistance to settlement and subsidence, even with occasionally dynamic charges during construction and operation.
- Location should be at a distance from the groundwater table and not a drainage area of a fountainhead or a reservoir for potable water.
- Low risk of flooding, erosion and landslides.

Comprehensive geological and hydrological studies, including in-depth soil investigations, are necessary to assess the suitability of the subsoil. The geological barrier is the ultimate (and the best) security if someday all technical installations fail. Compromising at the stage of site selection can have severe consequences later on.

Barrier *2* comprises the engineered protection systems, such as the base sealing, including the leachate removal substructure and the leachate drainage systems. Lateral liners can also be used and are made of the same material. A capping and cultivated restoration layer should be constructed after the landfill has been completed to limit further infiltration from precipitation. At the stage of aftercare, good capping and restoration are important for the long-term safety of the landfill as the base liner alone will only last for a limited time.

Barrier *3* forms the landfill content. Special waste, such as slurry charged with heavy metal, explosives, carcass, and liquid waste should be excluded. It is therefore wise to introduce a preliminary stage of separation before landfilling, where reusable materials can be collected separately. Regular controls and analysis of the leachate and gas emitted can be used to detect unauthorized deliveries.

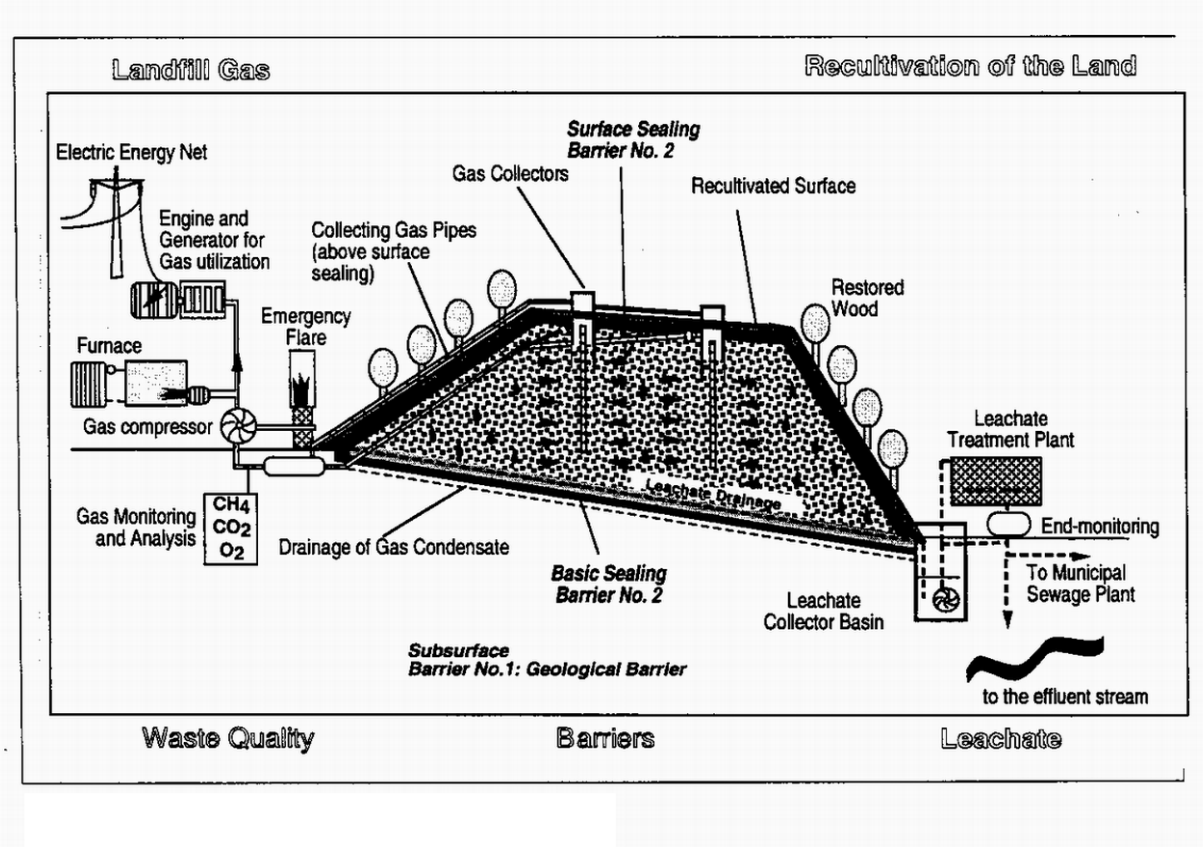


Figure 25: Basic features of a reaction landfill

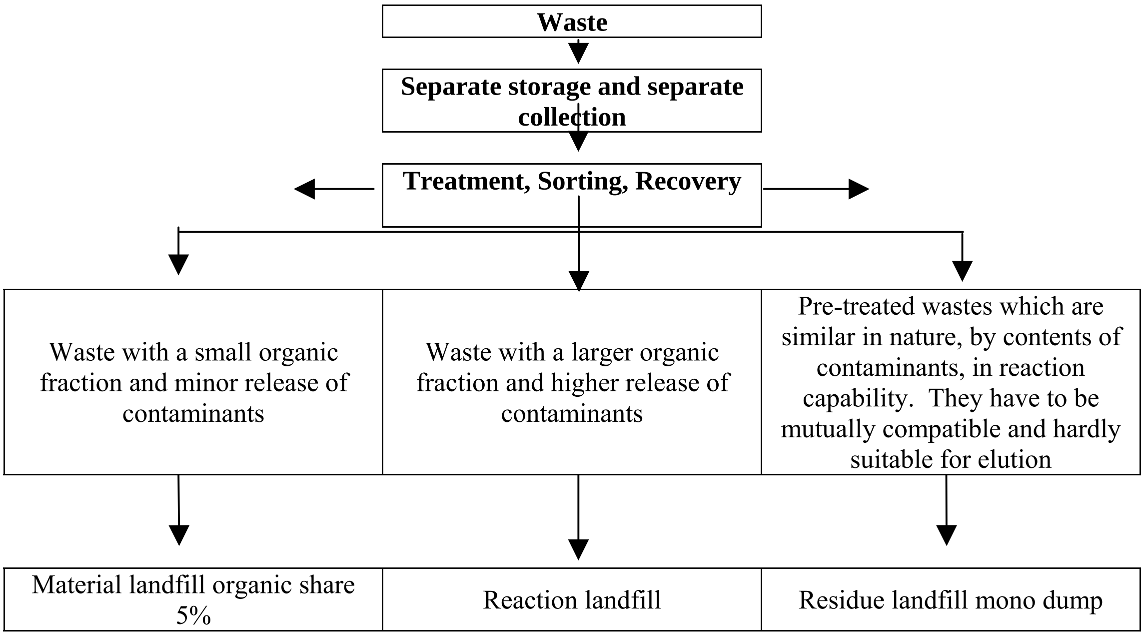
Optimal degradation processes within the landfill play an important function in terms of long-term security. A common landfill feature is a collector system for surface run-off, possibly in the form of intermediary sealing and reduction of leachate generation caused by external water supply. Ground stability is to be studied mathematically as excessively steep slopes may trigger landslides. Groundwater sampling can verify the efficiency of the technical barriers in place to minimize or prevent pollution. There should be a controlling system for sub-surface drainage, possibly with a storage basin as an emergency facility. Collectors for leachate siphons and gas recovery are needed to ensure that no air will penetrate into the pipes, possibly leading to degradation and congestion of the latter. There should also be flushing facilities on both sides; retention basins for interim storage in case the leachate treatment facility breaks down and gas collectors with regulation devices.

Further features of landfill construction should also be:

- an entrance linked to an access road
- a scale and an on-site waste verification station
- administration and sanitary facilities (lockers, showers)
- workshop and machine hangars, possibly a small laboratory with storage facilities for samples
- housing for the leachate treatment plant and the gas utilization facilities such as the gas motor
- a 2 m high fence to restrict access. Site access should only be permitted during working hours.

3.3 Types and forms of landfills

3.3.1 Different types of landfills



Erection

Material landfill	Reaction landfill	Residue landfill mono dump
Simple technical barrier Leachate capture Controlling If necessary, simple treatment	Expensive technical bottom, Side and surface barriers, Leachate catchment and purification, Landfill gas collection and recovery	Expensive technical bottom, Side and surface barriers Leachate catchment, monitoring. If necessary simple purification, Outlet channel

Standard requirements for all types of landfills

Site:

- Geological barrier
- Position relative to groundwater

Operation

- Planning
- Reduction of contaminants
- Controlling/monitoring
- Supervision
- Closing and aftercare

For residue landfills and mono dumps, the following maximum recommended organic shares are valid:

Ignition loss	≤5 mass %
TOC	≤3 mass %

These values can only be achieved with a preliminary thermal treatment, e.g. in an incineration plant. Then the practically inert slag will be deposited. All other waste has first to be immobilized (by washing, solidifying, neutralizing, etc.

Figure 26: Landfill types. Source: Rytec AG

Reaction landfills or co-disposal landfills contain waste that persists in bio-chemical reactions. The waste includes untreated municipal and commercial waste and unrecoverable residue from sorting facilities, compost plants and demolition sites. It generates leachate with high concentrations of organic and inorganic contaminants. The putrescible organic waste fraction can generate considerable amounts of landfill gas (200 - 300 m^3 in 15 years) along with other gases. Special measures for gas recovery are therefore imperative for the re-utilization of the treated waste and its by-products.

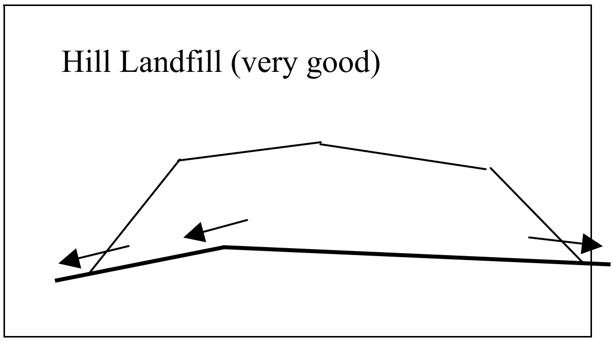
Residual/mono landfills are used for slag from incinerators possibly combined with sands from foundries. This type of waste also continues to react in the dump and the leachate is often salty and contaminated with metals. The leachate can be discharged after passing a control; however, if it contains contaminants other than salt, it must be purified beforehand.

Inert material landfills contain dry waste, which has low reactivity and contains only small quantities of substances suitable for elution. Materials such as stony demolition debris (< 5% wood) or slightly contaminated excavated material are acceptable. The leachate can be discharged directly into the river after passing a control. Often, an engineered barrier is not necessary for this type of landfill if the subsoil has optimal qualities. However, proper leachate drainage and a simple substructure are required.

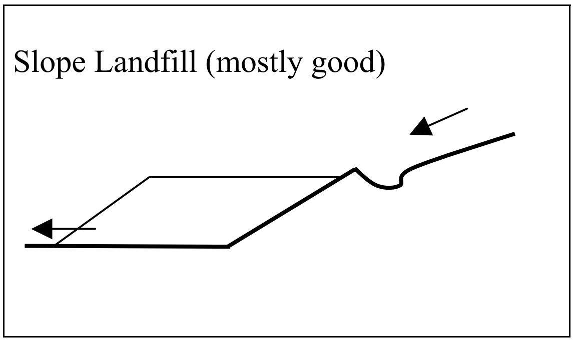
Hazardous waste landfill construction is extremely problematic. Hazardous waste has to be either incinerated or treated for disposal in mono landfills. Hospital waste, carcasses and industrial waste with a large share of potential pollutants such as paint are classified as hazardous waste. The long-term goal is to landfill only residual and inert waste.

3.3.2 Morphology of landfills

Landfills come in 4 main forms: Hill, Slope, Valley and Pit Landfill.



Hill Landfill (very good)



Slope Landfill (mostly good)

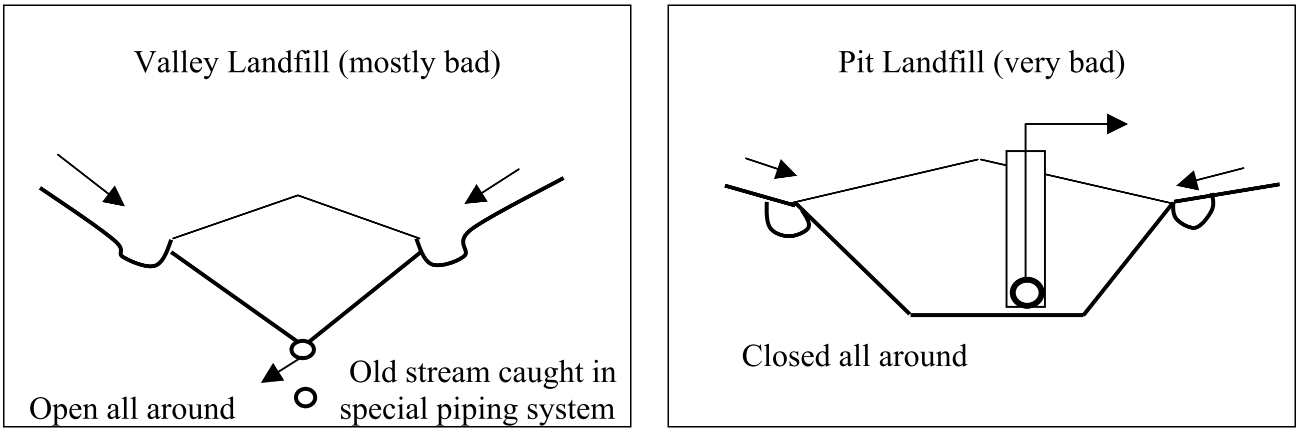


Figure 27: Forms of landfill

A **hill landfill** is raised on a flat terrain. The base is formed so as to allow gravity-drainage of leachate from all sides, which is collected on the edge. Lateral inflow of water into the landfill is thus excluded unless flooding occurs. The landfill is accessible from all sides, which allows for complete screening. The substructure with gradient turned outwards and it is relatively cheap as no lateral sealing is necessary. A drawback of the hill landfill is that it requires large areas of often fertile and easily cultivated land, and lacks aesthetic appeal.

The **slope landfill** is constructed leaning against a natural elevation, hence guaranteeing gravity drainage of leachate. The advantages do not differ much from the hill landfill, but the integration into the surrounding landscape is often easier. Many of these landfills cannot be distinguished from their surroundings once they have been completed and restored. The drawbacks include the additional lateral sealing, which has to meet the same requirements as the base sealing. The lateral sealing also has to be protected against the pressure of seepage build-up and landslides, and special drainage has to be placed underneath the sealing for seepage from the slope. All this can only be achieved with extra effort and at a higher cost. Furthermore, the landfill has to be protected against external runoff from the slope by the construction of circular trenches.

Valley landfills: Where there are valleys, there are also hills or even mountains and in such regions, precipitation is higher. Another drawback is the external inflow of water from the flanks of the valley. This can be limited by the construction of expensive circular trenches but their maximum capacity is quickly reached during torrential rainfall. Furthermore, trenches tend to get congested by falling plants and branches. The valley subsoil generally lacks homogeneity and connections with sources and aquifers are often discovered. Therefore a valley site requires sealing with an engineered barrier on all sides, which is quite expensive. Hence it is considered an unfavourable type of landfill.

Pit landfills: were quite popular in the past, offering a cheap possibility of raising abandoned quarries and then restoring them. However decades after the closure of the landfill, leachate still needs to be pumped from the base in order to avoid build-up. Furthermore, large aquifers are usually found under quarries where water easily infiltrates the landfill creating additional leachate. Even with excellent engineered barriers, the water cannot be protected against contamination by pollutants from the landfill. The quantity of leachate can only be limited later by good capping. The most expensive and contaminated sites in Europe are former pit landfills. As a rule, a site where many natural water bodies are involved should be avoided.

3.4 Site selection

The optimal site for a regional landfill is selected with the aid of a site assessment programme. It is important that all the necessary criteria are sufficiently accounted for as only few site-related drawbacks can be corrected by engineering. The multidisciplinary team should comprise of geologists, hydrologists, construction engineers, and transportation experts, landscaping architects, landfill experts and economists, among others.

Positive planning identifies areas that are in line with the framework of site requirements. Alternatively areas unsuitable for a landfill construction, in accordance with the set criteria, are charted on a negative planning map. Examples of unsuitable zones include areas of protected groundwater, dwelling zones and natural preserves. Framework conditions include access roads, size and topography. Later, sites from the preliminary elimination are roughly reassessed in relation to other framework conditions such as distance to dwelling areas etc. Finally, remaining sites from the general assessment are re-examined. At this point, special investigations, such as load-carrying capacity and/or geological surveys, are conducted. Assessment of the engineering qualities of the subsoil is important in deciding whether the substratum and the surroundings offer long-term stability. Swamps and marshland are not suitable for state-of-the-art landfill construction. The immediate surroundings of the landfill should also be protected and shielded from emissions generated by the waste until it no longer poses a threat to the environment. This is why the 3-barrier concept is necessary.

A Sample of Assessment Criteria:

Criteria	**Degree of Suitability**		
General evaluation	***Good***	***Medium***	***Bad***
1. Road access outside of dwelling areas	Available	Construction of detour possible	Construction of detour impossible
2. Situation relative to water preserves and key aquifers	Outside of groundwater areas	On the margin of a groundwater area	Inside recharging area of natural supplies for potable water
3. Distance from the drinking water catchment in the undercurrent	Larger than 2 km	1 to 2 km	Less than 1 km
4. Subsoil	Impermeable	Partially permeable	Void, permeable
5. Distance from next agglomeration of dwellings	Larger than 2 km	1 to 2 km	Less than 500 m
6. Disturbance of local amenity	Slight	Limited	Great
7. Quantities of rainfall	Small	Medium	Large
8. Distance from surface waters	Larger than 2 km	Larger than 500 m	Adjacent
9. Type of landfill	Hill Landfill	Slope landfill	Valley / Pit landfill
10. Suitability for agriculture or forestry	Bad	Limited	Good

‘Positive Planning’ Requirements:

	Landfill for Inert Waste	Residue or Mono Landfill	Reaction Landfill
Geology (natural barrier)			
Only slight permeability of subsoil $k_f < 1x10^{-7}$ m/s min. 5 m layer thickness or equivalent	☒	☒	☒
Hydrology			
No contamination of aquifers for potable water	☒	☒	☒
Sealing (engineered barriers)			
1. Base liner system		☒	☒
2. Lateral liners		☒	☒
3. Topsoil		☒	☒
Drainage (natural gradient drainage)			
4. Base drainage with flushing	☒	☒	☒
5. Leachate drainage control	☒	☒	☒
6. Leachate treatment	Depending on contamination	☒	☒
Gas recovery			
7. Active recovery by extraction			☒
8. Flaring of landfill gas (flare)			☒
9. Utilization of landfill gas			desirable
Operation			
10. Fencing, convenient working hours	☒	☒	
11. On site verification procedures	☒	☒	☒
12. Weighing of waste		☒	☒
13. Professional staff, permanently present	☒	☒	☒
14. Monitoring of volume and settlement	☒	☒	☒
15. Site manual		☒	☒
16. Periodical monitoring of groundwater and leachate	☒	☒	☒
17. Periodical monitoring of landfill	when required	☒	☒
18. Annual reports with documentation of incoming waste and the checking and verification procedures	☒	☒	☒

3.5 Landfill barriers

Residue and Reaction landfills need to be sealed off by barriers on the base and the flanks. The sealing has to preclude long term seeping of leachate into the groundwater.

3.5.1 Subsoil

The subsoil represents the main barrier of a landfill, which is actually the long term insurance, precluding a diffusive transport of emissions from the waste into the environment. Ideally the subsoil should be:

- stable and unaffected by settlement
- not exposed to avalanches, landslides, erosion, flooding or other natural hazards
- have a low hydraulic conductivity ($k_f < 1$ x10E^{-7} m/s at depths of 5 – 10 m)
- material with good adsorptive capacities
- should not be a supplier aquifer of potable water and should have sufficient distance to upper current and lower current
- have undergone hydrological investigations and groundwater assessment

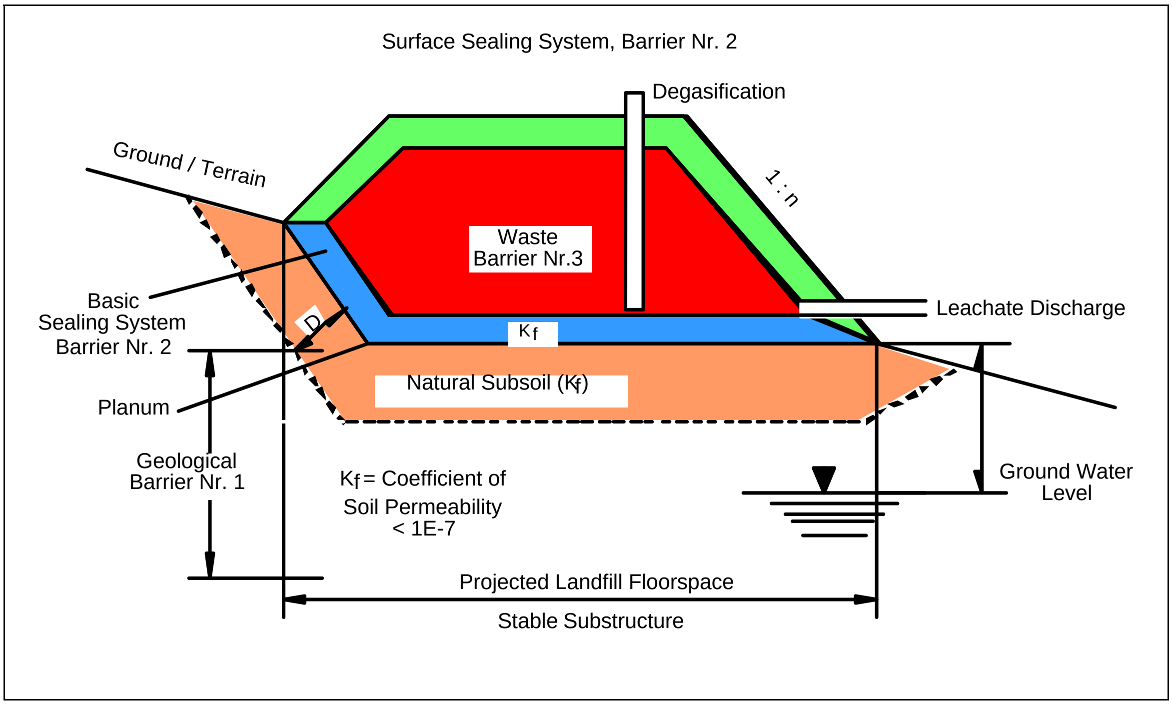


Figure 28: Barrier system – landfill lining. Source Rytec AG

3.5.2 Base and lateral liner system

The **base liner** system is the technical barrier over which the leachate can be drained. Below the liner, there is a monitoring drainage system in order to assess the permeability. The engineered liner has to guarantee long-term impermeability, with the following features in particular: High level of long-term effectiveness; resistance against chemical and biogenic corrosiveness of leachate at high degrees of contamination and varying mechanical stress and strain – especially during construction, operation and aftercare. It should be flexible; of non-toxic material, without external contaminants from liner degradation; have constant levels of quality and security during preparation and positioning over the entire surface; resistant to weathering, thermal variation and UV beams from sunlight; non-flammable, fire-resistant as far as possible; resistant to rodents; easy to monitor and repair; a short as possible construction time with great surface yields per working day; resistant to exposure; stability on slopes and possess a covering without qualitative loss on gradients up to 1:1.5.

It is important that all technical barriers are shaped with a gradient. Technical barriers featuring a gradient of about 5% drain the leachate better and are more resistive to differential settlement. Furthermore, the gradient precludes leachate build-up. The water gradient should not bear directly on the base, in order to limit damage at leaky points.

Examples of liner systems:

Purely mineral liners consist of 0.8 m mineral liner in 3 – 4 layers monitored under optimal conditions, with average conductivity $k_f < 10E^{-9}$ m/s. Quality control should be handled according to a predefined programme. The mineral barriers are produced from specially moulded and consolidated natural clay or bentonite enhanced soils.

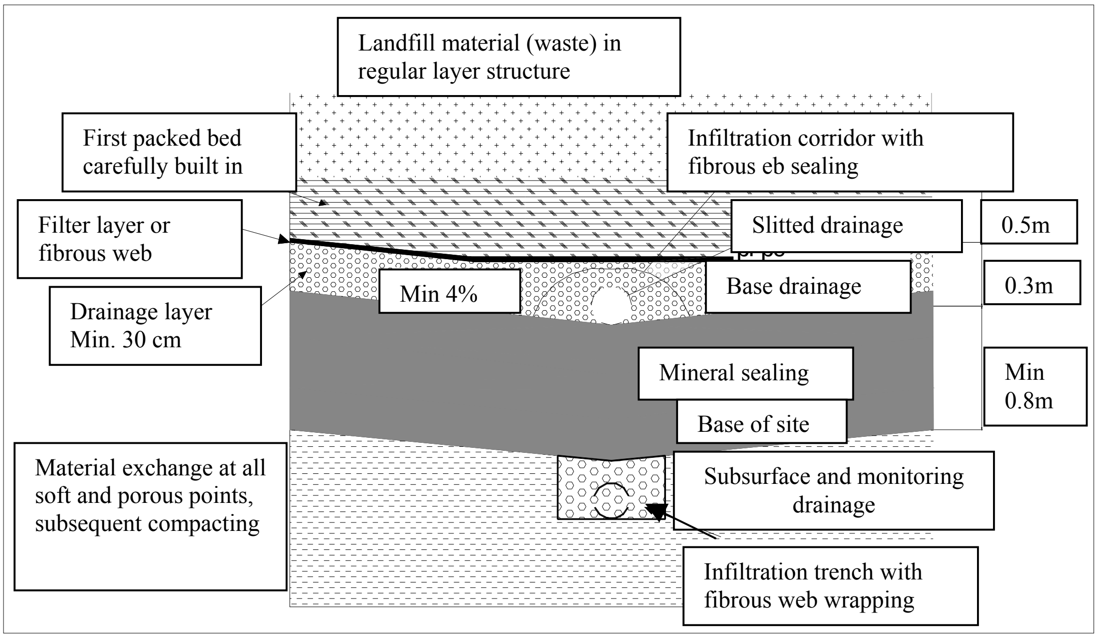


Figure 29: Schematic structure of a mineral liner. Source: Rytec AG

Composite liners: the schematic structure for this system is similar to the mineral liner, except that the mineral liner is in two layers reaching 0.5 m and capped by a liner of high-density polyethylene foil of at least 2.5 mm. The mineral and synthetic liners should form a compound. Before the drainage layer, there is a layer of protective fibrous web. The laying of the foil demands great skill. Specially trained staff as well as a quality control mechanism is recommended.

An asphalt-enhanced concrete liner is similar to the mineral liner, except that the first 0.3-0.5m from the base is packed with a granular stabilizing layer. Then there is the asphalt concrete layer of 0.08m over an asphalt binder layer of 0.07m. This system is popular as it offers many advantages, such as short construction time and resistance to exposure when under construction. However, it is very demanding in terms of technical application, logistics and infrastructure. With this type of liner system, gravel-pits and asphalt processors also have to be available at a reasonable distance from the landfill. The subsoil has to be compacted in such a way so as to minimize expected external settlement. The positioning of the liner has to be accompanied by constant monitoring in order that the required standard is met. Special care has to be applied when sealing the joints resulting from the interruption of work.

Lateral liners have the same function as the **base liners**. They have to be adapted to the gradient of the slope. The lateral liners require careful design and planning and the professional skill of the planner in order to achieve the following: Sufficient slope stability and stable structuring; sufficient subsoil compaction; imperviousness equal to base layer; protection of foil and mineral liner until completion and sufficient fixation and appropriate foil storage.

3.5.3 Capping

Capping protects against infiltration while in reaction landfills it hinders the uncontrolled escape of gas. The gas generated below the capping has to be collected and drained. The persistent avoidance of water penetration from the surface also limits the potential leakage on the sides, especially with synthetic and asphalt liners, which become permeable over time.

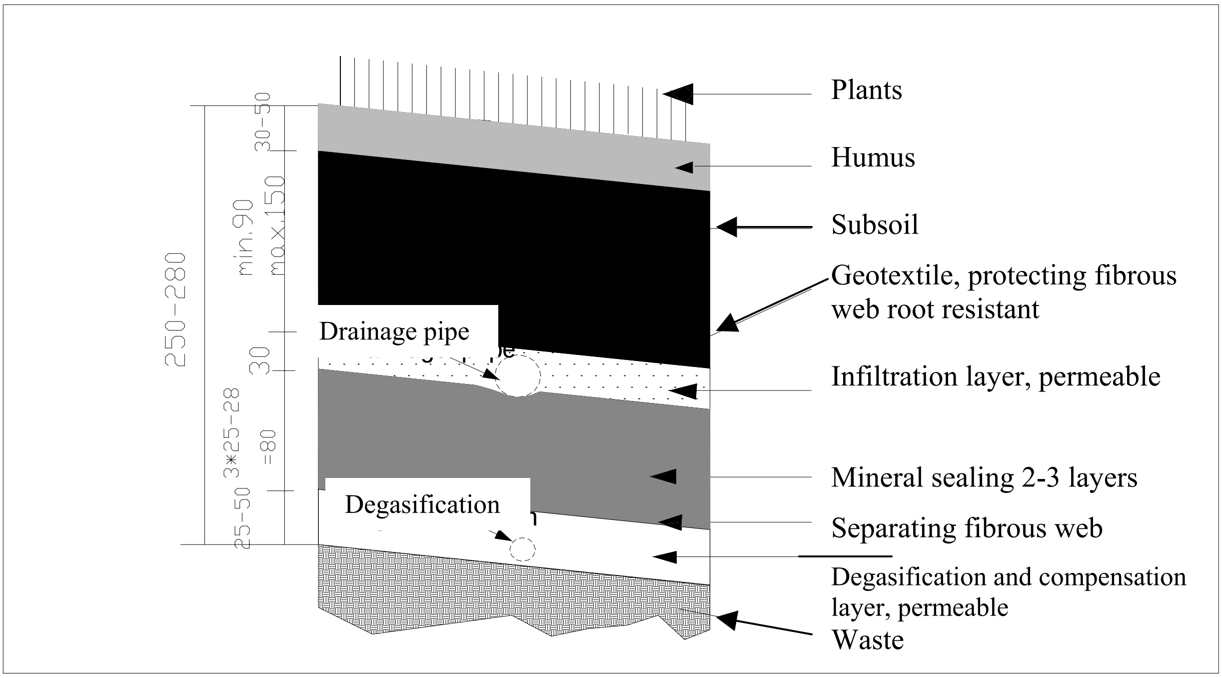


Figure 30: Schematic structure of mineral capping. Source Rytec AG

Because of different settlement of the deposited waste, material capping must be in place after settlement has ceased, especially in reaction landfills, as the decomposition process takes years. Furthermore:

- the liner system has to be flexible, resistant to residual settlement without suffering damage;
- Critical positions with differential settlement have to be monitored through intermediate capping and pre-loading with soil layers, the settlement has to be accelerated before constructing the definite capping;
- the greater the imperviousness of the liner, the lower the quantities of leachate;
- the modeling of the surface has to offer a maximum gradient so as to preclude the formation of drainage pits or strong shear cracks; at shear zones the lining has to be reinforced;
- vegetation may be replanted on a topsoil layer of sufficient strength.

3.6 Leachate

Almost all significant water pollution originates from the uncontrolled seepage of leachate into the subsoil and thus into the groundwater or a source. Surface water bodies can be also strongly pollute by the introduction of leachate often resulting in fish death.

3.6.1 Quantities

Rainfall has the main impact on leachate quantities. It is therefore better to refrain from construction of a landfill in a region with abundant precipitation. The material flow across a reaction landfill involves water from waste (WC) going into the landfill and subsequently stored; precipitation (P), some of which is stored and the rest evaporated (E); there are also landfill gas emissions (GE) and leachate drainage (L). The quantities of leachate per m^2 can be calculated with the following formula assuming: no seeping into the subsoil or through the capping, impermeability of the base liner, precipitation of 1000 – 2000 mm per year and no water retention by waste. Thus;

$$L = P + WC - (E + GE)$$

A practical case involving leachate quantities of 0.15 – 0.2 l/s ha at 1000 mm annual precipitation onto an open landfill resulted in 4000 – 6000 m^3 / ha / year or 13 – 18 m^3 / ha / day. It is important to have no discharge into the landfill from the sides. Higher water content increases the quantity of leachate. In order to facilitate better leachate forecasts, data on precipitation by area and region must be obtained.

3.6.2 Composition

Water supply, gas generation and leachate contamination are interdependent and are subject to great variations throughout the life span of a landfill. Leachate contamination, specifically, originates from the chemical processes inside the landfill, the leaching and the erosion of the discarded material or the storage capacities of the landfill body.

3.6.2.1 Leachate from inert landfills

Leachate can be discharged into the effluent stream. Only material with low reactivity and small amounts of mobile contaminants are acceptable. The leachate has to be periodically monitored for contamination. Occasionally, higher contamination occurs if construction waste is not built-in properly or if different types of material and leachate react together. This is often caused by heightened contents of organic material. Problems may also occur when silts are not built-in with the necessary precaution and overflow or are eroded. Clay sediments entering the effluent stream can seal the streambed or, as a turbid current, congest fish gills.

3.6.2.2 Leachate from mono landfills

Slag generates salty leachate but the contents of organic substances are a factor as the burnout is not complete with state-of-the-art incineration techniques. The contamination of leachate varies according to the setting process that demands a fixed quantity of water. For example, the contamination inside a mono landfill of slag consists of 1,000 mg/l COD, 500 mg/l Ammonium ($NH_4 - N$), 5, 000 mg/l Chloride (Cl) and 1,000mg/l Sulphate (SO_4).

3.6.2.3 Leachate from reaction landfills

At the stage of methane generation (segments older than 1 year), substances that are not easily degradable as well as ammonium and nitrogen compounds, remain in the leachate. Contamination varies significantly according to the season and throughout the operation period. For example, the leachate composition of a reaction landfill is 3,000 mg/l COD, 1,500 mg/l Ammonium (NH_4 – N), 2,000 mg/l Chloride (Cl) and 100 mg/l Sulphate (SO_4).

3.6.3 Collection

Leachate is collected from the landfill base into a drainage network bearing a natural gradient of at least 2%. Build-up at the base, behind the drainage or inside the landfill body has to be avoided. Air must not enter the drainage systems. This is to avoid organic decay and congestion. Pipes must be siphoned with a precipitation receptacle.

To reduce leachate quantities, the following precautions should be taken:

- Landfill should be divided into segments
- Surfaces not yet in use should be connected to separate clean water drainage.

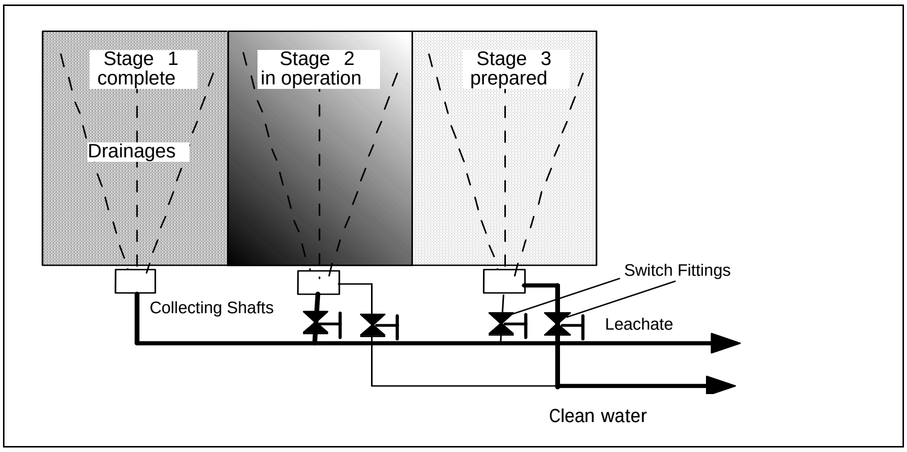


Figure 31: Leachate management (hill landfill). Source: Rytec AG

- Completed surfaces have to be covered with a temporary liner and later capped. The surface run-off has to be discharged into the clean water drainage network over a natural gradient. Vegetation should be planted on the surface.
- All external discharge must be collected and drained separately.

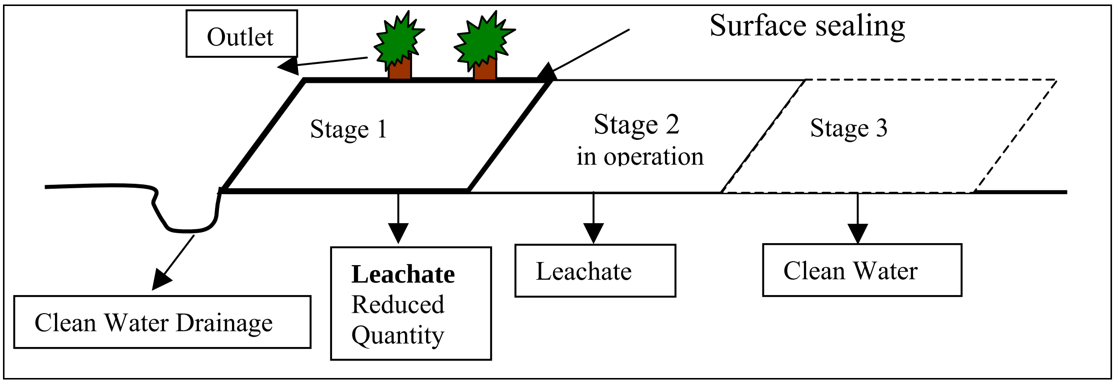


Figure 32: Segmentation on completed landfill segment. Source Rytec AG

The drainage on top of the sealing consists of good impermeable drainage and a filter layer over the landfill base sealing and on the flanks; special protection layers, such as fine sand or geo-membranes can be used to prevent early congestion of this filter. The drainage pipes must be pressure resistant. Regular exterior flushing (200m) should be carried out with specially designed high-pressure cleaning lances and the pipes should be embedded in a small trench filled with coarse gravel for drainage when the pipe is damaged.

3.6.4 Treatment

Because of the complex and high load of contaminants in the leachate, it must be treated and purified before being discharged into the effluent stream. Certain fixed critical values have to be respected, which are prescribed by the state and local authorities. As leachate is a complex mixture of salts and organic substances it cannot be purified in standard sewage treatment plants. Discharging leachate directly into the sewage treatment plants without pre-treatment is therefore not recommended.

Previous experiences with the treatment of leachate show that, the performance of a single process is mostly insufficient to meet regulations. Normally, a combination of several single processes is required.

3.6.4.1 Biological processes

Biological processes for leachate purification take advantage of the natural capacities of microorganisms to integrate organic and inorganic contaminants into their metabolism, degrading or just adsorbing them. The dead bacteria containing the contaminants, subsequently become sewage sludge that must be specially treated.

It is normal for biological treatment processes to be the first stage of treatment and in some cases the only stage of treatment.

Anaerobic biological pre-treatment

This process can reduce the high COD and BOD concentrations. Normally the concentrations of the effluent are between 1,000 to 10,000 mg/l COD. Thus a secondary aerobic biological treatment process is necessary to further reduce the COD. At the same time the heavy metals settle in the anaerobic sludge, which is usually dewatered and disposed of on a landfill. The organically fixed nitrogen compounds are set free into the water as NH_4-N contributing to increase the waste pH value. Methane can be used for energy production, or should be burnt by a flare to avoid releasing this gas to the atmosphere. Methane gas is a higher contributor to the greenhouse effect.

The use of external anaerobic reactors as well as the integrated anaerobic processes inside the landfill (use of a landfill sector as an anaerobic reactor) is essentially combined. Anaerobic reactors have been used for many years in the form of anaerobic fixed-bed plants and UASB (Up-flow Activated Sludge Blanket) reactors both in the USA and in Europe. In the UASB reactors the biomass is enriched by gravity. The use of external anaerobic process for waste treatment is efficient to reduce the initial high organic load of the leachate, but less useful when the stable methane phase in the landfill is reached, because anaerobic digestion within the landfill site has already occurred. It should be noted that the reactor can be used later either as a leachate storage basin or as an aerobic aeration tank.

The landfill itself can be operated as an anaerobic bioreactor. This is done by recycling leachate over an almost degraded waste layer (e.g., composted waste) at the landfill base. With this “leachate optimized” landfill operation, the leachate from the above layer is anaerobically treated.

When designing a plant, the following parameters should be considered:

- Hydraulic retention time: Minimum of 3 days
- COD load of the sludge: 15 kg/m^3 /d (depending on the chosen process)
- Temperature: Operating temperature of about 30°C should be ensured by subterranean and covered storing basins and thermal insulated reactors. Biogas recycling is useful to reach the necessary temperature, especially in wintertime.
- pH-value: About 7.5 to 8.5.
- Biogas production rates: 0.3 to 0.35 Nm^3 CH_4/kg COD degraded with a methane content of between 65 and 85%, so that preventive explosion protection has to be considered in all parts of the plant.
- Excess sludge: 0.05 to 0.15 kg TS/kg COD degraded

Anaerobic treatment is very sensitive to changes of temperature, pH and load due to the needs of the bacteria. It is difficult to keep these parameters under control as the quality and quantity of leachate are constantly changing. Equalizing basins and quality control at the inlet may improve the conditions.

Aerobic biological treatment

This can reduce the biologically degradable COD and BOD compounds. When designing an aerobic nitrification process, the denitrification should also be considered so as to reduce the nitrogen content.

The design criteria of nitrogen degradation should include temperature, the age of the sludge, the pH-value and the oxygen concentration. In the **nitrification** process ammonium nitrogen is oxidized under aerobic conditions via nitrite nitrogen to nitrate nitrogen. In the **denitrification** step the nitrate nitrogen is converted under anoxic conditions to molecular nitrogen. A biological pre-treatment plant that is designed for nitrification and denitrification will have a stable pH-value in the effluent (6.5 to 7) and a decreased buffer effect of the leachate.

In Europe conventional biological treatment systems are not often used to treat leachate because of the large space required and the considerable amount of excess sludge to discharge. Due to the high organic load of the leachate, biological processes with large biomass concentrations are preferable.

Membrane bioreactor systems are often used where there are further physical/chemical processes. In this process the suspended biomass is separated from the biologically treated leachate by micro or ultra filtration, which enables the plant to operate effectively and also increases the efficiency of the following steps.

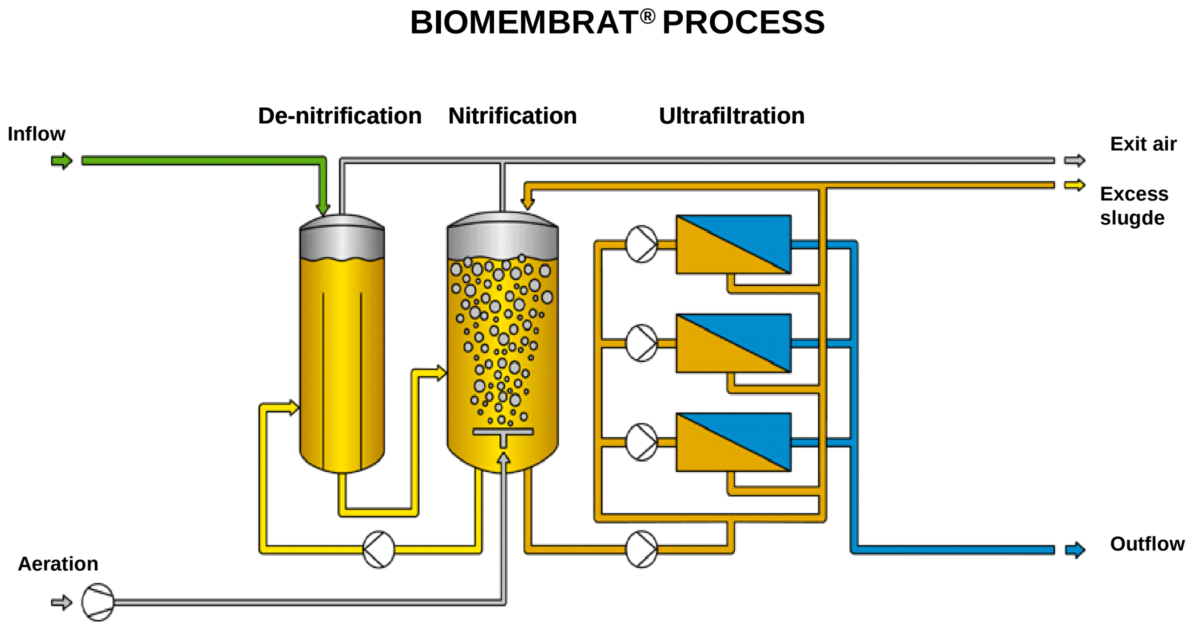


Figure 33: BIOMEMBRAT® Process

SBR (sequence batch reactor) plants are also used, in cases where there is only a single biological pre-treatment step prior to a municipal sewage treatment plant. A suitable method of solid removal after the biological stage must be considered if there are to be further treatment steps.

3.6.4.2 Chemical processes

Chemical oxidation (O_3, H_2O_2)

Chemical oxidation with ozone (O_3) or peroxide (H_2O_2) enhanced by ultraviolet radiation was mainly developed for the purification of drinking water but has also been applied to leachate treatment. Using this process the components that are not easily biodegradable and the organic contaminants contained in the water are turned into carbon dioxide and water or low molecular intermediate compounds (carbonic acids). However, salts remain in the purified water (inorganic contaminants are not degraded).

Ozone has to be produced on-site from dry air or oxygen. When produced from air 2-3 vol-% ozone can be reached; while from oxygen up to 25 vol.% is attainable. Oxygen operated ozone plants are normally used in the landfill leachate sector. Hydrogen peroxide can be bought and is fed in as a 30 to 50 % solution into the leachate. The reactive hydroxyl radicals have to be produced directly in the process under ultra violet (UV)-radiation, in the presence of bivalent iron, or by combining ozone and hydrogen peroxide. The usage of UV treatment has declined due to the high turbidity of the leachate.

The treatment of non-biologically pre-treated leachate with chemical oxidation cannot be recommended due to operating problems (e.g., formation of foam, precipitation of high calcium contents, etc.).

This procedure is rather costly. However it shows some economic advantages because the outflow is free from residual materials.

Flocculation and precipitation

Flocculation and precipitation is used for the removal of organic matter, metal compounds, and ammonium contents in the leachate. Flocculation occurs when finely dispersed and suspended substances (colloid or emulsified) are destabilized with the help of a flocculating agent and are conducted into a state where separation is possible. Precipitation occurs when ions in solution react chemically with the added precipitation agent entering into non-soluble chemical compounds and thus being precipitated from the solution. Metal salt polymers and hydrated lime are used as flocculation agents. The insoluble solids that have formed are taken out of the effluent by filtration or sedimentation.

This process can be recommended as a downstream process stage after biological treatment in view of the fact that the more effective the process is, the lower the BOD/COD ratio is in the effluent (ideal is BOD/COD <0.1). However, the use of this process in Europe is declining because of the relatively poor cleaning performance (i.e., COD removal of approx. 50%) and the heavy accumulation of the sludge.

3.6.4.3 Physical processes

Membrane process

Membrane processes physically separate the liquid flow (feed) into two flows: The filtrate, which passes through the membrane (permeate) and the retained concentrate with most solid contaminants. The level of the depletion or concentration depends on the retention capacity of the membrane. Different types of membrane processes are used in leachate treatment.

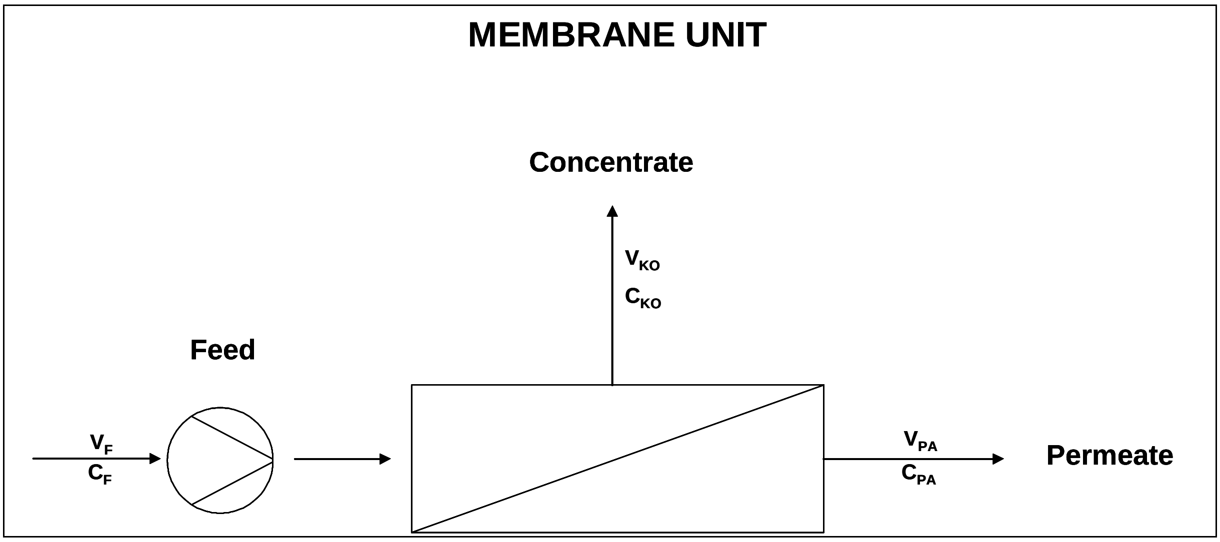


Figure 34: Membrane Unit

- Micro- or ultra-filtration: This is used to separate solid materials from the raw leachate and to separate biomass with an aerobic biological process, through porous membranes under the pressures of 0.2 to 10 bar.
- Nano-filtration (NF) is a further suitable step after an aerobic biological process to hold back COD and heavy metals, but not nitrogen. The attainable permeate yields are between 85 and 90%. NF is not suitable for use in untreated leachate because low-molecular-sized biologically degradable materials still need to be removed from the permeation. The pressures amount to 35 bar.
- Reverse Osmosis: This process meets the strict demands of the treatment requirements even without biological pre-treatment. The attainable permeate yields are between 60 and 75%. Reverse osmosis provides a good retention of nitrogen. Low-molecular biologically degradable materials are held back in the concentrate. Two stage processes must be taken to treat the previously untreated leachate. The permeation from the first stage (i.e., the separating out of the matter with the largest module size like Tubular or plate Modules) is then treated again in the second stage (i.e., the separating out of the matter with smaller module size). Reverse osmosis needs pressure of up to 75 bar. For further reduction the concentrate is further pooled by osmosis with a higher pressure of up to 200 bar.

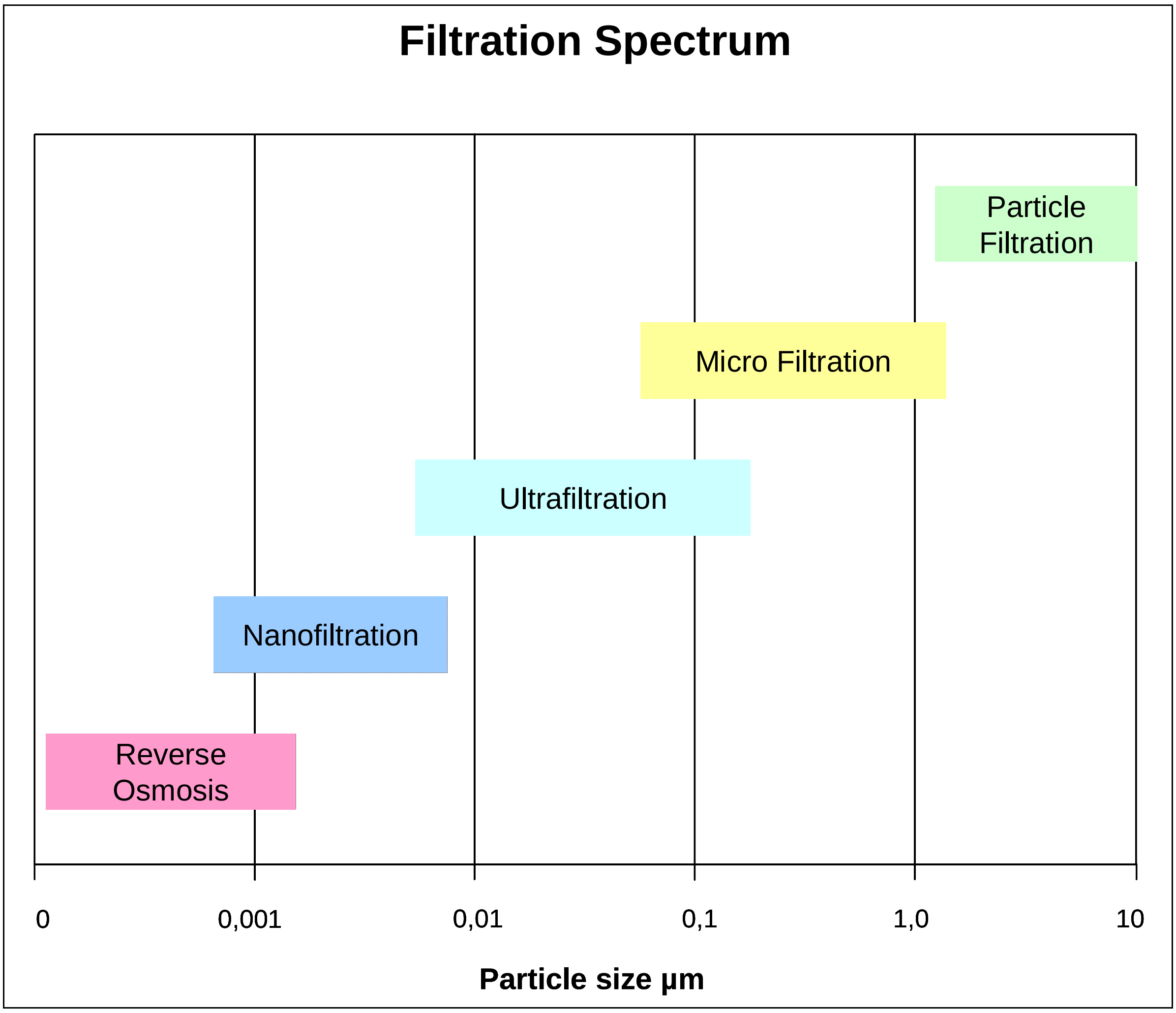


Figure 35: Filtration Spectrum

The disadvantage of membrane processes is that the concentrated matter has to be disposed of. The concentrates from nano-filtration can be treated by chemical oxidation or active carbon adsorption as well as flocculation and precipitation. The concentrates from the reverse osmosis process can be treated with evaporation or high-pressure reverse osmosis with downstream vaporization and drying. The solidifying of concentrates with binding agents can also be partly achieved.

The return of the concentrate into the heart of the landfill is not allowed in all countries in Europe. This would create environmental problems, namely that the salts and nitrogen compounds would be enriched in the leachate and the operation of a supersaturated plant would finally be brought to a standstill.

Stripping

For all dissolved and volatile contaminants such as ammonia, low-molecular hydrocarbons, etc. the process of air stripping can be applied. 80 to 95 % of the ammonium nitrogen can be eliminated with influent ammonium concentrations of 1000 mg/l.

The principle of stripping is to regenerate ammonia by a gas current in counterflow to the leachate. In order to do this the disassociation equilibrium between ammonium and ammonia in the leachate has to be shifted to favour gaseous ammonia by increasing the temperature and pH level. The ammonia loaded gas current is recycled after having been regenerated (elimination of the ammonia), and the ammonia is converted into a recoverable material. The following processes can be used:

- Acid washing (product: ammonium sulphate)
- Catalytic oxidation (product: elementary nitrogen)
- Rectification (product: ammonium water)

The concentration of highly volatile COD and BOD in the leachate must be taken into account as these can lead to offensive odours.

3.6.4.4 Chemical physical treatment

Activated carbon adsorption

The field of application of activated carbon adsorption is the same as that for chemical oxidation.

Adsorption is a separation process by which the particles contained in the leachate, which is to be disposed of, are captured on a surface made up of solid matter (i.e., an adsorbent). Activated carbon, which can be reactivated externally, is a predominant adsorbent for the removal of non-polar aluminium oxide compounds and non-polar COD (chemical oxygen demand) creating matter in the leachate.

Two alternatives can be used – downstream processing using active carbon adsorbents or the direct addition of activated carbon in the biological cleaning stage. However for leachate, this method is merely used for final purification from non-readily degradable organic substances.

Adsorption columns filled with activated particles of carbon (APC) or, alternatively, adsorption tanks, are used. Up to five adsorbers in series are usually brought on stream. The activated carbon in the first adsorber is filled up to the maximum height of loading. The discharge quality in the final adsorber is guaranteed by the downstream adsorber. If the final adsorber meets the discharge limit value, the activated carbon is taken out of the first adsorber and replaced by regenerated activated carbon. This adsorber is then switched over at the end of the row of adsorbers, so that the second adsorber, already partly laden, is moved into the position of the first. This rolling serial switching principle has proved successful in many landfill leachate plants.

Ion exchange

In ion exchange, on the surface of particular solid particles (called ion exchangers), the ions, which are bonded in active groups, are exchanged for other ions from one of the ion exchanger's overflowing liquid phase, for example, the leachate. The active groups have an acidic or basic character. The former exchanges cations and the latter anions. A possible field of application for an ion exchanger is the reduction of a high heavy metal concentration.

3.6.4.5 Thermal treatment

Vaporization with desiccation

Vaporization of leachate is the latest treatment procedure. Forced circuit vaporizers run at gradually increasing pressures and temperature levels. The vapours are then condensed and treated as condensed water in the municipal sewage plant. The final product is a mixture of powder and crystals that can be packed and disposed of in deep mine landfills. Vaporization is very energy-intensive but can be run with residual heat at low temperatures. Based on experiences in Europe, this process cannot be recommended without reverse osmosis.

Incineration

For reasons of economic and energy policy, direct incineration of leachate is not desirable. When the condensed water from the vaporization of leachate is incinerated, the organic compounds can be destroyed. The remaining residues are inorganic salts contained in the slag and the fly ash, which are disposed of in a landfill. But incineration has not become a commonly accepted method of leachate treatment.

3.6.4.6 Possible process combinations

Based on the relevant data about the leachate and the site, different combinations of the treatment technologies can be selected. Generally these can be classified into four main groups. The combination of processes listed here, however, does not cover all the process technologies available in the market.

- Biological treatment with downstream activated carbon adsorption or, alternatively, chemical oxidation.
    - Possible anaerobic pre-treatment.
    - Biological aerobic treatment.
    - Segregation of activated sludge by sedimentation (if necessary with downstream filtration) or ultra-filtration.
    - Physical or chemical treatment for the continued segregation of the organic pollutants (i.e. activated carbon adsorption or chemical oxidation).

- Biological/nano-filtration with physical/chemical treatment of the concentrates or concentrate re-circulation.
    - Possible anaerobic pre-treatment.
    - Biological aerobic treatment.
    - Segregation of the activated sludge by sedimentation or membrane filtration.
    - Further concentration by means of nano-filtration, draining-off the permeation (=> nano-filtration = final stage).
    - Treatment of the concentrate by means of activated carbon adsorption or oxidation and re-circulation into the body of the landfill, if necessary even without physical chemical treatment.

- Reverse osmosis with concentrate treatment
    - Possible anaerobic pre-treatment.
    - Nitrogen removal by stripping.
    - Subsequent two stage osmosis plant, (with permeate to direct discharge).
    - Concentrates possibly returned into the body of the landfill.

  - Concentrate treatment by means of evaporation and/or, for example, high-pressure reverse osmosis, and drying and consolidation.

- Biological treatment/reverse osmosis/treatment of the concentrate
  - Possible anaerobic pre-treatment
  - Biological aerobic treatment.
  - Segregation of the activated sludge by sedimentation or membrane filtration.
  - Subsequent two stage osmosis plant, (permeate to direct discharge).
  - Concentrates possibly re-circulated back to the body of the landfill.
  - Concentrate treatment by means of evaporation and/or, for example, high-pressure reverse osmosis, and drying or consolidation.

3.6.4.7 Design and operation considerations

3.6.4.7.1 The criteria for the selection of a process

Economic efficiency
Economic efficiency will usually be the first consideration when deciding which process or process combination to select.

Quantity and composition of the leachate
In addition to design load and design quantity, flexibility must be retained, given the development over time of the quantity of leachate and its composition, which is influenced by the changes of waste quantities and landfill operation, etc.

Requirements for the discharge of leachate
At the start of the design stage, clarification must be obtained whether the cleaned leachate is to be discharged into a drainage ditch (i.e. direct discharge) or into a downstream sewage treatment plant (i.e. indirect discharge). It would appear in the case of anaerobic pre-treated or lightly laden leachate (COD < 5,000 mg/l, NH_4-N < 1,500 mg/l) that the process combination of biological treatment and activated carbon is predominantly the most economic solution both for indirect discharge and direct discharge. At present in Europe, this preference only applies for heavily laden leachate destined for indirect discharge. In the case of direct discharge it must be studied in each individual case, which of the above mentioned process combinations are best placed to achieve the required discharge values, incurring least expenditure and with the greatest efficiency.

3.6.4.7.2 Disposal of residual materials

The majority of cleaning processes produce residual materials, which must subsequently be treated and disposed of in a landfill. In the following table an overview of the common processes is given in this respect.

<table>
<tr><th></th><th>sewage plant
COD < 400 mg/l</th><th>water body
COD < 200 mg/l</th><th>water body
Salt reduction</th></tr>
<tr><td>low loaded
COD< 2.000 mg/l
NH4-N< 500 mg/l</td><td>sand filtration
activated carbon</td><td>aerobic biology
chemical oxidation or
activated carbon</td><td rowspan="2">reverse osmosis</td></tr>
<tr><td>medium loaded
COD< 5.000 mg/l
NH4-N< 1.500 mg/l</td><td rowspan="2">aerobic biology
chemical oxidation or
activated carbon</td><td rowspan="2">aerobic biology
nanofiltration
activated carbon</td></tr>
<tr><td>high loaded
COD< 15.000 mg/l
NH4-N< 3.000 mg/l</td><td>aerobic biology
reverse osmosis</td></tr>
<tr><td>extremely high loaded
COD< 60.000 mg/l
NH4-N< 5000 mg/l</td><td colspan="2">anaerobic biology
aerobic biology
nanofiltration/activated carbon</td><td>anaerobic biology
aerobic biology
reverse osmosis</td></tr>
</table>

Table 10: The key operating methods, the residual materials arising from the processing and also the necessary subsequent treatment stages of various processes for the treatment of leachate

Only chemical oxidation and stripping with catalytic oxidation of the exhaust air produce end results that are virtually free from residual materials.

3.6.4.7.3 Supply of auxiliary agents

The essential details of the chemicals and additives used in different processes can be found in Table 2. The use of auxiliary agents should be minimized as far as possible so as to limit residual materials and costs.

3.6.4.7.4 Energy requirements and supply costs

Depending on the process, electrical power and thermal energy for heating will be required. For activated carbon adsorption, the regeneration outside the landfill requires additional quantities of energy. The possibility of use of available waste heat or electrical power should be taken into account.

3.6.4.7.5 Operational safety

Operational safety requires that in the case of a plant breakdown, no leachate should be discharged.

3.6.4.7.6 The possibility of using centralized plant solutions

If leachate treatment plants have to be designed for several landfills, all possibilities should be investigated, from decentralized treatment to centralized treatment on one site. An interim solution could be, for example, further concentration of the leachate before transporting it to a common treatment plant. The decision is dependent on many factors specific to the site, for example, the available space in individual landfills.

		anaerobic treatment	**aerobic treatment**	**activated carbon**	**flocculation precipitation**	**nano-filtration**	**reverse osmosis**
degraded		**X**	**X**				
concentration				**X**	**X**	**X**	**X**
residual waste		bio. sludge	bio. sludge	wet carbon	sludge	concentrate	concentrate
residual waste inflow	%/m3	1	1 - 5	0,1 - 0,5	0,1 - 0,3	10	10-30
residual waste options		dewatering landfill	dewatering landfill	reactivation or dewatering landfill	dewatering landfill	landfill or physical chemical treatment	landfill or evaporation drying
energy consumption	kWh/	2 - 4	5 - 15	2 - 4	2 - 4	2 - 5	3-8
lime dosing without de-nitrification	kg/m3		0,5 - 3				
lime dosing with de-nitrification	kg/m3		0				
phosphorus acid	kg/m3		0,1 - 0,2				
sulfuric acid dosing without aerobic biology	kg/m3						1,0 - 4,0
sulfuric acid with aerobic biology	kg/m3				1,0 - 2,0	0,5 - 1,0	1,0 - 4,0
activated carbon	kg/m3			1 - 5			

Table 11 The type, quantity and relevance for pollution control of the operating and additive agents used for the different processes in leachate treatment.

3.7 Landfill gas

3.7.1 Generation of landfill gas

3.7.1.1 Generation

Inside a landfill that has been compacted by heavy caterpillars and compactors, microorganisms degrade kitchen, paper and organic residues anaerobically and consequently generate landfill gas. Gas production begins shortly after disposal and may last for decades. Several years' delay is normal for gas generation on old landfill sites. However, it must be assumed that with a sufficient water supply, the available carbon share of the waste body will be recombined into landfill gas. The organic materials in the waste are biochemically degraded in different stages, during which the composition changes. A breakdown of these stages is shown below:\

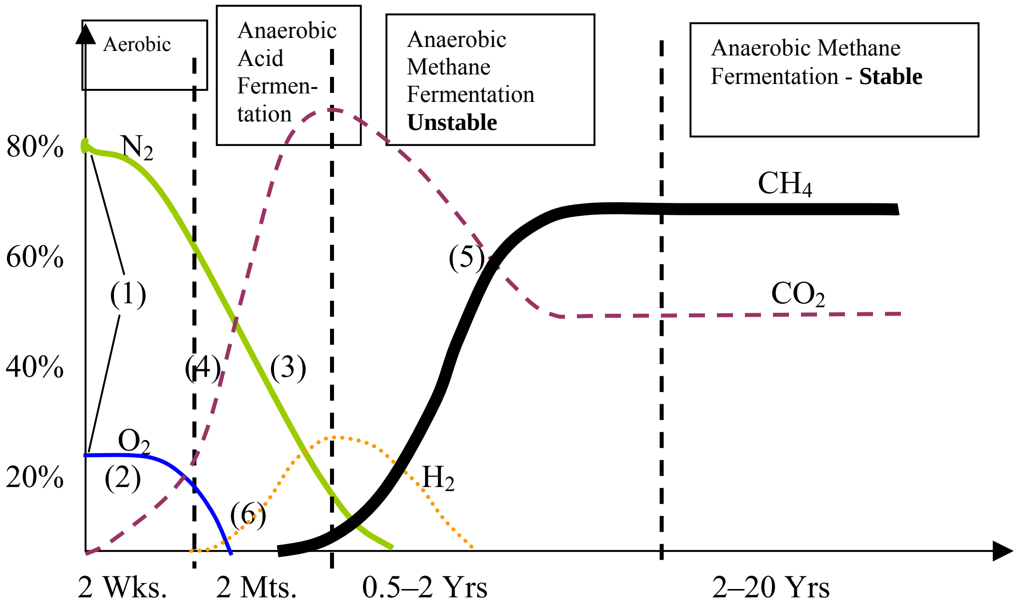


Figure 36: Gas composition during decay of household solid waste (according to Farquar/Rovers)

① Initial concentration corresponding to the composition of air (nitrogen (N_2) 78% / oxygen (O_2) 21%)

② O_2 – decrease: Consumption by aerobic degradation before the outset of acetous fermentation. Leachate is acidic during this phase.

③ N_2 – decrease: Eviction of nitrogen by generated landfill gas

④ CO_2 – increase: Reflects the activity in degradation processes, mainly of the acetous fermentation. CO_2 is the end product of aerobic and anaerobic decay.

⑤ CH_4 – increase / CO_2 – decrease: Visible effect of the activity of methane bacteria

⑥ H_2 (hydrogen): The methane bacteria need H_2 for the production of methane. H_2 is continuously generated during acetous fermentation. During the stable methane phase, methane bacteria continuously consume the newly generated H_2.

Complex, non-quantifiable processes within the landfill (distribution of humidity and nutrients) influence gas production. Theoretically, the gas produced relative to methane content of 55 % reaches its maximum after 12.5 years, ranging from 1,500 – 2,500 m^3/h. After the completion of waste settlement, the easily degradable organic substances have decayed and the gas production can decrease more sharply than initially estimated. Deposited chemical substances can also inhibit the intensity of gas production. Environmental factors that have an impact on landfill gas production include: Temperature, oxygen availability, moisture content of landfill material, pH level, nutrients and refuse particle size; which, in turn, affect the quality of biogas produced.

3.7.1.2 Estimation of landfill gas generation

Future landfill gas production can be calculated using computer software. An important assumption for a realistic quantification of gas production is the correct selection of parameters such as: The share of degradable carbon (nutrient) contained in the waste, waste temperature, waste humidity, type of deposits and possible inhibiting substances. The gas prediction model generally works with the following basic data: Records of the waste quantities during operating years, waste composition and temperature, evaluation criteria and empirical values of the waste; the biodegradable carbon share of the waste as a base value for the total possible quantity of landfill gas per ton of waste; and transformation of the carbon into methane as an exponential function of the first order based on the remaining carbon still to be transformed. According to this, the generation of landfill gas is modelled on the following equation where G (t) = gas quantity per ton of waste; C_o= biodegradable carbon share per ton of waste produced up to the time t; t = time of decay; k = annual constant of decay (taken as 0.03 – 0.05; i.e. the larger part of the decay takes place during the first 10-20 years):

$$\mathbf{G\,(t) = C_o \bullet e^{-k \bullet t}}$$

A simplified formula states:

$$\mathbf{G(t) = 1.868 \bullet C_o \bullet (0.014 \bullet T + 0.28) \bullet 1 - 10^{-k \bullet t}}$$

1.868 = stoichiometric number; T = temp. of 30 – 40 °C mean value); C_o – degradable carbon.

Alternatively, if gas predictions are done using computer software, the following parameters need to be known: T = average temperature inside the waste body (°C); d = loss factor from diffusion (0.75 for a capped landfill/0.50 for an open landfill); mc_o = average share of biodegradable carbon (%); m = average waste quantity disposed of per year (t/a); t = time of operation of the landfill site in years (a); $\rho_{1,2}$ = biological decay time for carbon degradation.

3.7.2 Composition and properties

3.7.2.1 Composition

Depending on the origin and the composition of the deposited waste, a large number of barely traceable gases, such as aromatic hydrocarbons, halogenated hydrocarbons and hydrogen sulphide, are present in the landfill gas. Halogenated hydrocarbons, such as CFHC, cause damage to gas engines as they can be mineralized to form hydrochloric and hydrofluoric acids, which are corrosive. Thus in places where condensate accumulates, only corrosion-resistant materials should be used. Many gas engine operators are confronted with the problem of silicate incrustations on the inside of the motor. This leads to rapid abrasion of the pistons and the cylinders. However, with temperature cooling, down to –20°C, this problem can be resolved. The water vapour content in landfill gas is approximately proportional to its temperature.

Generally, high quality landfill gas contains methane (CH_4) of more than 45% Vol. oxygen (O_2) contents fall below 1% Vol. and the amount of contaminants and trace gases remains below certain limits (e.g., the sum of the halogens is below 100 mg/Nm^3). This makes the landfill gas suitable for electrical power generation with gas engines.

In low quality gas, CH_4 falls below 40% Vol. (min. 25% Vol. should be allowed), O_2 contents exceed 1% Vol. (up to max. 3% Vol. - above this, safety is compromised) and the amount of contaminants and trace gases becomes too high such that the gas can only be burnt with a high temperature flame. Note that one cubic meter (1m^3) of landfill gas corresponds to the calorific value of about 0.5m^{3}natural gas or 0.5l fuel.

3.7.2.2 Points of gas release

The highest gas concentration is found at the edges. It has been observed that the embedding and compaction of waste favour horizontal gas migration far more than vertical migration. In addition, marginal segments are less compacted than the rest of the landfill, thus the radial segments become gas collectors. Attention should be paid to the venting of all marginal segments.

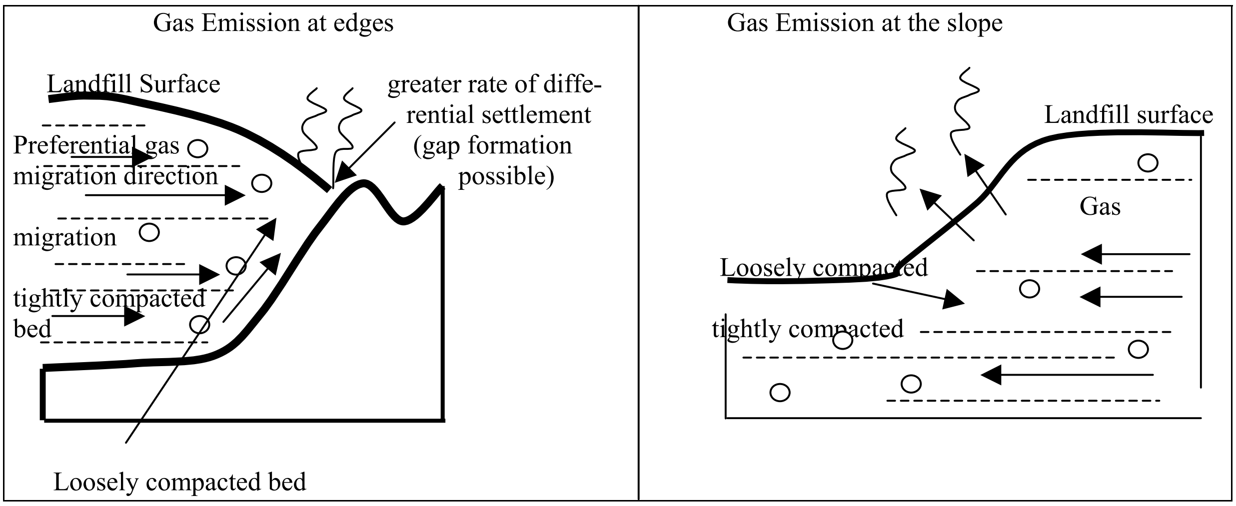


Figure 37: Gas release at the edges and slopes of a landfill. Source: Rytec AG

Unsealed slopes are points of gas release. Therefore, sealing should be done with binding material or bark compost. Generally, all vertical cavities act as gas collectors.

3.7.3 Gas drainage systems

3.7.3.1 Systems

With **passive venting systems**, the landfill gas is drained along special drains such as leachate pipes, trenches and coarse leachate drainage bodies. In landfills with low gas production, passive venting systems are installed below the capping. However, only small amounts of gas are drained with this technique. Depending on the type of capping, a large share of the gas migrates by diffusion. The passive venting system is only suitable for small and old landfills that produce gas in small quantities. As a drawback, gas may enter surrounding buildings without detection. Hence a popular primary measure is the **active gas extraction system**, which uses an internal, mechanically positioned, partial vacuum. Thus a major part of the landfill gas is pumped off via the gas collectors and the drainage system. When sealing and placing the drains and wells, special precautions to avoid air being sucked into the system should be taken. Furthermore the generated condensate should run off freely. The drains and wells have to be designed in such a way so that probing and monitoring is possible.

Monitoring requirements include testing for possible explosive mixtures of air and methane; regular abstraction of the partial vacuum; gas composition; testing for contents of CH_4, pollutants and extracted gas should be submitted to incineration by a flare, in an engine stoke hold, and be mineralized completely; placing a ditch filled with permeable material between the landfill and surrounding buildings as a secondary passive venting measure and a foil reinforcement sealing on the side of the ditch that is away from the landfill.

In general, for each new reaction landfill, the gas extraction has to be designed from the outset. Gas collection and thermal gas treatment can begin six months after the commencement of on-site disposal. The form of the landfill body is subject to constant modification as a result of settlement, operation and daily loading. The facility has to be designed in such a way as to permit its constant adaptation without interrupting the gas extraction and hence posing new dangers.

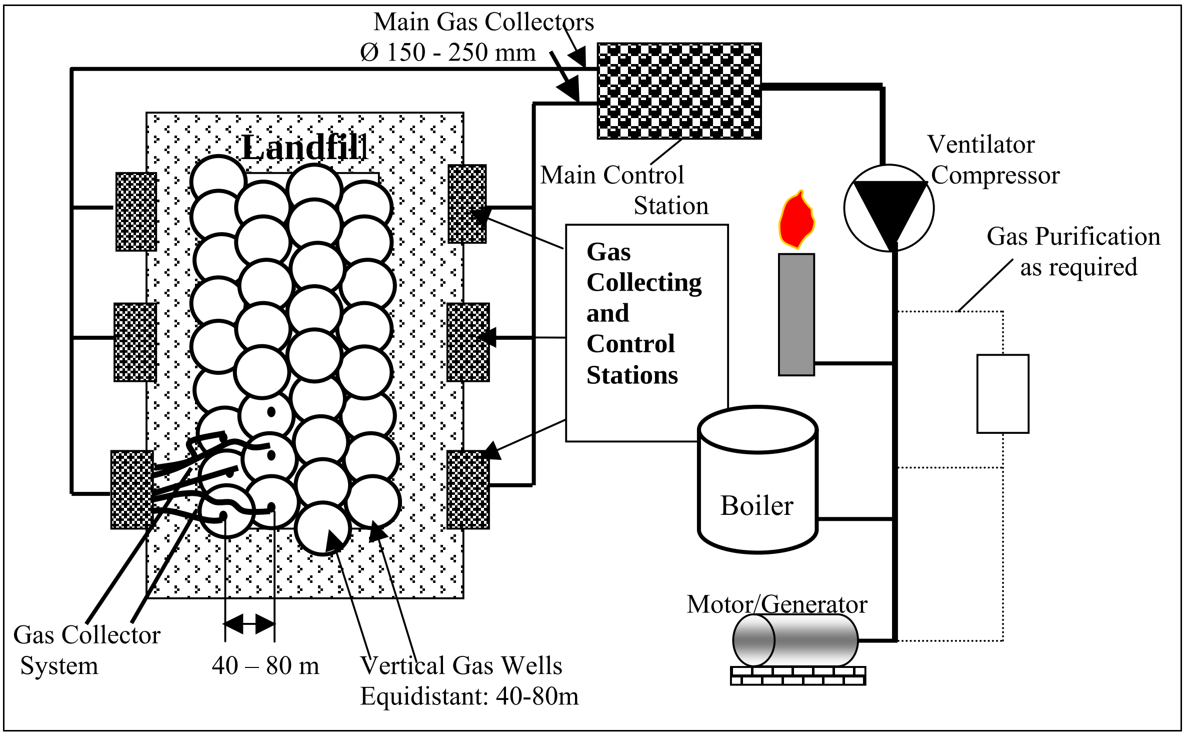


Figure 38 Gas extraction and gas utilization facility

3.7.3.2 Gas collection

Vertical gas wells

For vertical gas wells, a hole about 0.8 m ø is drilled into an existing landfill. Depending on the drilling technique and the landfill, depths of 15 to 30 m can be attained. The drill hole is then filled with non-calcareous gravel for about 50 mm of its length. Generally, alignment distances of 40 – 80 m between the epicentres of the wells are sufficient, but in the marginal segments, the wells should be placed more densely than in the central part of the landfill. It is important that the gas wells can be drained from the base. In special cases, when there is leachate build-up inside the landfill, pumps are integrated into the gas wells, to permit regular pumping-off of the sewage. Horizontal gas drainage systems also exist but tend to silt up easily as it is more exposed to settlement and its drainage area is limited.

Gas-collecting pipes

Each well is connected to the main gas conduit via horizontal gas pipes. The pipes are connected to the main conduits with enough allowance for connecting parts. Preferably, the pipe from each well is extended to the foot of the landfill where it can be separately collected and controlled via a gas-regulator. All pipes should be laid at frost level and protected against sun and UV rays. At the lowest point, the pipes have to be drained with well-dimensioned inlet tubes that are protected against partial vacuums.

Since the landfill gas pipes are inside the range of settlement, there is a risk of water pouches interrupting the gas flow. Landfill gas is very humid and can precipitate up to 50 g H_2O/m^3. Assuming a production of 1000 m^3/h, several hundred litres of gas condensate accumulate daily which needs to be treated with the leachate. Flow velocities of 10m/s are normal, and the diameter of the pipes has to be sufficiently large to withstand such velocities. Preferably, the minimum pipe diameter should be about 80–100 mm, if congestion is to be avoided. HDPE material with wall strength resistance up to 10 bars of pressure has proven to be sufficiently solid. Pipe gradients between 5–10% are recommended so that even with subsequent settlement, water build-up can be avoided. If the main conduits are placed on the border of the landfill on natural ground whenever possible, a gradient of 1–2% is sufficient. The condensate and the gas should always flow in the same direction.

3.7.4 Impacts

The main potential risk of landfill gas comes from methane. In terms of global warming, methane is 20 times more harmful than carbon dioxide. The amount of methane generated globally is estimated at 400–600 d /yr (d = 10^{12} g or 1 million tons); 30 to 70 d are generated by landfills. This is equivalent to an annual increase of 50–60 d. Several potentially toxic effects on humans are known to originate from the different landfill gas components. However, with the concentrations at which they are found in landfill gas, the immediate toxic effects are of secondary importance. Of primary significance are the cancerous effects. The main ecotoxic impact is the supplanting of soil air with landfill gas via gas migration.

3.7.5 Explosion prevention

Gas collected in pits, low ground, basements, wells and trenches through underground migration is potentially explosive. The lower limit of explosive concentration for methane lies at 4.9 %Vol. Thus a 10% mixture of air and landfill gas is already explosive. Methane is odourless; therefore its threat can only be assessed with explosion detectors. Ineffective substructure sealing and/or porous landfill subsoil can assist this underground gas migration. On the other hand, if the subsoil sealing is effective but the capping less so, the gas can be emitted into the atmosphere and any vegetation above the landfill dies off. In either case, a source of ignition such as cigarettes or matches may start a fire or trigger an explosion.

The landfill itself does not produce explosive gas but as the landfill gas is extracted at sub-atmospheric pressure, there is a risk of explosion on the inside of the pipe as well as the entire plant because of the danger of air entering the system. Therefore the whole construction must be designed so as to be resistant to pressure shock (6 bars or more) and measures have to be taken against the introduction of external sources of ignition. Landfills still under operation are especially vulnerable to the entry of atmospheric air. A measurement device must therefore be installed, to preclude the risk of supporting explosive mélanges over longer periods of time. Low quality, unusable gas has to be flared with a gas flare at high temperatures (~1200°C) and a lingering rate of 0.3 s. These requirements have to be met if all contaminants are to be mineralized or destroyed. The flaring temperature is automatically regulated by the air supply.

3.7.6 Gas Purification

Landfill gas is contaminated with inert gases (CO_2, N_2) and many polluting trace gases (hydrogen sulphide, halogenated hydrocarbons, etc.). If any of these concentrations are too high for utilization in motors, the gas has to be partially purified by some of the following processes:

Adsorption
Adsorption is suitable for the separation of trace gases containing hydrogen sulphide, chlorine and fluorine. Adsorption by activated carbon (particularly well-suited due to important surface structure) in a fixed-bed reactor has been a popular method of landfill gas purification. The adsorption is most effective at low temperatures and under high pressure. As soon as the activated carbon is completely loaded with trace components, it must be replaced or otherwise stripped of the contaminants.

Absorption
Absorption is the process wherein contaminants are bound to a liquid (detergent) by a chemical or physical reaction. For the separation of carbon dioxide gases, water, for example, can be used. For the absorption of trace gases from the landfill, special detergents such as Selexol are more suitable. Due to the general difficulty and high expense of this procedure, the latter is only recommended in special cases.

Lyophilization
Depending on the degree of contamination, the gas can be purified by simply cooling it to below freezing point. Good results have been achieved by lyophilization of the gas at -10°C down to –30°C. The contaminants and trace components are thus separated along with the water vapour that condensates as a result of the rapid cooling.

3.8 Operation and safety

3.8.1 Preparation

In preparation for landfill construction and maintenance, the following should be kept in mind:

Communication: Direct lines to emergency services, communication between site entry control and positioning.

Staff training: Staff has to be trained according to a special programme (as per the subjects listed below). It is important to correctly inform the staff of any potential dangers and a security plan should be mapped out in collaboration with them.

Hygiene: First aid room with first aid kit (1 - 2 people have to be trained in first aid techniques), showers, toilets, etc. The staff has to be vaccinated against Tetanus and Hepatitis. Special attention must be paid to clothing: High quality shoes and boots with steel caps, clothing to protect against weather conditions, facial dust masks and ear protection are standard.

Positioning design: Division of the landfill into compartments and sections allows for optimal leachate management. The positioning design must take into account aspects of stability, gas recovery and unloading. The surface under operation must be kept as small as possible. If this surface is too large, cleanliness and hygiene problems may arise. The landfill has to be filled by sections and in compartments. In so doing, the results obtained are: Reduction of leachate quantities, constant control of the size of operations, cleanliness of the surface operated on, prevention of littering, stench and infestation and limitation of undetected release of landfill gas.

Landfill construction material: A reserve of construction material has to be kept for the maintenance of the landfill roads and unloading points (gravel, coarse material from construction debris). Only special dumping vehicles should roll on the landfill body.

Lighting: The site entry and unloading point have to be illuminated with mobile halogen lamps, allowing operation after dark. The entry area has to be illuminated even outside working hours to ward-off trespassers.

Fire control: The best way to control a fire on a landfill is to smother it with dirt dumped laterally onto the source of the fire with a tyre loader (tyres made out of 100% rubber). Therefore a reserve of dirt must always be kept on the landfill site. Outside working hours, no machines must be left on the landfill body. Trespassing should be strictly forbidden. The site must be locked outside working hours.

3.8.2 Operation

Positioning

With positioning, the area under operation grows constantly. The waste is first spread, and then ground, then embedded and finally compacted. It is bad operational practice to just dump the waste in the space provided and let it pile. The staff should be warned about wrong dumping, as illustrated below:

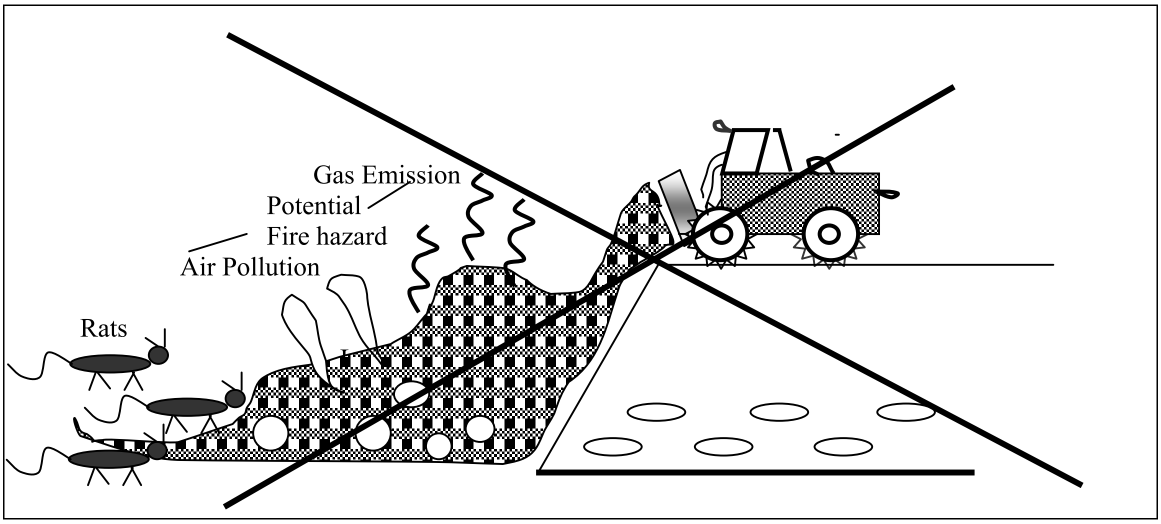


Figure 39: Incorrect Dumping. Source: Rytec AG

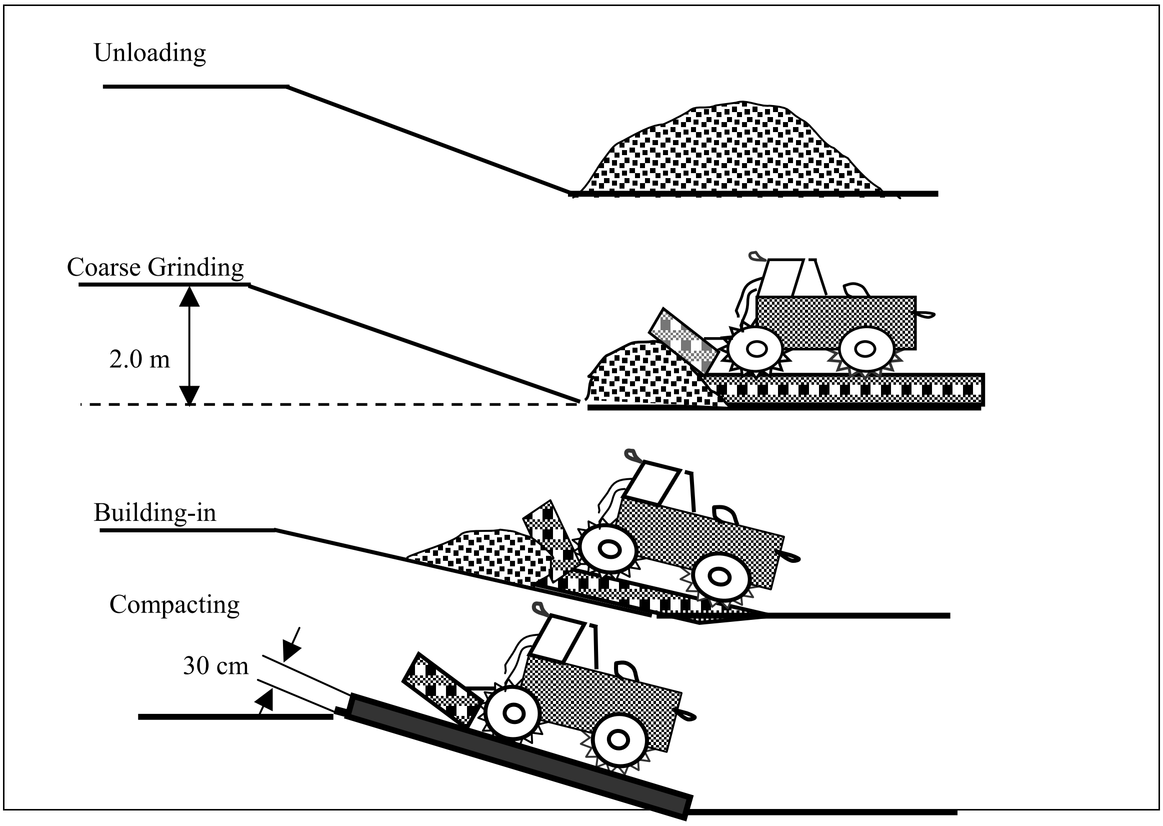


Figure 40: Representation of upward leveling. Source: Rytec AG

The best method is upward positioning. After the waste is compacted, the surface can be leveled again at the end of the day. As a further advantage, the old waste surface is again effectively compacted.

An equally acceptable possibility is downward leveling – as long as the machine operators follow the positioning rules. It is basically the same as upward leveling, except that the waste is unloaded at the top of the incline and compacted downwards.

Compaction

Compaction can lengthen the operating lifetime of a landfill, it can reduce sedimentation and voids, prevent infestation, littering and odours, reduce the daily cover layer, optimize leachate and gas recovery, gas production and reduce the cost of machinery maintenance. A single compacted layer should not be more than 0.3m thick. Generally the waste layer of the area under operation is compacted in 3–4 runs. The final degree of compaction for the waste should be 1–1.2 t / m^3.

Compared to the bulldozer, the compactor offers many advantages, such as: Clean drives (caterpillar-drives are vulnerable to damage from entwined plastic); good shredding of bulky goods; compaction to depths of 0.3 - 0.5 m; and dovetailing of the waste surface makes it resistant to littering and infestation.

Slopes

For the landfill slopes, the following security measures must be taken: Low gradient, 1:3 up to a max. of 2:3; drainage in the slope area, possibly placed behind the marginal cut-off wall; no positioning of wet waste or sludge within 10–20 m of the slope; high compaction in the slope area; gradient of the positioning layers always towards the interior of the landfill; design enhanced cut-off walls as fixed end support.

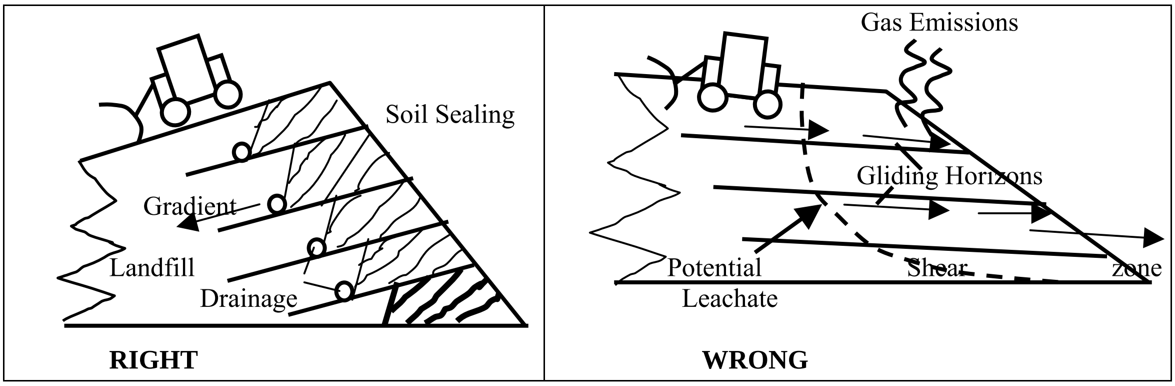


Figure 41: Positioning in the slope area. Source: Rytec AG

3.8.3 Treatment and covering of the waste surface

Daily cover

Depending on the waste composition, a good surface structure can be obtained with compaction using a compactor equipped with a stampeding roll. If this is not sufficient, a light daily cover becomes necessary which also prevents fly infestation. The daily cover should preferably consist of non-consolidating material such as ground construction debris, bricks or sand. Slopes that are less compacted must be covered with 0.5 m of soil. Slopes are the preferred areas of infestation by vermin and rats and thus need special attention. Despite all efforts, strong fly infestation cannot be completely eliminated and can only be controlled by the use of biodegradable pesticides.

Temporary cover

A temporary cover should cover segments that are not under operation over a certain lapse of time. The surface can be covered with grass on a thin layer of earth. A temporary cover that discharges rainwater is of benefit. The discharge, however, has to be carefully planned otherwise it can do more harm than good. To this end, the surface has to be leveled with a gradient. Intermediate sealing that retains the water is bad for the cleanliness of the landfill, thus an orderly landfill has no puddles on the surface.

Definite capping

A definite capping has to be designed as a barrier eventually. The layer strength has to be well dimensioned to fulfill its function and prevent erosion. Alternatively, afforestation is the best guarantee for long-term security.

3.8.4 Training

3.8.4.1 Training of operating staff

Subjects	**Contents**
Legal foundations	Waste acts, landfill prescriptions, air and water protection acts, decrees
Knowledge of waste	Types of waste, material properties, purification processes
Special/hazardous waste	Types, classification, characteristics, handling, prescriptions
Ways of treatment and disposal	Treatment and disposal facilities, sorting criteria, types of landfills
Processes inside the landfill body	Compaction, decay, leachate, landfill gas, settlement
Leachate	Collection, drainage, contamination, monitoring, groundwater protection, accidents, investigations, purification
Landfill gas	Collection, operation of installations, maintenance, gas quantities, utilization
Disposed material	List of authorized material, special treatment
Waste acceptance	On-site verification, documentation, detailed probing
Positioning technology	Embedding, compaction concept, temporary cover, positioning of special wastes
Surroundings, maintenance	Cleanliness, planting
Machinery, infrastructure	Extent, operation, maintenance, limitation of emissions, construction, guidelines
Accident prevention	Strategy, fires, gas explosions, characterization of the devices, security measures, work protection
Avoidance of stench, flies, vermin and rodent control	General measures, periodical covering, monitoring of emissions
Monitoring	Impact on the immediate surroundings of the landfill
Reports on internal operation	Measurement of emissions, surveying, leachate quantities, weather forecasts, land filling quantities, statistics
Completion	Completion work, surface sealing

Professional training must be periodically repeated and adapted to the latest regional conditions.

3.8.4.2 Training of Planners

(List should be adapted to regional variations)

Waste planner (specialist for master plan)	Overall conception for waste treatment, assembling of fundamentals, waste quantities, determination of the collection logistics, separate collection, recycling methods, transports, levies, etc.
Geologist versed in local geology and hydrology	Subsoil permeability, contamination, stability, settlement behaviour, earthquakes, groundwater, sources, effluent stream, protection of potable water
Civil engineer versed in landfill construction, deep works, dike construction etc.	Knowledge of foundations, materials, engineered barriers, filter construction, dynamic loading, soil stability, charge impact, slope stability (gliding horizons), material characterization of waste and its modification by decay, drainage, drain pipes and canalization, drainage impact, basin and tank construction, infrastructure, roadways, buildings, etc.
Biologist versed in process technology and chemical facilities	Knowledge of sewage treatment and leachate values, leachate treatment (biological, physical and chemical processes), quality of effluent stream, impact of contaminants on ecosystem, characteristics of waste, knowledge of gas generation and gas production, vermin control (impact on leachate)
Process engineer versed in plastics processing	Construction of landfill gas facilities, hydraulic calculations, gas drainage, energy recovery motors, electrical power generation and electrical installations, construction of sewage plants, conveyors etc.
Landscape engineer versed in forestation and agronomy	Landscaping, surface design, cultivation, embedding into the local amenities, etc.
Mechanical engineer versed in vehicle construction	Workshop design, scales, destination, maintenance and operation of construction machines, recharging and conveyor facilities, etc.

3.8.5 Controlling installations

The ground water should be monitored well and if necessary, re-enforced with a double base liner. The ground water should be checked for its quality, leachate loss and the condition of its upper and lower current. The water cycle in the landfill body should be equipped with vertical drainage shafts and should be checked for leachate build-up on the base liner. The leachate should be pumped out if necessary. The landfill gas should have an analyzer installed on the gas pipes and should be checked for volume flow, methane, carbon dioxide and oxygen content, trace gases and release of explosive mixtures. Odours can be controlled with the help of neighbours and the evaluation of the odour emissions. Vermin should be controlled by persistent cleanliness of the landfill surface and pesticides.

3.8.6 Monitoring

Current monitoring involves determining the parameters every 2–4 weeks, always on the same weekday. It calls for leachate analysis before and after purification at each landfill segment. The following parameters should be measured: Discharge (m^3/day), colour, turbidity, odour, temperature (ºC), pH level and conductivity (µS/cm). The gas analysis should include the percentage by volume of the methane, carbon dioxide and oxygen.

Intermittent monitoring ensures that the parameters are determined quarterly or twice a year. Leachate analysis should also be done before and after purification at each landfill segment. The parameters monitored should be: Discharge (m^3/day), colour, turbidity, odour, temperature (ºC), pH and conductivity (µS/cm), BOD (mgO_2/l), COD mgC/l, NH_4N (mgN/l), NO_2 (mgN/l), Cl_2 (mgCl/l) and SO_4 ($mgSO_4/l$). The gas analysis should be done at each measuring point of each gas well. The parameters checked should include: The percentage by volume of methane, carbon dioxide, oxygen and the parts per million (ppm) of carbon monoxide, hydrogen sulphide and halogens.

All-round monitoring involves determining the parameters once a year (autumn or spring). Whenever suspicious results appear during the current or the intermittent monitoring, all-round monitoring can be ordered. The observation of the environment must also be integrated into the monitoring concept.

All the results from the operation and the investigations have to be presented and interpreted in monthly and annual reports. The reports are to be complete with charts illustrating, amongst other parameters, the relationship between precipitation and leachate quantities, as well as the relationship between incoming waste and gas production levels.

3.8.7 Conclusion

In conclusion, landfills offer a means of waste treatment as well as a secondary source of energy, if the validated methods of construction and operational activities are adhered to. Gas recovery and utilization requires a high degree of specialized knowledge, an excellent design and continuous professional maintenance by the operating staff and specialists. For reasons of safety, air pollution, global warming and energy recovery, it is paramount that only competent people work on landfill construction and operations.

4 Introduction to incineration technology

A condensed version of the chapter on
‘Incineration technology’
from the UNIDO Training Manuals on MSWM
prepared for the project
“Cleaner Solid Waste Management in China”

4.1 Introduction

Incineration is an environmentally and technically superior method of waste disposal, offering reliability, safety and efficiency if correctly performed. On the other hand, it is highly controversial and expensive. However, with increasingly stringent environmental regulations, and the concern about ground waters pollution, due to incorrect solid waste management processes, etc., incineration has become the preferred method over land filling and other waste management technologies. Incineration involves thermally decomposing matter through oxidation, hence reducing the waste volume and destroying its toxicity. It is suitable for industrial, municipal and hazardous waste, as long as they contain organic matter, since organic substances are capable of sustaining thermal degradation. After incineration, waste is converted into CO, CO_2, water and ash. Depending on the composition of the initial waste, compounds containing halogens, metals, nitrogen and sulphur may also be produced.

The main advantages of incineration are: Considerable reduction of weight and volume of waste (e.g. 1,000 Kg of solid waste could be reduced to 300 Kg of solid material after incineration; $1m^3 =< 0.1\ m^3$); complex organic compounds are broken down into simple substances. The residues that must be deposited (ash, slag) are almost inert.

4.2 Incineration process

4.2.1 Phases of the process

Incineration is a complex process, consisting of the following phases:

Drying ➔ Degassing ➔ Ignition ➔ Gasification ➔ Combustion ➔ Burn out

The drying phase occurs at 100 - 180°C. Waste is dried by pre-heated primary air while the water evaporates. Degasification occurs at 250°C, where low temperature smoulder gas is generated (H_2, CH_4, H_2CO, etc.) and heat is delivered as radiation heat from combustion processes. Ignition is the third phase and involves waste ignition and the burning-off of combustible gases. The next phase occurs at 400°C and is called gasification or carburation. Gasification involves the decomposition of organic matter by oxidation by primary air and the formation of combustible gases (e.g. CO). This is followed by combustion at 850-1000°C. In this phase, secondary air helps in the complete oxidation of the combustible gases. The final phase, termed 'burn out', occurs at 250°C. In this phase, the carbon content in ash (slag) is reduced to a minimum, smoulder gases are produced and then burnt off, and unburned material is eliminated.

The completeness of the incineration process is essential for: the reduction of environmental pollution caused by greenhouse gases escaping the incineration plant; the prevention of material corrosion of incineration plant components; and the reduction of waste degradation time in the landfill (production of greenhouse gases and dissolving of heavy metals).

For this reason, less than 40 mg CO/m^3 in flue gas, 5% loss on ignition in ash and 2% organic carbon in ash should be the target end products. Complete incineration can be achieved by using an excess air supply (oxygen) at a rate of 1.6 to 2.0 as well as good mixing of the combustion gas in the combustion chamber and an even distribution of well-mixed waste on the grate.

4.2.2 Technical overview of an incineration plant

4.2.2.1 Step 1: Entrance and weighbridge

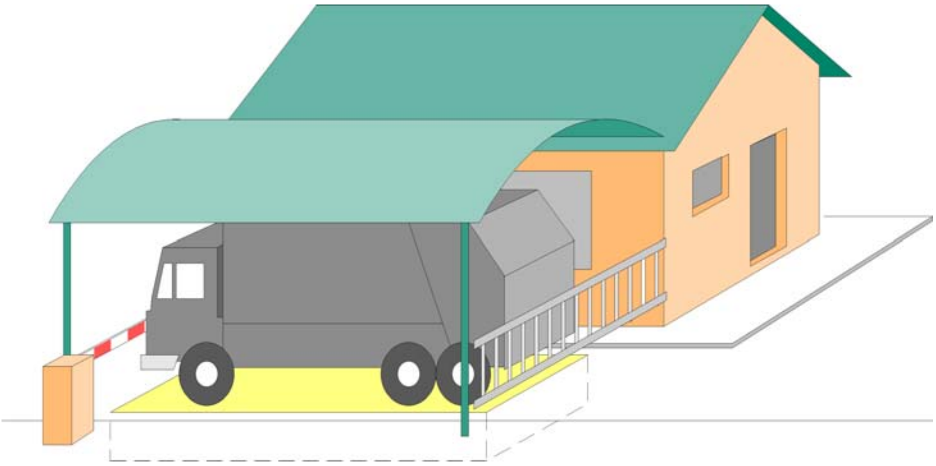
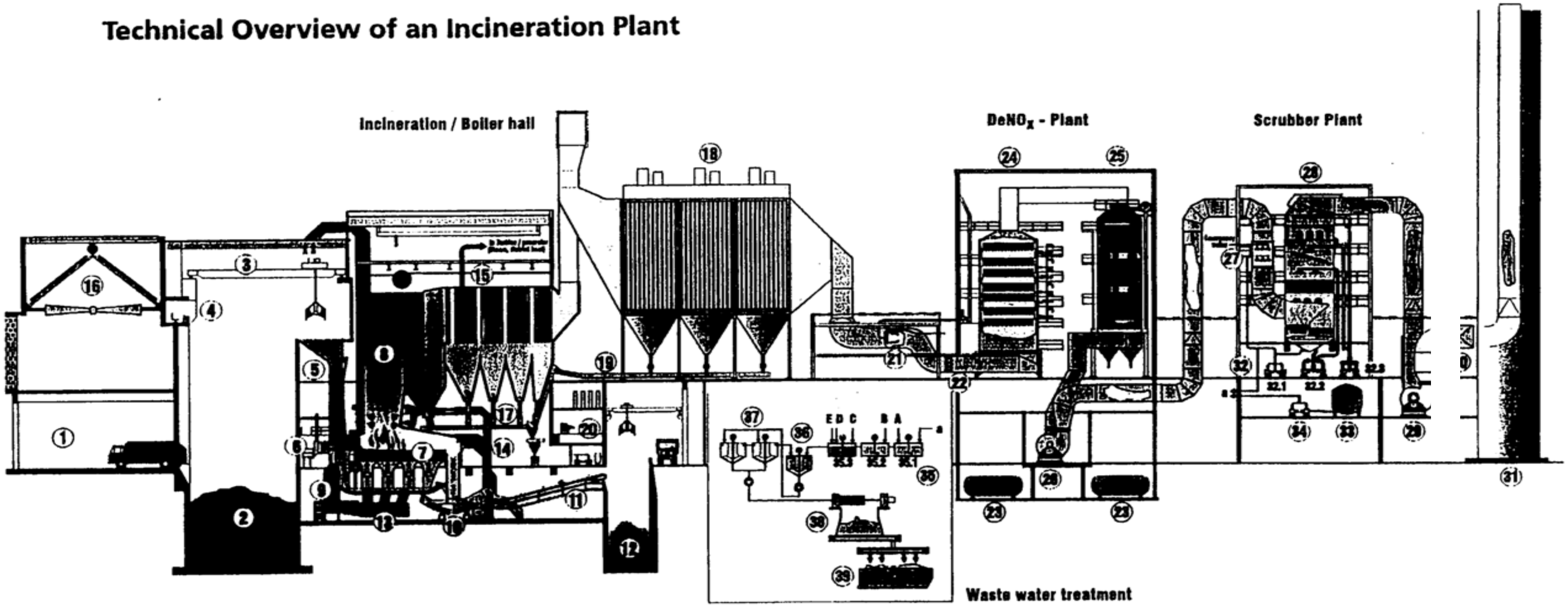


Figure 42: Weighbridge

The purpose and functions of the weighbridge and entrance procedures are to control access to the site, weigh the quantity of waste and other goods delivered, record the composition of the waste and collect the waste-tipping fee. Factors to be considered during its design include:

- Size and capacity of weighbridge, considering that trucks will be larger and heavier in the future.
- Gate access is part of total plant access control system (lockable access door)
- Good view of incoming vehicles from weighing house (building on the right)
- Two scales, one for incoming and one for outgoing vehicles or as spare if the other in repair.
- Good lighting for the grounds surrounding the weighbridge.
- Information sign outside the gate about opening times.
- Roof covering the weighbridge area.
- The whole area around the weighbridge has a good slope for drainage to prevent water from flowing into the weighbridge.

Other items that can be included in the construction/set-up of the weighbridge are: A lockable gate outside the weighbridge and weighing house; an electronic scale with computer and weighbridge program. Eventually, in a network with an accounting computer; a loudspeaker for communicating with drivers, a barrier after the weighbridge which can be operated from the weighing house, ventilation of the weighing house from the opposite side of weighbridge; good locking system for the weighing house and a safe for the money collected.



1: Tipping Area
2: Waste bunker
3: Waste crabe
4: Crane operator’s cabin
5: Charging hopper with chute
6: Waste feeder unit
7: Horizontal W+E grate
8: Combustion chamber
9: Grate siftings conveyor
10: Wet discharger
11: Slag conveyor belt
12: Slag bunker
13: Primary air system with air preheater
14: Secondary air system
15: Steam boiler
16: Air condenser plant
17: Fly ash transport system (boiler)
18: Electrostatic precipitator
19: Control room
20: Control room
21: Burner
22: NH_3-injection
23: NH_3-storage
24: Catalysator
25: Waste heat boiler
26: Induced draught fan, dry
27: Quench
28: Wet scrubber
29: Induced draught fan, wet
30: Silencer
31: Stack
32: Scrubber pumps
  32.1: Quench pumps
  32.2: Tower packing pumps
  32.3: Ring jet pumps
33: Emergency tanks
34: Feed back pumps
35: Neutralization
36: Sedimentation tank
37: Sludge stacking tank
38: Filter press
39: Filter press

A Lime milk
B TMT 15
C HCl
D $FeCl_3$
E FHM

Figure 43: Waste to Energy Plant, Zurich - Josefstrasse, Unit 1, ABB Enertech Ltd. Components of an Incineration Plant

In terms of operation and maintenance, the scales should be checked twice a year; the opening-times should be published regularly in local newspapers and telephone books; written instructions for personnel should be provided on the operation of scales and computers; the delivered waste quality and storage and bookkeeping of money should be checked. Precautions should also be taken against potential danger of carbon monoxide (CO) from truck exhaust.

4.2.2.2 Step 2: Discharge, crusher and bunker

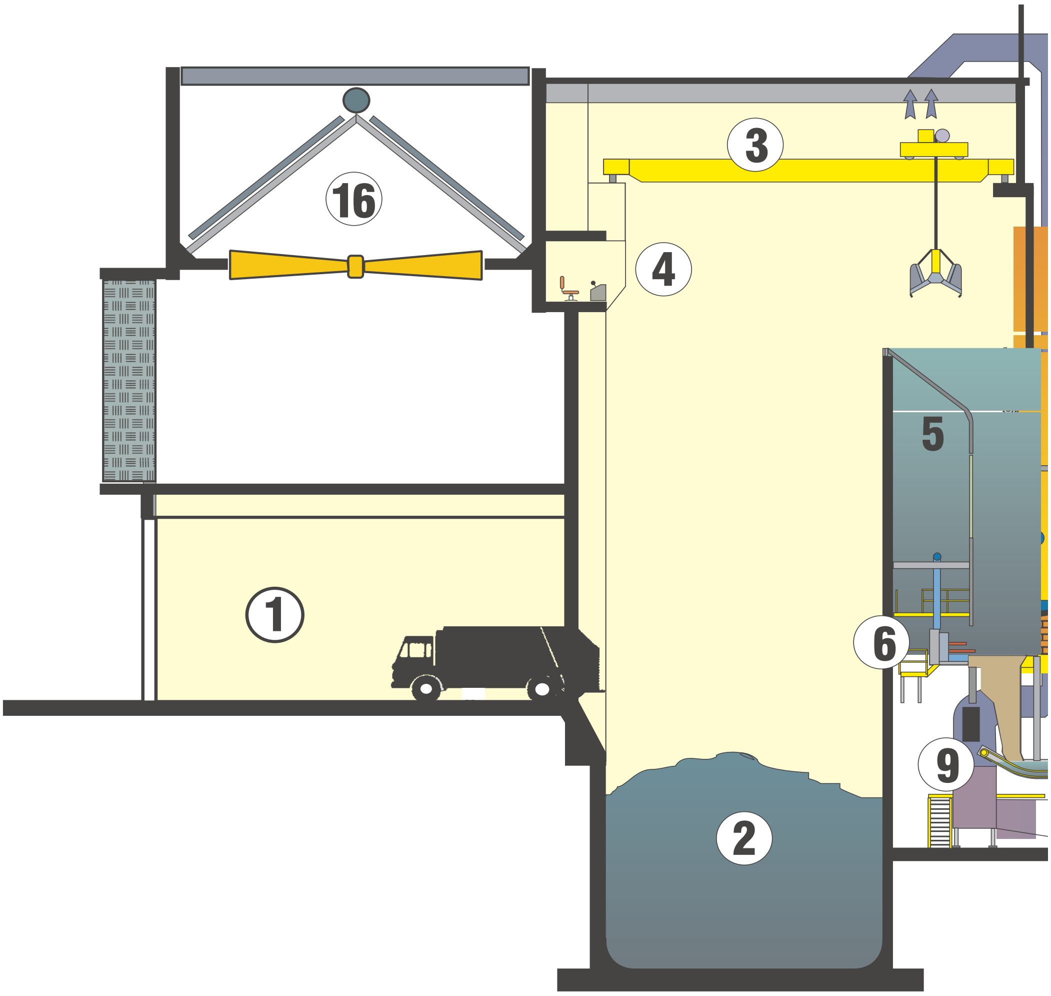


Figure 44: Discharge, crusher and bunker:
1 Discharge hall; 2 Solid waste in bunker; 3 Crane; 4 Crane operator room, 5 Waste intake; 6 Feeder; 9 Primary air blower; 16 Air condenser

The purpose and function of this step includes, tipping of the waste, crushing of bulky waste, compressing and storing of waste, dewatering and feeding of waste. The design of this device should be such that it has one week storage capacity, four days dewatering capacity, two cranes, each with a capacity three tons and two scales (one as spare), for 365-days-per-year, 24-hours-a-day operation, crane cabin (if possible, equipped as a control room), prevention of odour emission system, groundwater protection and fire protection.

This step (discharge) is potentially a dangerous one to carry out. Consequently, the following precautions should be taken:

- Roof covering tipping area should be high enough for long (high) tipping vehicles.
- The bunker should be deep and a watertight reinforced concrete construction should be used. The steel reinforcing bars should be covered with a particularly thick concrete layer, as sometimes the crane polyp-lug touches and scrapes the concrete.
- Railings to prevent people falling into bunker.
- Stop button for crane at discharge area.
- Closing doors for discharge openings.
- To avoid bad smell, the bunker should be kept under negative pressure by a ventilation system and the foul-smelling air should be used as the secondary air.
- The bunker should have a drainage system. The drainage water may be pumped to the slag extractor, to be evaporated.
- The bunker should be well lit.
- For fire protection, there should be a sprinkler system, which could be activated either automatically or manually from the crane cabin. The crane cabin should have a separate telephone line to call the fire brigade in case of emergency. Fire hose connections should be provided inside and outside the bunker for fire extinguishing.
- Handrails should protect waste feed hoppers. For people working in the feed hopper area, safety ropes should be provided.

The discharge area must be supervised. For ease of operation and maintenance, the following material should not be discharged into the bunker: liquids (solvents, oil, sludge, etc.), metal pieces, stones, sand, industrial sands and cinders, ashes, dead animals, explosives, compressed gas bottles, hazardous waste, tyres, fluorescent lamps and batteries. Bulky waste (items longer than 50 cm must pass through the crusher before they are fed into the bunker) and no bulky goods, which may block the feeding entrance, are to be fed into the waste hopper. Additionally, smoking should not be allowed in the bunker area and clear instructions should be given to the staff working there as to what to do in case of fire. There should be sufficient spare crane cables in stock, to ensure continuity of operations. Finally, the waste in the bunker should be frequently mixed in order to obtain a uniform mixture of waste to feed the incinerator.

4.2.2.3 Step 3: Feeding

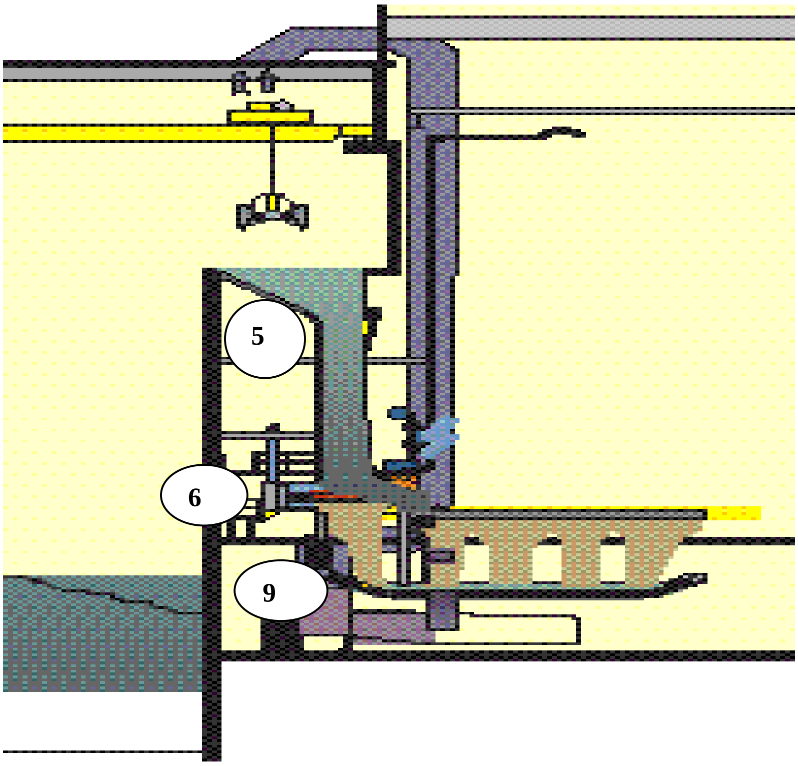


Figure 45: Feeding system: 5 Waste intake 6 Waste feeder 9 Primary air blower

The purpose and function of the feeding system is to seal the combustion zone from the bunker area and thus prevent any leaking of air into the combustion zone or leaking of burning parts from the grate into the bunker. It also aids the controlled feeding of waste into the incinerator grate.

The design of the feeding system should include an adequate slope for the waste hopper, a water cooled waste chute to avoid backwards burning of the waste, a waste chute flap for sealing the chute in periods when it is not filled with waste during start up and shut down periods, and a waste feeder operated by hydraulic cylinders, which is controlled by the combustion control system. The manufacturer normally decides the design of the feeder. It is also important that the hydraulic cylinders of the feeder are constructed outside the feed casing, as sometimes back-burning occurs in the feeder area, and that the feed drawers are manufactured of heat resistant steel (2-3% Mn) or that they are water-cooled.

Operation, maintenance and safety highlights include: that the crane operator take care and ensure that the chute is always filled with waste so as to prevent fire coming backwards and igniting the waste in the bunker; that the wall thickness is measured by ultrasound during each maintenance shut down as the waste hopper and chute are subject to abrasion; and that the feeder drawers are checked for damage from possible heat and abrasion during every maintenance shut down.

4.2.2.4 Step 4: Grate and combustion zone

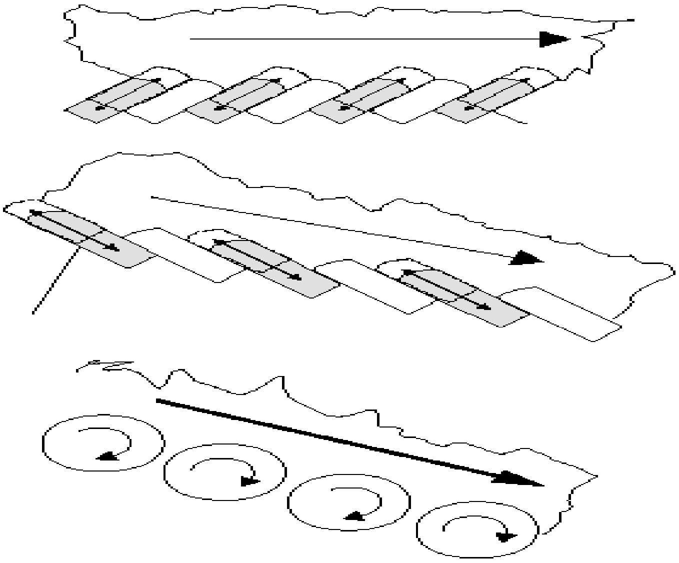


Figure 46: Grate types from top to bottom: advance / in feed grate, reciprocating grate, roller grate

The grate and combustion zone serve the purpose of combusting the waste with primary air; controlling delivery of the needed quantity of primary air; distributing the primary air over the various zones of the grate; uniform distribution of the primary air through the waste bed; transporting the waste from the feed zone to the slag chute (retention time is about one hour), by a loose mode of transport without compression; and controlling the addition of secondary air by nozzles to produce high turbulence.

Among the relevant design considerations are the following:

- In order to reduce environmental pollution, the following should be considered: Complete burn out of the slag: Less than 5% LOI (loss on ignition) / less than 2% organic carbon. Complete burn out of the gas: Less than 40 mg CO/m^3.
- The grate is subject to high temperature exposure and at the same time high abrasion of the waste, thus the grate bars should be designed to be cooled by the primary air.
- Water-cooled grates of a single piece should be manufactured in carbon steel without a temperature scale. As they are not primarily cooled by primary air, the operation is more flexible regarding the ratio of primary to secondary air.
- Grate movement can be adjusted for varying frequency and speed. The grate movement depends on the type of grate (see figure above).
- The primary air is equally distributed through the grate. Some grates apply high-pressure drops of 120 to 150 mm WG (water gauge) for good air distribution; others apply only 50 mm WG.
- The complete gas combustion is achieved by controlled addition of secondary air.
- The secondary air is delivered by a ventilator, which is controlled by the oxygen content of the flue gas. The oxygen content is between 6 and 10%. With 6%, high thermal efficiency can be achieved. With 10%, there is less danger of CO

generation. The oxygen and the CO content in the gas are measured after combustion. The CO content must be low not only for the reduction of the greenhouse effect, but also for corrosion-prevention for the boiler.

- The secondary air is added to the combustible gases through nozzles on the inlet and outlet side to produce a high outlet velocity for mixing the gases. In this phase, very high temperatures will be produced, and NOx will be formed. To avoid this, some companies add some secondary air in two stages.
- For calorific values of the waste below 8'500 kJ/kg, the primary air must be preheated and coal or heavy fuel oil may be added to the waste.
- For calorific values below 7’200, kJ/kg an oil burner must be installed, to reach the necessary minimum combustion temperatures of 850^{o}C (during 2 seconds).

Design parameters for the grate

Area (A)

It is very important to have a sufficiently large grate area considering the thermal load. If the grate is too small, it will be damaged due to excessive temperatures. The specific heat load for an ordinary grate should be 600 kW/m^2 for a normal load and 750 kW/m^2 for the maximum specified load. The specific heat load of a water-cooled grate is 2’000 kW/m^2.

$$A[m^2] = \frac{H[kJ/kg] \times Q[t/h] \times f_c[kWh/MJ] \times 1000[kg/t]}{SL_G[kW/m^2] \times 1000[kJ/MJ]}$$

where,

A = grate area [m^2]

Q = capacity [t/h]

H = calorific value [kJ/kg]

f_C = conversion factor [kWh/MJ] = 0.28

SL_G = specific heat load of grate [kW/m^2].

Design parameters for the combustion chamber

Volume (V)

The combustion chamber should have a specific heat load of 1’250 GJ/m^3(=350 kW/m^3).

$$V[m^3] = \frac{H[kJ/kg] \times Q[t/h] \times f_c[kWh/MJ] \times 1000[kg/t]}{SL_C[kW/m^3] \times 1000[kJ/MJ]}$$

where,

V = combustion chamber volume [m^3]

Q = capacity [t/h]

H = calorific value [kJ/kg]

f_C = conversion factor [kWh/MJ] = 0.28

SL_C = specific heat load of combustion chamber [kW/m^3]= 350 kW/m^3.

Construction characteristics of the grate and combustion system include:

the grate should be a rigid, simple construction; have air-cooled grate bars of high temperature resistant material like such as a nickel-containing foundry material;

good control of grate movement;

TV camera for fire supervision;

pyrometer for occasional measurement of combustion zone temperature;

openings to visually control various parts and levels in the combustion zone;

CO and O_2 emission measurements from the combustion chamber; and
a collection and transportation system for the fine material passing through the grate.

The following operation and maintenance considerations for the grate should be observed:
the fire should be bright and clear without much smoke (danger of Dioxins);
the fire should be visually supervised frequently.

Depending on waste composition and combustion conditions, liquid slag may sometimes stick to the walls. Such material often accumulates, solidifies, and then falls into the grate in large, heavy pieces; this may damage the grate. Special waste composition (high plastic content) may often be the cause of this effect. Changes in the primary air distribution to the grate often solve this problem. Additionally, the grate should be subjected to a high thermal load and at the same time high abrasion from the waste and the slag. The operation conditions of the grate must be checked once or twice a year. The lifetime of the grate will depend on the operations and maintenance conditions.

4.2.2.5 Step 5: Slag extraction storage and disposal

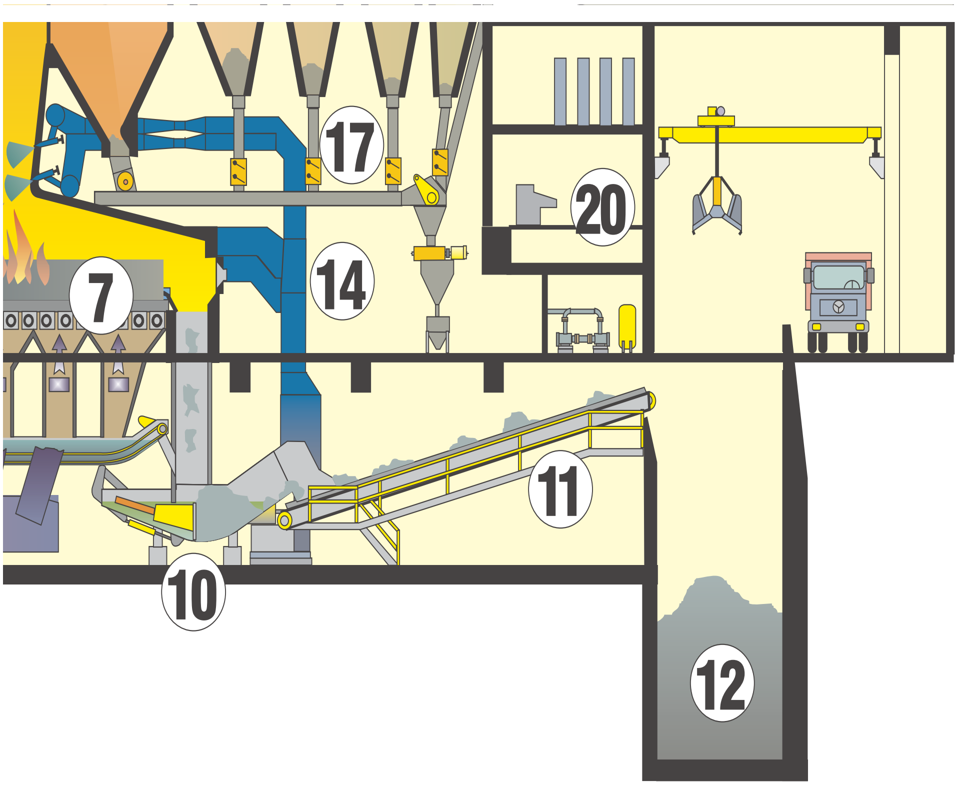


Figure 47: Slag extraction storage
7 Grate 10 Slag discharge 11 Slag conveyor 12 Slag bunker 14 Secondary air
17 Dust discharge 20 Control room

The Step 5 serves the purpose of sealing the combustion area, extracting, cooling down, storing and unloading of the slag.

The design considerations take the following points into account:
the slag extraction is an indispensable operation for the whole process and must be very reliable;
the slag pit has a maximum volume of 5-7 days slag production;
the wastewater from the dewatering slag pit has a high lead and sulphate content, therefore it should be pumped to the slag extractor;
there should be two cranes with shovel lugs for unloading;
as much iron as possible should be recovered from the slag;
the quality of iron extracted from the slag is normally poor as it has a high tin content;
an important parameter for the utilization or disposal of the slag is the unburned material (loss on ignition, organic carbon content);
the slag can be used in road construction, however, a number of design and construction parameters must be followed.

This is however, a source of environmental pollution. The slag should be disposed of in separate slag landfills. The leachate of slag landfills contains high lead (Pb) and zinc (Zn) contents as well as high sulphate (SO_4^{2-}) and chloride (Cl) ions. The sulphate content may be higher than 400 mg/l and therefore this leachate may be damaging to concrete. Thus, the landfill being constructed has to be built with this in mind. If necessary, the leachate has to be treated to remove the iron and zinc.

In the construction of the extractor, the preferred material is carbon steel and the slag extractor should be rigidly constructed. The same applies for the conveyor belts.

As far as operation, maintenance and safety go, overfilling the slag pit should be avoided; and as a precautionary measure, the slag pit should have solid walls and hand rails where there is no wall, so that nobody falls into the pit.

4.2.2.6 Step 6: Boiler

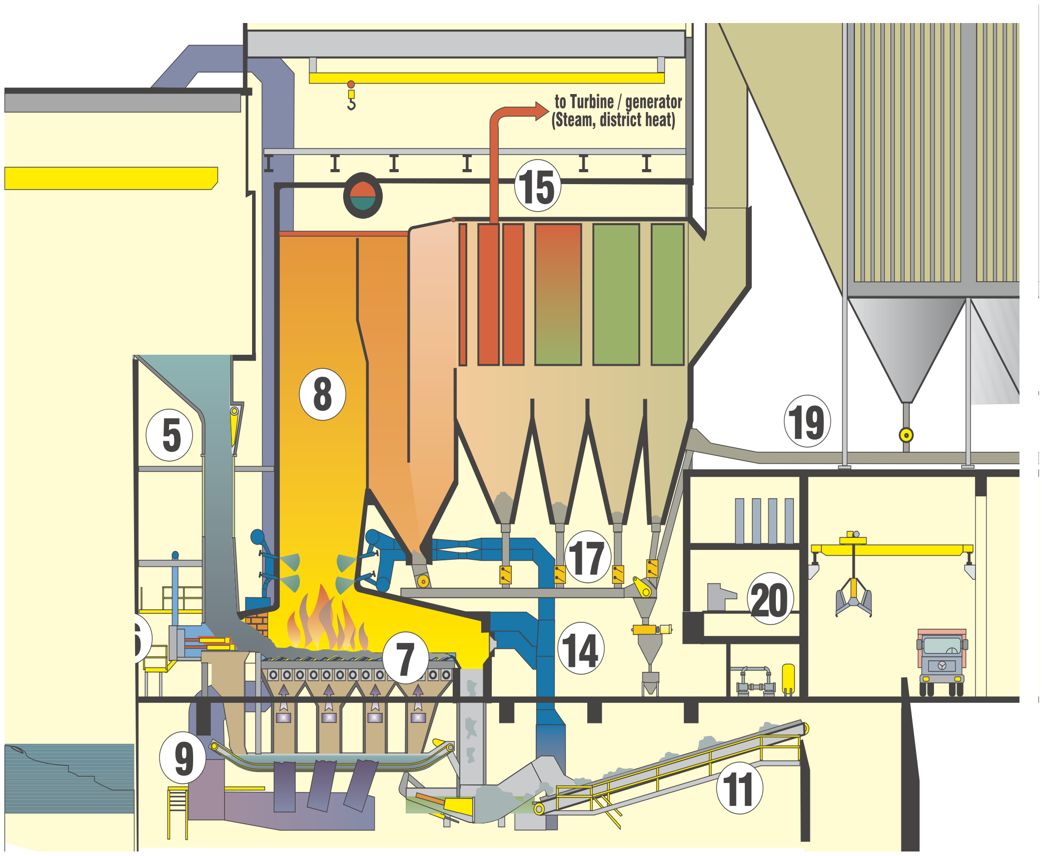


Figure 48: Boiler
5 Waste intake 7 Grate 8 Combustion chamber 9 Primary air blower
11 Screw conveyor 14 Secondary air 15 Boiler 17 Ash extraction
19 Ash conveyor 20 Control room

The function of the boiler is to utilize the heat of incineration to produce steam, cool down the combustion gases, and absorb dust. The boiler consists of different sections:

- Pre-evaporation section (to cool down the very hot gases using well-cooled pipes)
- Superheating section in which the steam is superheated, to avoid condensate formation in the steam turbine
- Evaporation section in which the water is boiling in the tubes
- Economiser in which the feed water is preheated – the feed water and condensate circles are the same as in a conventional thermal power station.

The following considerations should be borne in mind during the design, construction and operation of the system:

- The boiler, with its feed-water and condensate system is a highly complicated system. Thus, any work done should be supervised by an expert and the workers involved should be thoroughly trained.
- There are vertical boilers and horizontal boilers, the horizontal boiler is specially suitable for waste incineration plants
- The main considerations for waste incineration design are: the high corrosion rates in the combustion chamber due to high CO content; and the super heater tubes due to high chlorine content and high temperature.
- The recommended design pressure and temperature for the incineration boiler are: 37 bars for steam pressure and 420^{o}C for steam temperature. The above is because in cases where higher temperatures and pressures could be applied, very rapid corrosion processes could occur on the boiler tubes.
- The dew point of the flue gas depends on the composition (mainly the sulphur content) of the waste incinerated, but generally lies between 120^{o}C and 150^{o}C. To get high-energy efficiency, the boiler should be designed for a flue gas outlet temperature of 170^{o}C in order to be safely above the dew point.
- The fly ash collected from the boiler has a considerably higher content of heavy metals than the slag. This fly ash should therefore not be used for road construction and brick fabrication; it should be disposed of in a special sanitary landfill.
- The combustion chamber is exposed to high temperature, high turbulence, high dust content (abrasion), as well as unburned CO. Thus, the boiler pipes should be covered by a 20-30 mm thick layer of mineral cover or silicone carbide plates.
- The superheater is exposed to high corrosion and abrasion. Two to five rows of evaporator tubes protect the superheater from extra high temperatures. The tubes in this section should be covered by a half tube welded to the side from where the gases are coming.
- A substantial amount of dust is deposited on and between the tubes of the boiler. If nothing is done to reduce this, a considerable pressure drop may occur across the boiler. To clean the boiler during operation, special knocking devices are installed. Soot blowers, as installed frequently in coal-fired power stations, are normally not applied in incineration plants. However, ultrasonic or sonic devices (ship horns) are used.

In terms of operation and maintenance, the following safety precautions should be taken:

- Incineration boilers sometimes crack in the area of the combustion zone. This is very dangerous for the boiler since in a short time, a lot of boiler water is lost which cannot be replaced fast enough. Consequently, the water level drops fast and parts of the boiler may run dry. To avoid damage to the boiler due to heat, the primary and secondary air should be stopped automatically when the level in the boiler drum falls below the required minimum.
- Wall thickness of the boiler should be measured ultrasonically, according to a standard measuring programme, once or twice a year.

- The superheater packages should be changed every three years (preventive maintenance).
- All safety standards and measures in connection with steam and steam boilers should be strictly followed.

4.3 The Dioxin (TCDD) and Furan (TCDF) problem

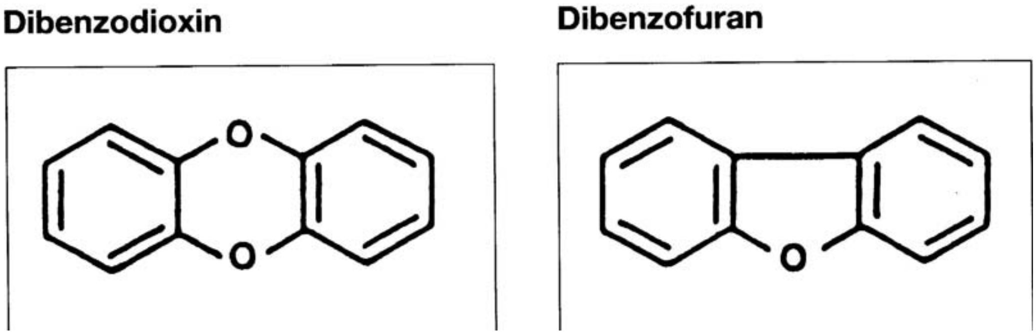


Figure 49: Lehmann 182/183 (Dibenzodioxin and Dibenzofuran) (Source: Dioxin - a chemical time bomb)

Towards the end of the seventies, MSW incineration plants started to be examined for Dioxin and Furan emissions. A group of scientists published their initial results from controlled runs, showing the prevailing dibenzodioxin and dibenzofuran levels in flue gas and fly ash from three Dutch MSW incineration plants. Since then, there has been a lot of concern about their presence in waste matter. Chlorinated Dioxins and chlorinated Furans are very toxic substances. It has been established that the prerequisites for Dioxin formation are organic compounds, so-called radicals, oxygen, chlorine and thermal energy. The purpose of primary measures is to destroy the 50 ng/kg Dioxin/Furan already present in the waste when it is delivered to the MSW incineration plant. However, it is an established fact that Dioxin/Furan is generated during the incineration process. So primary measures should also ensure that factors contributing to the formation of Dioxin and Furan during the later stages of incineration are eliminated, or at least kept to a minimum. The way to achieve minimal formation during the process is to optimize the incineration of the waste.

Thus, the following points should be examined:

- Optimized combustion control:
  - fuel homogenization
  - optimization, in other words, minimization of surplus oxygen (for instance via flue gas recirculation)
  - improvement of automatic combustion control system to optimize waste through combustion air injection and the burn out of fly ash, slag and flue gases (the smaller the component of organic substances which leave the combustion chamber unchanged, the smaller the quantity of Dioxin and Furan re-appearing by De Novo synthesis)

  - good mixing of combustible gases containing oxygen, exposing the gases to high temperatures for as long as possible
- Avoid dust deposits:
  - It can be taken for granted that dust deposits in the combustion chamber and in the boiler area contain Dioxin and Furan. Dust penetration from the combustion area should therefore be minimized. The waste heat boiler should contain as little dust as possible (preventive action to avoid deposits- frequent cleaning is also recommended). The above also applies to electrostatic precipitators.
- Inhibition in the combustion chamber:
  - The formation (De Novo synthesis) of Dioxins and Furans requires heavy metal catalysts such as copper compounds that are readily available in flue gases and fly ash. By adding inhibitors (to inhibit or retard chemical reactions) the catalytic re-development of Dioxins and Furans can be measurably reduced. The inhibitors must be added in the combustion chamber or in the boiler unit. Triethanolamine, triethylamine, urea and ammonia are all examples of inhibitors. Dioxin emissions have been determined during the experiments conducted when developing the selective non-catalytic reduction (SNCR) denitrification process. The results show that by adding ammonia to the combustion chamber of an incineration plant, the Dioxin formation can be reduced by up to 90%.

For the dry flue gas cleaning process, it is necessary to add activated charcoal to the flue gases to keep the mercury levels within the emission limits. A positive side effect is a reduction in Dioxin/Furan levels in the flue gases because the activated carbon absorbs these organic compounds. For wet scrubbing systems, it is possible to add activated carbon to the flue gases (either before the flue gas cleaning stage or to the scrubbing water of the wet scrubbing stages) and thus achieve a considerable improvement in the level of Dioxin/Furan adsorption. An adsorption level of up to 90% can be obtained. Dioxin/Furans are adsorbed by the carbon and removed from the system by the scrubbing sludge. Dioxins and Furans are destroyed by post incineration in the catalyst, $DeNO_x$, at low temperatures. Depending on the catalyst, elimination levels may be between 90 and 95%.

4.4 Flue gas treatment

The aim of flue gas cleaning is to reduce the quantity of *emissions*[6] in order to minimize the impact of *immissions*[7] on the biosphere. Gas cleaning was not originally done to improve the quality of the air or to protect the environment. Gas cleaning systems were mainly used to clean *throat gas*[8] from blast furnaces. They enabled the site to utilize the high energy content of the gases in boilers or gas motors and to recapture dust, which could then be re-used.

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6) Emissions: a type of pollution, given out by a mobile or fixed source, which is released into the atmosphere, water or ground, including noise, radiation and heat.

7) Immission: pollution of the air, water or ground, including noise, earth tremors, radiation and heat, which affects humans, animals and plants.

8) Throat gas: gas compounds exiting from the throat of the furnace consisting of CO_2, CO, N_2, H_2 and other gases. Combustible mixture which is useable in air pre-heaters for example.

4.4.1 Options for flue gas treatment equipment

It has been stated that there are various hazardous substances in dust, aerosols and gases, which need to be removed from the flue gas. There is also a choice of several technologies (e.g. cyclone dust separators, wet scrubbers, bag filters and electrostatic precipitators). In order to measure the effectiveness of any precipitation equipment, the composition of the potential precipitants needs to be known.

Dust produced by MSW incineration sites mainly consists of:

- silicates (SiO_2), about 30% of the weight;
- oxides of the following heavy metals: zinc, aluminium, calcium, lead, magnesium, iron, copper, cadmium;
- and salts: gypsum (calcium sulphate $CaSO_4$), salt (sodium chloride: NaCl), calcium fluoride (CaF_2), etc..

The flue gas at the exit of the steam boiler contains 3 to 5 g/m^3 dust whilst the exhaust dust at the chimney contains less than 10 mg/m^3.

Aerosols consist of particles that have a smaller diameter than dust. Precipitation is successful therefore, where aerosol particles can be increased in size using methods such as condensation and agglomeration.

Flue gases from waste incineration are typically composed of: Air (21% by volume O_2, 79% by volume N_2), Nitrogen, N_2, Steam, $H_2O(g)$, Carbonic acid, $CO_{2(l)}$, Hydrochloric acid, HCl , Hydrofluoric acid, HF, Sulphur dioxide, SO_2, Nitrogen oxide, NO_X. Gases and vapours are easily eliminated by absorption via particles or liquids.

Generally, mechanical precipitators and electrostatic precipitators are effective in dust precipitation but only partially effective in precipitating aerosols and not at all for gases. Wet precipitators are generally good at precipitating gases, dust and sometimes aerosols. The condensation scrubber is a wet precipitator that is effective at precipitating dust, aerosol, as well as gases. The venturi scrubber is also very effective at precipitating hazardous gases. Combination equipment is either completely or partially effective in the precipitation of all three hazardous substances. The best of them include: the wet electrostatic precipitator, which is mainly used in aerosol precipitation; the electrodynamic venturi, which is used for fine dust and aerosol precipitation; and the ionized wet scrubber, which gives improved aerosol and fine dust precipitation.

4.4.1.1 Wet precipitators

Wet precipitation is based on the principle that, absorbing particles into water droplets increases their size, thus making them easier to precipitate. The task involves bringing hazardous substances in the gas into contact with droplets or a film of water. The second step is to remove the water from the gas flow. The third step is thorough treatment of the contaminated water. The scrubbing liquid used for this process is generally water because it is readily available at a low price. Unfortunately, wet precipitators work for gases as well as solids. Thus to improve gas precipitation, the water can be conditioned by adding acids or alkalis.

A scrubbing tower without packed beds is a type of scrubbing tower used if hazardous gas precipitation is required and if there are solid substances present in the scrubbing water. Scrubbing towers achieve a reasonable absorption ratio of hazardous gases. The degree of precipitation depends on the different types and densities of droplets contained in the gas. Other contributing factors are the size of the contact surface between the flue gas and the scrubbing liquid and how readily soluble the hazardous substances are contained in the scrubbing liquid.

A packed bed column is of similar construction to a scrubbing tower. The difference is that there are packed beds installed in between the injection levels. The beds increase the contact surface of flue gas and scrubbing liquid. Towers with packed beds achieve a far higher degree of dust precipitation than scrubbing towers without packed beds due to the extra turbulence in each stage and increased contact surface.

4.4.1.2 Condensation scrubbers

Very small particles cannot be separated by partial pressure differences, even though their behaviour is somewhat similar to gaseous substances. A very efficient way to remove small solid particles from the flue gas is using condensation scrubbers. Condensation in the gas stage is induced by super-saturation of the flue gas with steam. Super-saturation is achieved by mixing two gases. At least one of them (or both) has to be saturated with steam. *Adiabatic expansion*[9] (flue gas cooling using the principle of the *heat pump*[10)] and cooling down (cold surfaces via injection of cooling agents) can also be used to trigger condensation.

Steam condensation initiates a variety of mechanisms, which influence particle precipitation, such as:

- Piggy-back diffusion: Steam molecules travelling to the condensation location carry particles piggy-back style;
- Turbulent agglomeration: Particles which have been moistened in steam condensation tend to agglomerate better than dry particles; and
- Particle growth by joining with condensate: It has not been clearly proven whether the larger particles (shallower surface curving) or the smaller particles serve as condensation nuclei.

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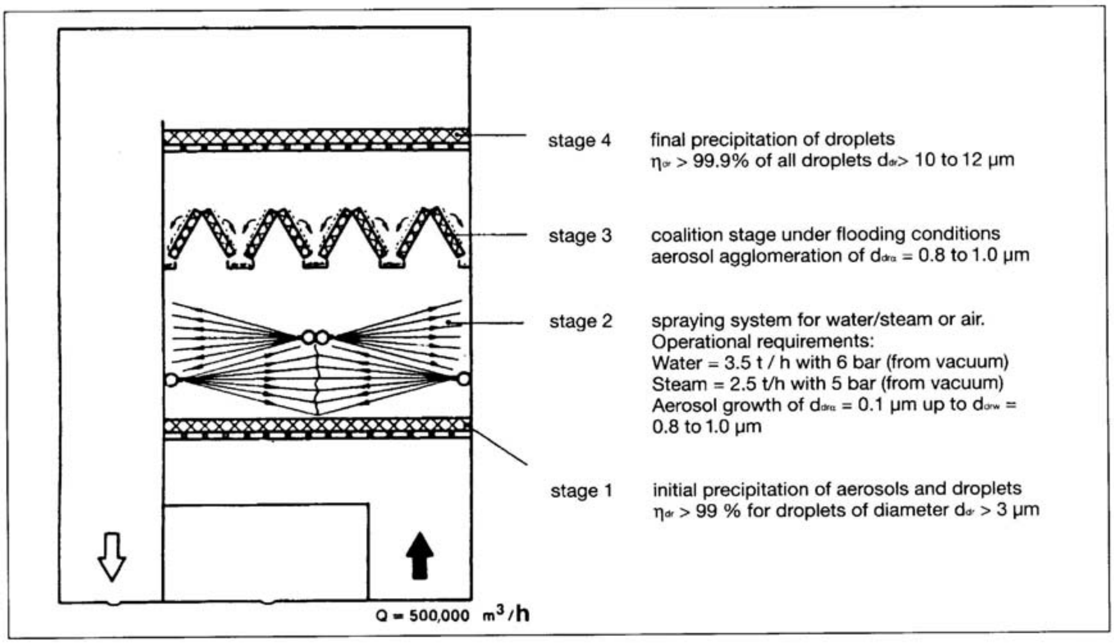
9) Adiabatic expansion: Expansion without temperature exchange with the surrounding medium. Condensation is only possible if the cooling is stronger than the shift of the condensation line due to pressure changes.

10) A heat pump utilizes the principle of adiabatic expansion:
1. vaporization at low pressure (=low temperature) by heat absorption
2. compression
3. condensation at high pressure (= high temperature) by heat emission

The Figure 50 presents the application of the condensation principle for multi-stage aerosol precipitation, consisting of the following stages:



(Source: Symalit Ltd documentation)

Figure 50: Condensation scrubber

4.4.2 Criteria for satisfactory flue gas cleaning

A flue gas cleaning system must combine several types of equipment and processes to fulfil the following criteria:

- dust separation (silicates, heavy metal oxides, salts)
- aerosol precipitation (HCl aerosols, ammonium salts, metallic mercury)
- hazardous gas absorption (hydrofluoric and hydrochloric acid, sulphuric acid and nitrogen oxides, Dioxins/Furans)
- compliance with all government regulations regarding emission levels (dust, hazardous gases, heavy metal compounds, Dioxins/Furans)
- minimization of hazardous residue production (heavy metal compounds) because this residue poisons landfills
- recycling of all useable materials (hydrochloric acid, sulphuric acid, gypsum, cooking salt) provided that buyers are available
- minimization of consumption of energy and resources
- high reliability and operation safety because there are no “holidays” in municipal solid waste incineration

The fundamental prerequisite of a flue gas scrubbing system is *never* to exceed the emission threshold values for cleaned gas, even if the incoming gas is heavily loaded with hazardous substances.

In the early 1980's experts argued fiercely about which flue gas cleaning system, dry, semi-dry or wet was the most efficient. The wet process has now been proved to be the most efficient and currently dominates the market place. The other two systems persist in niche markets only.

4.4.3 Wet flue gas cleaning systems

Wet systems use combinations of flue gas cleaning equipment. Fly dust is removed from flue gases in a multi-field electrostatic precipitator (2 - 3 fields) after the gas has left the boiler. With a precipitation level of more than 99% to 10,000 mg/Nm^3 dust in crude gas prior to treatment, less than 50 mg/Nm^3 in treated gas) a large percentage of the heavy metal dust is collected in the electrostatic precipitator.

	fly ash in electrostatic precipitator			fly ash after electrostatic precipitator		
Fe	1360	g	96.5 % by weight	60	g	3.5 % by weight
Pb	273	g	73.0 % by weight	56	g	17.0 % by weight
Zn	840	g	88.0 % by weight	115	g	12.0 % by weight
Cd	12.6	g	75.9 % by weight	4.0	g	24.1 % by weight
Hg	Practically no precipitation because mercury is gaseous in the flue gas.					

After removal of the dust, the flue gases proceed to the scrubbing area. The scrubbing area consists of the following stages, each of which is effectively a complete flue gas cleaning unit:

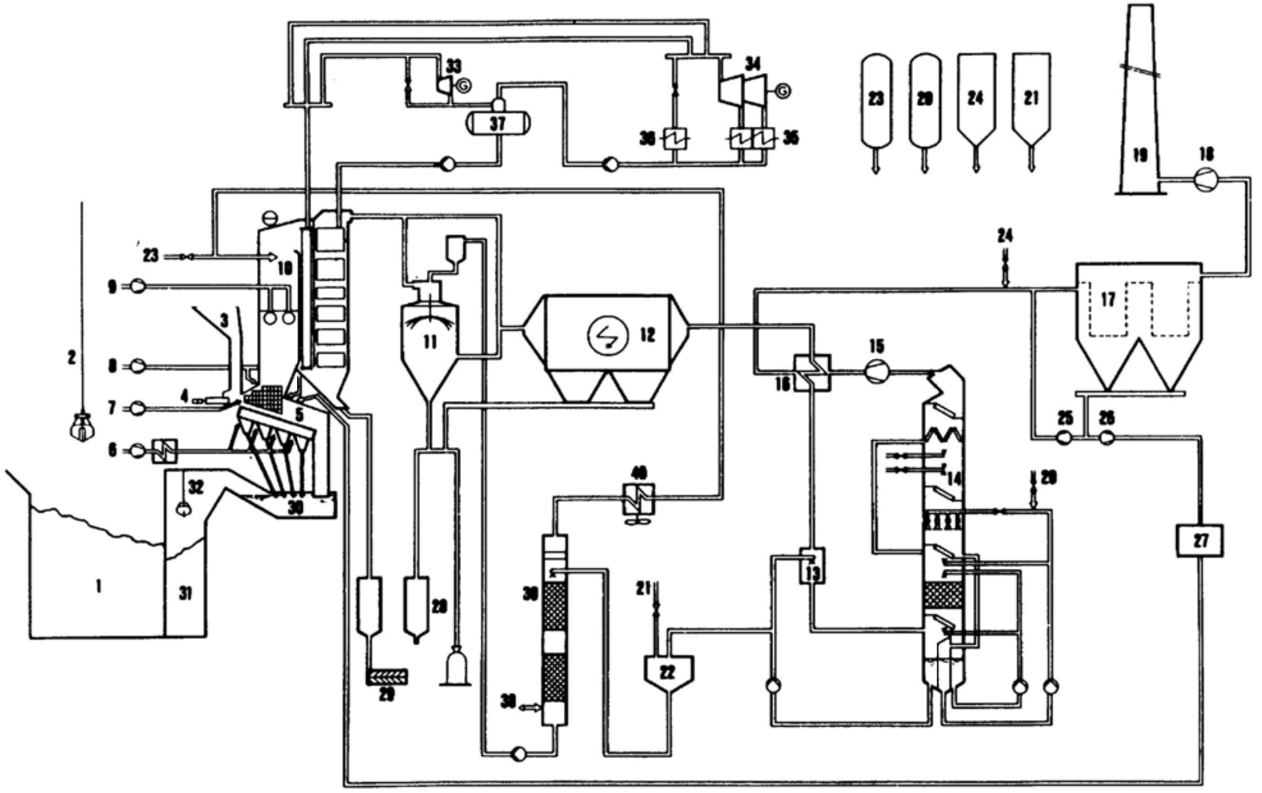
- Quenches: flue gases are cooled and saturated
- Acidic scrubbing: HCl and HF are precipitated
- Neutral scrubbing: usually by caustic soda, for sulphur dioxide precipitation
- Finest dust and aerosol precipitation

Each stage can be fitted with flue gas cleaning equipment. For example, quenches, neutral and sour scrubbing can be done by scrubbing towers with (neutral/acidic scrubbing) or without packing beds and a venturi scrubber. Fine dust/aerosol precipitation can be done by a venturi scrubber, wet electrostatic precipitator, electrodynamic venturi, ionized wet scrubber and a condensation scrubber.

Combinations such as these make it possible to fulfil all the legal requirements for safe emissions, with two exceptions: *nitrogen oxide emissions* – which can be filtered out using additional catalytic equipment – and *Dioxin emissions*. It is possible to reduce the amount of Dioxin emission by increasing the level of fine dust and aerosol precipitation, but at present, Dioxin precipitation still requires special equipment.

Wastewater is a major problem for operators of wet flue gas cleaning systems. In most systems, the water flow is counter current to the gas flow. This means that fresh water enters at the last gas cleaning stage and effluent water is ejected in the first gas cleaning stage. This is not the case in systems that have a sludge discharge outlet in each cleaning stage. This can be an advantage in the recovery of valuable materials. The example on the next page describes a flue gas cleaning system that operates bi-directionally, that is, the scrubbing water flows in counter current to the gas flow. In the MSWI-plant of Winterthur, the scrubbing water is treated in a multi-stage facility. Sludge and water contaminated with salt are the waste products. In the MSWI-plant in Bonn, the neutralized wastewater is vaporized in a spray drier. In this case, the waste product is a solid powder.

Process flow chart of the flue gas cleaning system of the municipal solid waste incineration plant Bonn



1. waste storage
2. waste crane system
3. waste feeding hopper
4. ram system
5. incineration grate
6. primary air supply as underwind
7. side wall cooling air supply
8. secondary air supply oil burners
9. support oil burner
10. steam boiler
11. spray drier
12. electrostatic precipitator
13. quench
14. scrubber
15. ID-fan 1
16. flue gas heat exchanger
17. baghouse filter
18. ID-fan 2
19. stack
20. NaOH dosage
21. Ca(OH)2 dosage
22. neutralisation system
23. liquid ammonia to injection
24. additives
25. recirculation of additives
26. outward transfer of residues
27. Dioxin/Furan destruction
28. loading of residue from flue gas cleaning
29. loading of boiler ash
30. slag removal
31. slag storage
32. slag crane
33. turbine for electricity production required by plant itself
34. Turbo generators (heating and power station)
35. district heating and condensation system (heating and power station)
36. support condensator (heating and power station)
37. feed water container
38. steam injection
39. ammonia stripper
40. ammonia cooler

(Source: Von Roll Ltd, Zurich)

Figure 51: Process flow chart of the flue gas cleaning system of the municipal solid waste incineration plant, Bonn - equipment by Von Roll)

4.4.4 Nitrogen oxide elimination

NO_x emissions from an MSWI-plant (around 95% NO and 5% NO_2 at an incineration temperature higher than 650°C) can be controlled by applying a combination of primary and secondary processes. Primary processes affect NO_x production during incineration (nitrogen reduction in fuel, construction of combustion chamber, air distribution, air ducting, and optimized air surplus); while secondary processes remove existing NO_x molecules, usually by splitting them into nitrogen N_2 and an oxygen compound – for instance water (H_2O) – as steam. Secondary processes may be dry or wet. Wet processes involve the oxidation of NO to NO_2 or a direct reduction of NO to N_2. Both reactions may occur either before or after absorption in scrubbing liquids. The selective catalytic reduction (SCR-), the selective non-catalytic reduction (SNCR-) and the electro-beam process are examples of dry processes.

The dry SNCR denitrification process is based on chemical reactions occurring between nitrogen oxide, NO_X and ammonia, NH_3. If the ambient temperature is high enough, these reactions take place without catalysts.

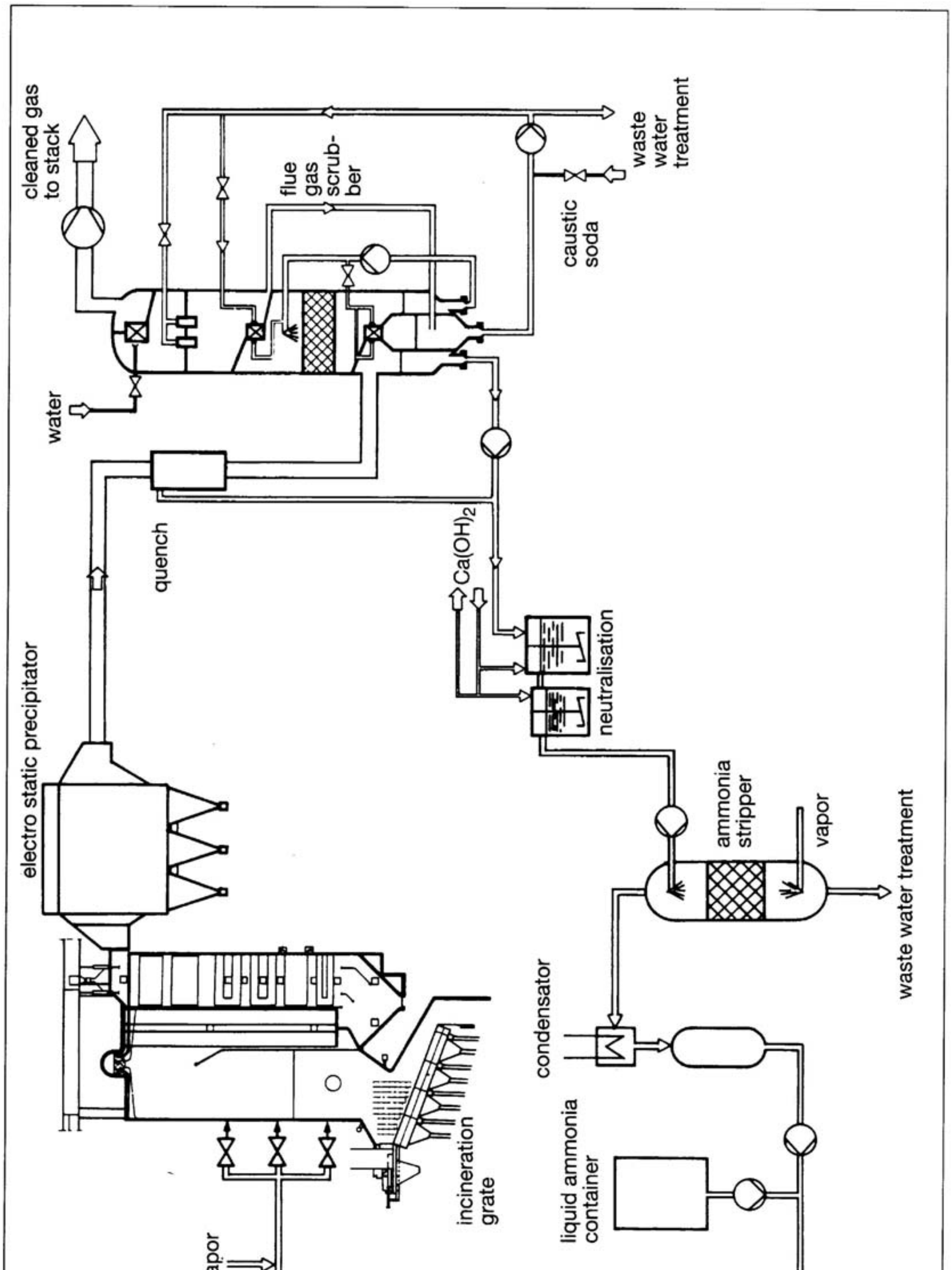
There are three important reactions here:

a)	4NO	$+ 4 NH_3 + O_2$	$= 4N_2 + 6H_2O$
b)	$4 NH_3$	$+ 5 O_2$	$= 4 NO + 6H_2O$
c)	$4 NH_3$	$+ 3 O_2$	$= 2N_2 + 6H_2O$

Equation a) is the desired reaction which reduces nitrous oxide to nitrogen and water. It occurs in the temperature window, 850 and 1000°C. Above 1000°C, the undesirable reactions b) and c) are predominant. These two reactions occur during the combustion of ammonia. Should the temperature at injection level drop below 850°C, reaction a) still occurs, even without a catalyst; but the reaction proceeds very slowly unless a large amount of NH_3 is added. It is preferable to carry out this type of denitrification using an added wet gas scrubbing system. Then the process can be driven at the lower end of the temperature window and ammonia combustion is therefore kept to a minimum. However, a threefold stoichiometric surplus is required for operational results. A large percentage of the surplus ammonia is flushed out into the wet scrubber where it is then dissolved.

Ammonia is sprayed into the radiation part of the waste heat boiler as 25% liquid ammonia.

Von Roll SNCR-DeNO$_x$-process



(Source: Water, air, industry 1987)

Figure 52: Von Roll SNCR-DeNOx-Process

The temperature profile of a municipal solid waste incineration boiler is subject to large fluctuations. This is why several injection levels are required. On the side of the boiler, the injection valves are built directly into the fine tube walls to maintain a spray that covers as much of the gas flux space as possible. The wastewater from this flue gas cleaning system must be specially treated for ammonia overload. This is done in a steam-filled stripping column, which is preceded by a lime milk neutralization process. By raising the pH value of the ammonia from 0.5 to about 11, the ionized form reconverts to the molecularly dissolved variant. Since lime milk is used as the neutralization substance, it is essential that there is no sulphur dioxide in the sludge. This would cause gypsum generation as a side effect and so cause congestion in the stripping column.

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