



ACP-EU Cooperation Programme in Higher Education (EDULINK)
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CHE 5103 - MECHANICAL, BIOLOGICAL AND THERMAL WASTE TREATMENT

Design limitations (waste quality and quantity), treatment process, biochemical reactions and microbial ecosystems, thermodynamic waste heat generation and effects on pathogen die-off, biological treatment: anaerobic digestion, composting and mechanical biological treatment, aerobic and anaerobic treatment of bio and green wastes, mechanical and biological treatment of residual waste (MBT), process design to maximize methane production, digester designs, biogas collection and utilization, biomass and biofuel production, thermal waste treatment technologies.

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1 Introduction

Waste can be treated in various ways. All these different treatments have different reasons and objectives. These include the separation of a recyclable fraction and its accumulation to bring these resources back into the resource loop. Even pollutant elimination can be achieved with waste treatment. In this way the accumulation in landfills and resource loops can be reduced. Another point is the improvement of the sorting capability as well as the inertization of waste to protect the environment from pollutants. Finally a waste treatment leads to a volume and mass reduction. This saves transportation costs and reduces the volume of landfills. Normally waste treatment with subsequent recovery serves the resource conservation and climate protection. Figure 1 gives an overview on the different treatments paths.

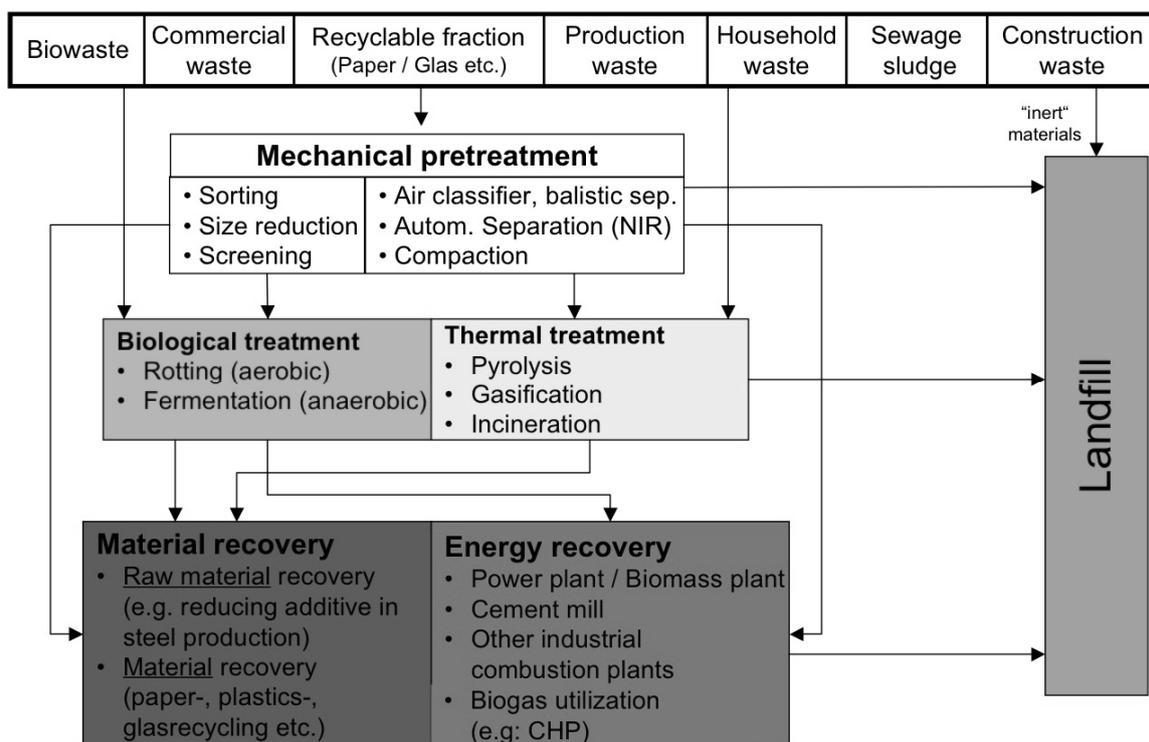


Figure 1: Basic operations for Treatment and Recovery of waste [according to Albers, 2008]

2 Mechanical Separation

The objective of mechanical waste treatment is recycling, which means the extraction of secondary raw material or fuel. It is desirable to recover all materials from the waste streams if technological and economical feasible. On one hand materials could be recovered for reuse, processing or recovery. If this is not feasible the energy content of waste could be used to produce electricity and heat. The problem is that in many cases waste has not the quality to be used directly in a production process or for energy generation. The waste has to be treated in different ways before utilizing partial fractions from the heterogeneous mixtures of materials. Basically the mechanical treatment of waste can be classified in two different category groups: First the modification of disparity through fragmentation or compaction and secondly the modification of mixing conditions by mixing or separation. For this purpose different techniques are used to recover single materials for reuse from the waste streams. This includes various processes like size reduction, classification, sorting or compaction. Which processes and technologies are coming into operation depends on the following selection criterions and requirements:



- Type and characteristics of the treated waste
- Quality requirements of the 'products'
- Quality and quantity of the residues
- Cost-effectiveness; Treatment costs (operational and investment) and revenues compared to costs for disposal
- Safe disposal

All processes mentioned above and the involved techniques are described in the following.

2.1 Size reduction

Size reduction means the transfer of objects (waste) into smaller particles with the help of mechanical force. Generally the objectives for size reduction are the increase of the specific surface for the subsequent processes (chemical, biological and thermal), decrease of volume, production of other particle size distributions and homogenization or disintegration of composite material for further treatment steps. For the selection of appropriate treatment methods or techniques some prerequisites like the physical characteristics of the material (particle size, structure, hardness etc.), subsequent processing steps, or required properties of the 'end-product' (particle size distribution, specific particle size etc.) must be considered. After taking into account all relevant aspects it is possible to select an adequate technology for size reduction. Advantages and disadvantages of these techniques are briefly described below.

2.1.1 Hammermills

Generally hammermills can be distinguished in horizontal-shaft or vertical-shaft constructions with attached flexible blades. Hammermills have been established for crushing of scrap automobiles as well as construction, commercial, and paper waste [Bilitewski, 1994].

In a horizontal hammer mill (see Figure 2) a number of hammers are mounted around the shaft or rotor disc which rotates at high speed. Waste is reduced in size by being stuck against breaker plates or cutting bars fixed around the periphery of the inner chamber. The crushed material exits through the bottom of the mill [McGraw, 1993].

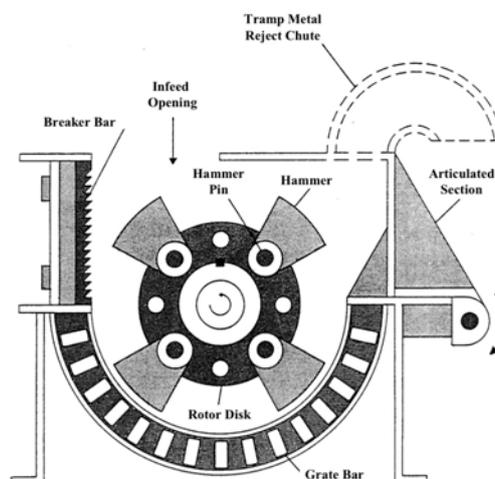


Figure 2: Cross-section of a horizontal hammermill [CalRecovery, 2005]

The vertical hammer mill (see Figure 3) has a vertical rotor equipped with hammers. It was designed specifically for the processing of household waste. Air is drawn out through a side vent at the time of charging



because of the low initial input. This way it is possible to grind lightweight fractions like paper or plastics with a high throughput as well. Because this hammer mill has no grate for the limitation of particle size, the number of hammers in the mill adjusts the particle size distribution only. An increasing number of hammers results in a finer particle size distribution but also a lower flow-rate. For controlling the size of particles it is necessary to keep the distance between the mill housing and lowest hammer level constant [Wittmaier et al. 2009].

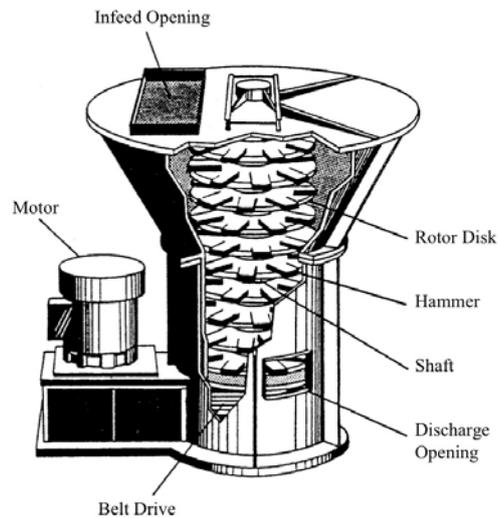


Figure 3: Vertical hammermill [CalRecovery, 2005]

2.1.2 Impact Crusher

An Impact Crusher (see Figure 4) is constructed of a multisectional body and breaker plates. The rapidly rotating roller has exchangeable hammers. To vary the size of the output it is possible to adjust the distance between the breaker plates and the hammers as well as the inclination of the breaker plates. If crush-resistant material enters the crusher, the breaker plates can withdraw upward and the material is ejected downwards. The material is filled into the crusher from above and crushed matter is discharged below.

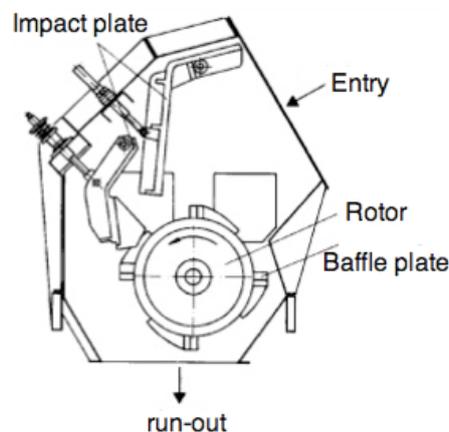


Figure 4: Principle of an impact crusher

Any substance is grabbed by the hammers and dashed against the breakers plates. The breaker plates are arranged so that material remains in the mill until it is fine enough to pass through the opening between the



rotor and the breaker plates. If such a crusher is used to grind construction debris, it is necessary to cut up and shorten concrete reinforcement bars before they are inserted so that they do not wind around the rotor and cause a system lock-up [Bilitewski, 1994].

2.1.3 Chippers

Chippers are low speed mills. The mill has single or double horizontal shafts. The shafts rotate in opposite direction against a cutting edge, thereby drawing the material towards them. The comminution of the material occurs between the cutting edges regardless of whether the material is soft, elastic, or hard. The size reduction of plastics is one application of this mill type.

2.1.4 Cascade Mills

A Cascade mill is a rotary drum with a diameter of 4.0 to 4.2 m, which is slowly rotating. The ratio of diameter to length is approximately 3:1. The mill is filled with about 17% of steel balls. The optimum rotation is 14 to 20 rpm and the size reduction occurs by the grinding and rolling action of the steel balls against the waste material. After the waste has attained the correct particle size, holes in the housing walls allow for discharge. The steel balls must be replaced continuously, because they wear off and leave the mill based on their own size reduction. If unbreakable material is inserted into the mill, it can also serve as grinding body. This is also called "semi-autogenous grinding process" [Bilitewski, 1994].

2.1.5 Rasp Mills

Rasp Mills have been designed and constructed for waste treatment in composting plants. After inserting the waste into the mill, the material is dragged around by a rasping arm that turns above the screen. Materials like glass, paper, or kitchen and yard waste, which are easily shredded, fall through the screen after a short retention time. More resistant material like metals or plastics are discontinuously pushed out through a side discharge. Rasp Mills are rarely used for processing solid waste, due to their ineffectiveness in comparison with hammermills and their discontinuous operating control.

2.1.6 Jaw Crusher

Jaw Crushers are normally used for hard and brittle material, primarily in the construction and demolition industry. The material is dropped between two swinging jaws from above. Because of the movement of these jaws, the material is crushed and ground. The particle size can be adjusted by the opening of the jaws (space between the jaws).

2.2 Classification

Classification means the separation of material in classes of same particle size. It can be divided into two different classification forms: sieve classification and flow classification. Sieve classification is the separation of material by particle size with screening (Trommel screen, Disc screen, etc.). With flow classification the material is separated by its sink rate in a separation medium like air (air classifier). The objectives of classification are:

- Production of saleable products with defined particle size
- Separation of fine and coarse material for facilitation of subsequent sorting or size reduction processes (protection against attrition or blockage)
- Use of selective accumulation of individual components in certain sizes or form classes for sorting

The different processes and techniques of classification are described in the following section.



2.2.1 Screening

Screening of material is a segregation of various sizes into specific particle size categories. This process can also be called classification. By contrast to screening, separation and sorting involves the separation of material into components of different types and characteristics. Waste can be screened according to particle size and also at the same time separated into different material characteristics, assuming that the material remains in the same particle size range. In this case the screening can also be used for separation. Screening is performed by separating particles based on the size of the openings on the screening surface. If the particles are smaller than the openings, they fall through the moving screen and become a part of the fine fraction. The other part of the material contained above the screen is considered the oversize fraction. Normally a certain percentage of the fine fraction remains in the oversize fraction. Furthermore, design flaws or wear out of the screen surface can result in oversize material falling into the fine fraction. This fraction is called outsized fraction. The particles which have exactly the same size as the screen openings play a critical role. These particles have a tendency to get stuck and cause wear on the screen. The efficiency of the screening is based on the relationship between the fine fraction which passes the screen openings and the fine fraction in the initial feed. The screen efficiency rating is influenced by various factors:

- Machine dependent factors (e.g. screen width and length, screen angle and form, vibration frequency and amplitude, revolutions),
- Screen surface dependent factors (e.g. surface type, opening size, screen material), and
- Screening dependent factors (e.g. feed input, surface dampness, particle size, distribution and fiber content).

Fine grained, damp, and sticky material can clog the screen surfaces. In this case the opening areas are reduced and the screen output decreases. To reduce the clogging it is possible to add screening aids including brushes, chains, screen heaters, air blasts or adding water to increase the capillary pressure between the sticking parts [Wittmaier et al. 2009].

Trommel screen

The Trommel screen is a proven classification technology for the processing of solid waste. It is one of the most versatile types of screens. It can be used for primary screening as well as for final size reduction. A trommel screen consists of a large-diameter screen, formed as a cylinder which is rotating on its horizontal axis [McGraw, 1993]. Figure 5 shows a basic trommel screen.



Figure 5: Trommel screen [Vu, 2001]



Different parameters have an influence on the screening efficiency. These include Trommel diameter, rotational speed, size of the screening openings, the type and number of baffles and the inclination of the cylinder. The classification of material in more than two fractions is possible by using different screen openings together inside the trommel. Figure 6 gives an example of a screening plate.



Figure 6: Screening plate

The effective screen area is relatively small, therefore deflectors and other wall assemblies are installed to carry the waste as high as possible up the trommel wall in order to receive the maximum screening potential. The trommel walls are equipped with spiral shaped deflectores to transport the material through the trommel regardless of the degree of the trommel. This also leads to an increase of the screen efficiency rating [Wittmaier et al. 2009].

Oscillating screen

The oscillating screen is a dynamic screening method. It is a clog free and productive screening method, which has proven for the screening of compost. The screen consists of a flexible woven mesh made of rubber or plastic attached to oscillating arms moving in opposite directions. The automatic operation of the arms causes a wave-like movement of the woven mesh with openings of 30 to 50 mm. During the screening process, oscillating frequencies of 1/600 to 1/800 minutes⁻¹ are reached. This causes a relatively strong impact of the screening material against the woven mesh [Billitewski, 1994].

Bucket screen

The bucket screen was developed for the treatment of waste with bulky and fine components like construction, demolition or commercial waste. The operation is easy and clog free. During the process the fine fraction falls into buckets and is discharged from the highest point of the screen via conveyor. The screen is open-top and s-shaped in the active screening area. Coarse grained particles are sliding down the inclined surface of the bucket screen and are carried away at the end by a conveyor.

Balistic separator



The construction of the ballistic separator was developed for the separation of household and commercial waste. With this appliance the waste streams can be separated into light (e.g. paper, plastic foil etc.), heavy (e.g. stones, metals, etc.) and fine fraction. Figure 7 illustrates the separation of these fractions with a ballistic separator.

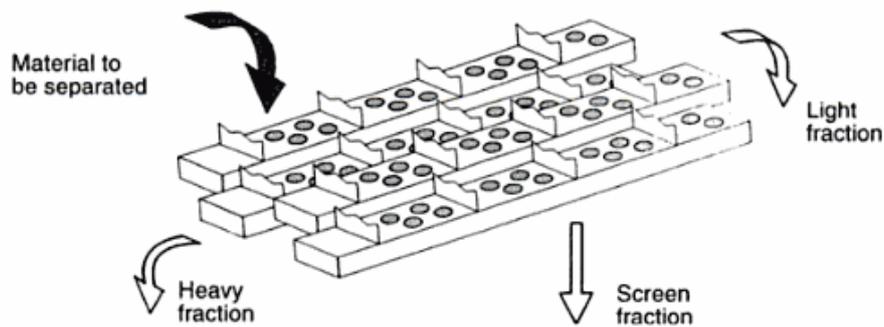


Figure 7: Schematic drawing of a ballistic separator [Billitewski, 1994]

The ballistic separator is used for the production of RDF from municipal solid waste or paper sorting. It consists of a moveable, inclined and perforated lat screen deck and a feed hopper. The deck of the gadget is divided into rows of vibrating elements. Depending on weight and form, the material is transported up or down. The heavy particles (heavy fraction) move down and the light particles (light fraction) move toward the highest level of the deck. The third fraction fine particles are falling through the perforated bottom of the deck (see Figure 8).



Figure 8: Ballistic separator

Disc screen

A disc screen consists of sets of parallel, interlocking, rotating discs. Fine waste falls through the spaces and oversized materials are carried over the top of the discs as on a conveyor belt [McGraw, 1993]. The distance between the discs determines the size of the screen opening of each grate.



2.2.2 Air classification

Air classifiers are separating according to the descent rate of particles. It depends on the form of the particles and the specific weight. The design of an air classifier requires calculation of the waste-loading rate (kg/m^3) or the reciprocal value. This is necessary, because a value above or below the certain value affects the separation into light and heavy fraction negatively. Figure 9 shows the principle of a horizontal air classifier.

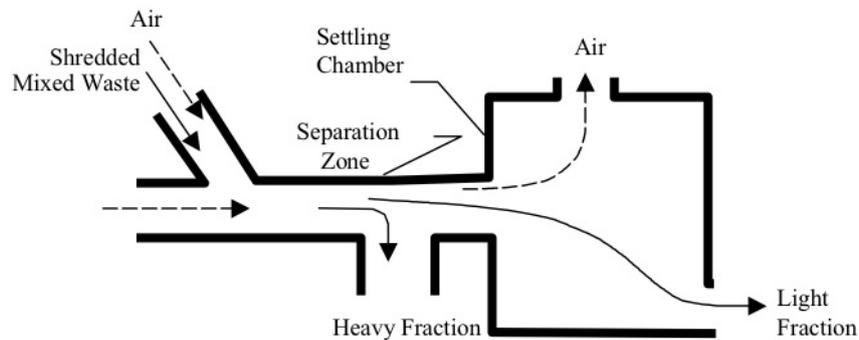


Figure 9: Principle of a horizontal air classifier [CalRecovery, 2005]

A lot of other parameters are relevant for the efficiency of an air classifier. This could be moisture content, waste composition, density, previous size reduction or agglomeration tendency. Depending on the characteristics of the material or pre-treatment these factors have a positive or negative influence on the process. For waste processing two types of air classifiers are in use: The zig-zag air classifier and the rotation air classifier. Typical operational area are the sorting of light packaging, plastics, production of RDF or treatment of household and commercial waste.

Zig-zag air Classifier

A zig-zag air classifier consists of a continuous vertical column with internal zigzag deflectors, through which air is drawn up at a high rate. Waste is introduced in the upper range and air is introduced at the bottom [McGraw, 1993]. The zig-zag air classifier is well proven in waste treatment. It is often used for the separation of household waste. One advantage is the low error rate, because in each corner of the classifier the material is resorted. This is the result of cross-current flow of the air stream at these points. The material can be sorted in a zig-zag air classifier into heavy and light fraction. Specific light and plane particles are lifted in the air stream and thus reach the light fraction. Specific heavy particles are not lifted and stay at the heavy fraction. To get a higher selectivity, parameters like input or speed of the air stream have to be adjusted. A disadvantage of this method is the low operational capacity. Figure 10 shows the schematic principle of a zig-zag air classifier.

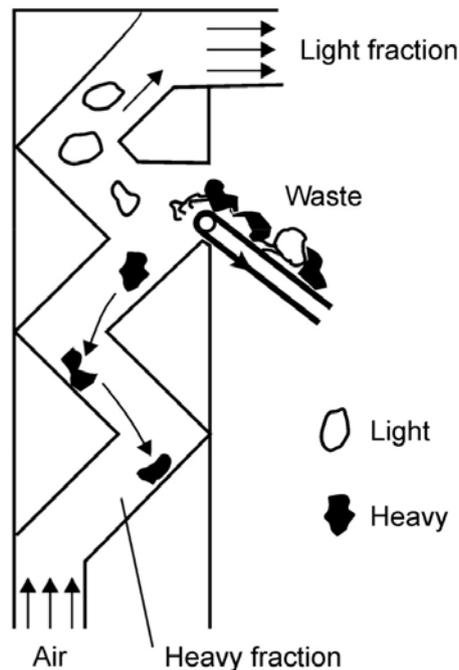


Figure 10: Schematic principle of a zig-zag air classifier [Bilitewski, 1994]

Other air classifiers are the rotary air classifier, the suction hood or the cross-current air classifiers. They are all sorting with the same principle, the separation of light and heavy fraction with air.

2.3 Sorting

Sorting means the separation of material on the basis of other characteristics than particle size. This could be colour, optic, flotation, kind of material, density, shape, conductivity, and so on. For each of these characteristics there are various kinds of sorting techniques and aggregates. The sorting process takes advantages of the physical characteristics of each waste fraction to separate different waste streams. A lot of techniques developed for sorting are not useful for heterogeneous and mostly wet waste streams. Furthermore they are too expensive in most cases. Separators, which have established in waste management, are magnetic separators, hydrocyclones, flotation separators and density sorters. Beside these midgets the manual sorting still plays an important role.

2.3.1 Magnetic Separation

For the magnetic separation, either permanent magnets or electromagnets can be used in different configurations (single or multistage system). The objective is the separation of ferrous metals. Operational areas are the separation of iron-crap from metal mixtures, tin plate separation at light packaging sorting or the separation of ferrous contraries from waste streams. Generally the separation happens with an overhead magnetic separation system (see Figure 11).

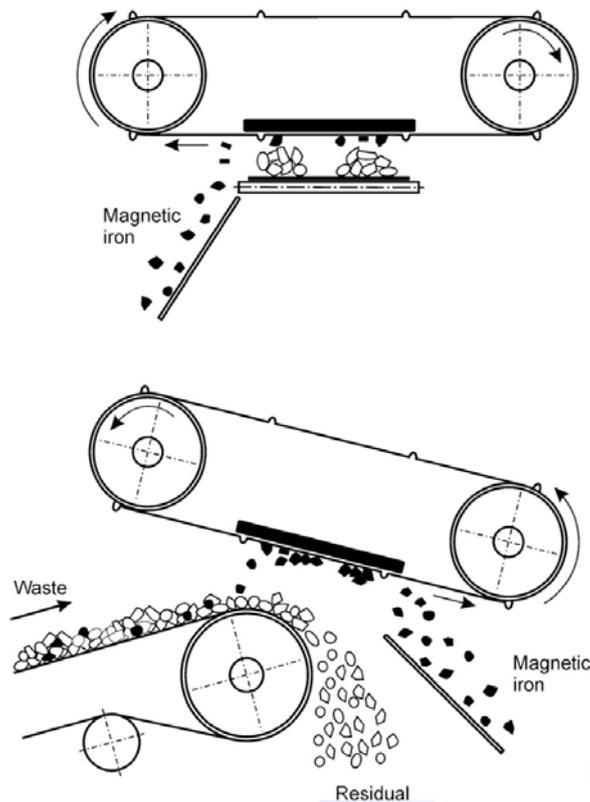


Figure 11: Principle of magnetic separation

With the magnetic separation ferrous material can be removed from the waste stream. This system also needs a pre-treatment step to be effective: size reduction. After reducing the size of the particles in the waste stream the ferrous material is separated from other materials and can be caught by the magnetic separator. Magnets of all dimensions are available, therefore the system is not limited by the size of the material. By the treatment of municipal solid waste the ideal particle size ranges between 10 to 100 mm [Wittmaier et al. 2009].

2.3.2 Eddy Current Separator

Eddy current separators provide a mechanism for sorting waste mixtures of similar density grades, e.g. aluminium and glass. The technology of these separators relies on the induction of eddy currents in metal objects in response to an electromagnetic field [Bilitewski, 1994]. The sorting criterion is the electric conductivity, which is different for various waste particles. A good separation is possible for i.e. aluminium, magnesium, or copper whereas zinc, tin or lead are not reliably sorted with this method. Operational areas are scrap treatment, wood treatment (aluminium fittings), glass treatment (closure), sorting of aluminium packaging and other recycling processes. Requirements for the use of eddy current separators are pre-separation of light components like plastic foil (components, which are able to 'fly') and a well separation / Isolation of the waste stream. The principle is shown in Figure 12.

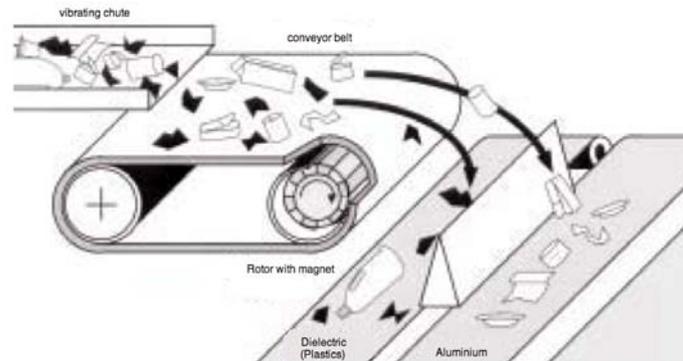


Figure 12: Principle of Eddy Current Separator

If a conductor (object) such as aluminium is placed in a time-varying magnetic field, a voltage is generated in the material. This voltage will cause a current to flow and induce a magnetic field that is opposite in polarity to the applied field, thus producing a magnetic force, which thrusts the object out of the magnetic field [McGraw, 1993].



Figure 13: Eddy current separator [Wittmaier et al. 2009]

2.3.3 Optical Sorting

This treatment version for waste streams was especially developed for sorting mixed, crushed glasses into the different colors. For separation manufactures have developed electro-optical sorters, which recognize the color of the glasses based on their opacity, and with the aid of a blast of compressed air, deflect the particle from its flight path into appropriate catch bins. While sorting glass it is practicable to achieve a purity grade of 98 %. To achieve this degree of separation it is necessary to sieve and reduce the particle size and to individualize the glasses. Singular glass particles are optically inspected in the following order: flint glass, green glass, brown glass and nontransparent. This method is also used for the separation of plastics. Advantages are the good separation rate (98%) and the low personnel requirements. On the other hand, optical sorting has high technical efforts and high maintenance costs. Figure 14 shows the optical sorting of plastics.



Figure 14: Optical sorting of plastics [Wittmaier et al. 2009]

2.3.4 Flotation

Flotation is typically used when the components of material mixtures have similar specific densities. Then these components are separated by a fluid. Contaminants in barite, ore, coal, slag, plastics, printing ink, etc. could be removed with flotation. The most important operational process is the flotation deinking process for the production of high quality graphic paper from waste paper. This process contributed to the increasing of the paper waste recycling [Wittmaier et al. 2009].

2.3.5 Density Sorting

Density sorting with the help of a fluid medium was developed by the ore industry. Waste management also tried to use this process for sorting of waste components like nonferrous metals, glass, plastics or contaminants. The most used treatment process is the density sorting of plastics. There are two types of density sorting with fluid medium:

- Float-sink method
- Hydrocyclones

Float-sink method

With this separation technology purity grades of over 98% could be achieved for mixed plastics. The presence of fines in the input material is one reason for the rejects. Pre-treatment of the waste streams by air classifier can be used to collect most of the fines. The separating fluid (for example water with a density of 1.0 g/cm^3) must be adjusted to the density range of the mixed plastics components from household and commercial waste ($\text{PE} < 0.98 \text{ g/cm}^3 < \text{PS } 1.05 \text{ g/cm}^3 < \text{PVC}$) [Bilitewski, 1994]. In this case the heavy fraction comprises PS and PVC. An essential point for the success of this separation process is the fact that no turbulences should occur in the separation zone. These turbulences could cause the heavy fraction to become suspended.

Hydrocyclones

The separation of different types of plastics by a hydrocyclone is accomplished in the centrifugal force field within the cyclone. The geometry of a hydrocyclone creates an upwardly spiraling inner-vortex that carries out the light fraction, while an outer-vortex spirals downward and brings out the heavy fraction. The principle is



shown in Figure 15. The hydrocyclone has a simpler construction, no complicated components and a higher feed rate in comparison with the float-sink method. The quality of the output components of a hydrocyclone is affected by the type and quality of pre-treatment [Bilitewski, 1994].

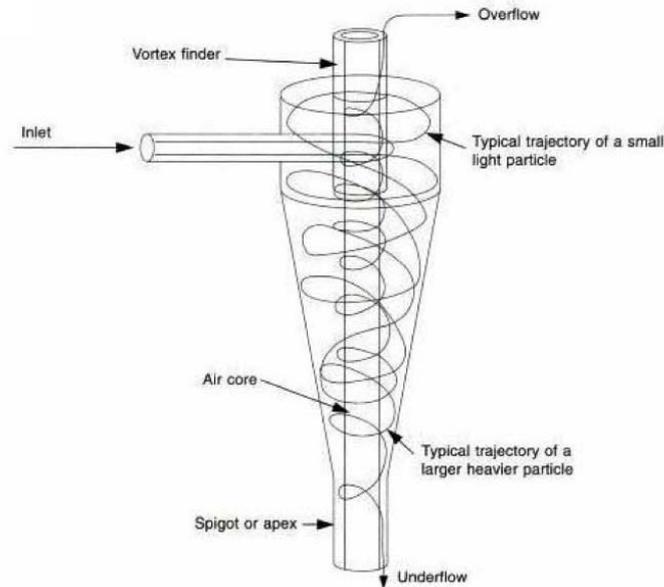


Figure 15: Principle of a hydrocyclone [Lenntech, 2007]

2.3.6 Manual Sorting

Manual sorting is a cheap, easy and fast way to treat waste streams. It's a very reliable method to separate secondary products from waste streams. Manual sorting can be distinguished into positive and negative sorting. At positive sorting (e.g. plastics) the recyclables are removed from the waste stream and placed into appropriate bins. The discard remains on the sorting belt. At negative sorting the process works exactly contrary wise (e.g. at composting). With negative sorting it is possible to achieve higher collection rates. But the quality is lower than with positive sorting. Instead the collection rate is slower with positive sorting.

Manual sorting can take place for sorting of various kinds of glass, wastepaper or polyethylene with different qualities. Also contaminating materials could be removed out of the household or industrial waste streams. An advantage of manual sorting is the flexibility. The sorting process could be adapted quick to possible fluctuations in market prices of secondary raw material. Moreover manual separation is an easy process with high availability and reliability with low technical complexity.



Figure 16: Manual separation of waste streams in Vietnam [Wittmaier et al. 2009]

Disadvantages of manual sorting are the costs, at least in industrial countries. By combining manual and mechanical sorting methods, the effectiveness could be increased and the costs could be minimized. For this purpose different kinds of sorting techniques could prepare the waste streams for the manual sorting. This helps to raise the efficiency rate of the sorting staff.

In developing countries manpower often is not so expensive and sometimes cheaper than high end gadgets. Thus the personal intensive manual sorting could be the more economic way in such countries. Other disadvantages of manual separation are the healthy burden for the staff and the fact that small particle sizes (< 40 mm) are difficult to separate.



Figure 17: Manual sorting at composting plant in Phnomh Phen, Cambodia



2.4 Compaction

The primary objective of compaction is to reduce the surface area and the formation of bigger agglomerates. Two typical methods for compaction are used in the field of waste treatment. On the one hand the build-up agglomeration, this uses the influence of binding agents or added fluids after drying the material. On the other hand compaction could be produced by outside acting forces (press agglomeration). The binding mechanisms for MSW are basically the same for both procedures and can be described as:

- Binding via adhesion and cohesion forces,
- Solids bridging,
- Capillary force attraction and
- Interlocking bridging

The build-up agglomeration is primarily used to transform dust particles (e.g. from flue gas scrubbers) into solid granulate. However, the press agglomeration is more important for waste management. It is quite important in the logistic field of the waste management, due to the lower costs for transportation and storage of waste. Other advantages are the rising energy density of the waste by compaction especially for thermal recovery as RDF, the avoidance of bridging in silos and transport conveyances and the improved flow and proportioning characteristics of waste.

The compaction methods are divided into solid resistance compaction (e.g. bale press or the compactor) and extrusion moulding (e.g. pellet press, briquette press and extruder). While the former uses the walls of the pressing chamber as a solid resistance, the latter uses formed mould plugs or briquettes for resistance. When the maximum pressure is reached, the mould plugs retract from the sides or the front and rear, the compaction process stops and the waste briquette is ejected. Extrusion moulding can be a continuous, semi-continuous or batch process. The continuous process (e.g. compactor) is used for wet, fine-grained material. The semi-continuous processes (e.g. pellet press) are pug mills where rollers rotate over slotted plates or ring matrices. In a batch process mechanical or hydraulic rollers compress the material in successive lifts into open moulding channels [Wittmaier et al. 2009].

2.4.1 Bale press

The use of balers is quite common for different materials. These materials are for example paper, plastic wrapping, metal cans or paperboards. Bale presses are used for the agglomeration of sorting residues, household or bulky waste. Figure 18 shows a typical bale press.



Figure 18: Bale press

Typical dimensions of a bale are 1,5 m length and 1 m height. The weight of the bales depends on the material (household waste could be compressed to a density of 600 kg/m^3 with an antechamber press; the weight of a paper or light packaging bale is around 500 kg/m^3). The bales are robust and it is an available and cheap technique. The bales are showing a good storage performance, which means less dust formation or danger of smolderings.

2.4.2 Other compaction methods

Other compaction methods like pelleting are used primarily to produce refused-derived fuels (RDF) for combustion in incineration, gasification or pyrolysis systems. Another application area is the compaction of discards after material recovery has occurred. In the following two technologies will be described:

- Briquette presses
- Pellet presses

Briquette presses work as a piston rod with flywheel. First the waste is pre-compacted in a screw press. After that, it is fed batchwise via a conical feed chute to the compression moulding die. The brikollare-press is another application. In this process die-formed mouldings consisting of garbage/sludge mixtures with a moisture level about 55 weight-% are produced (tumbling under hydraulic pressure) [Bilitewski, 1994].

In the RDF industry pellet presses have a higher preference compared to briquette presses. The reasons are higher input rates and greater size reduction in a pug mill. There are different types of pellet presses for compaction in use, e.g. John Deere presses, ring matrix presses and flat matrix presses. The John Deere press consists of a ring of vertical press channels. Material, which has to be compacted, is added onto the roller track above the press channels. Then the material is pressed into the square channels by the roller. The material is formed into strands that are subsequently cut by stationary blades. The ring matrix press (vertical press) consists of rollers circling within a ring mould (see Figure 19).



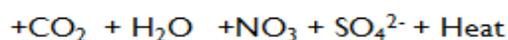
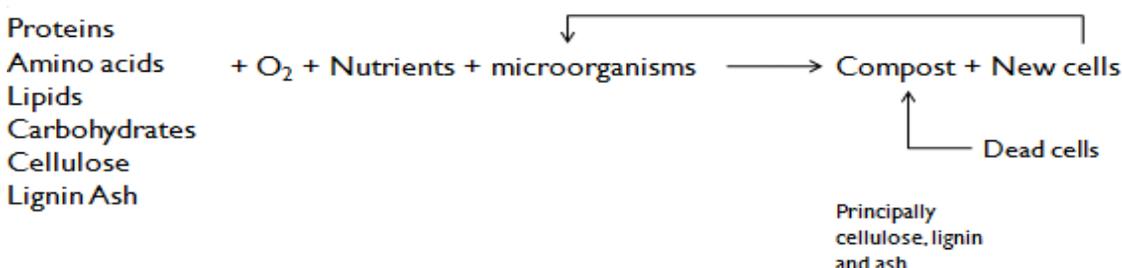
Figure 19: Ring Matrix Press

Either the ring mould or the rollers are powered. The material is pressed from within through the boreholes within the ring mould. Number and size of the rollers is determined by the interior size of the ring mould. Flat matrix presses are constructed with a round and a flat mould with powered rollers rotating above. Material is pressed through the channels perpendicular to the axis. Numbers of rollers and distance between the rollers is more adjustable than with ring matrix presses. The material, which should be compacted, is fed from above the pressing unit. Guiding plates or force feed mechanisms are not necessary.

3 Biological Waste Treatment

3.1 Composting

Composting is the biological decomposition and stabilisation of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plants seeds, and that can be beneficially applied to land (Haug, 1993). The general equation is:



Aerobic composting is the decomposition of organic substrates in the presence of oxygen (air). The main products of biological metabolism are carbon dioxide, water, and heat.



The objectives of composting are:

1. to transform the biodegradable organic materials into a biologically stable material, and in the process to reduce the original volume of waste
2. to destroy pathogens, insect eggs, and other unwanted organism and weed seeds that may be present in MSW
3. to retain the maximum nutrient (nitrogen, phosphorous, and potassium) content, and
4. to produce a product, compost, that can be used to support plant growth and as a soil amendment.

Materials that can compost are organic in nature and have high moisture content. Typical substrates are

- Municipal biosolids
- Industrial sludges
- Manures
- Yard wastes
- Food and agricultural wastes
- Municipal solid wastes

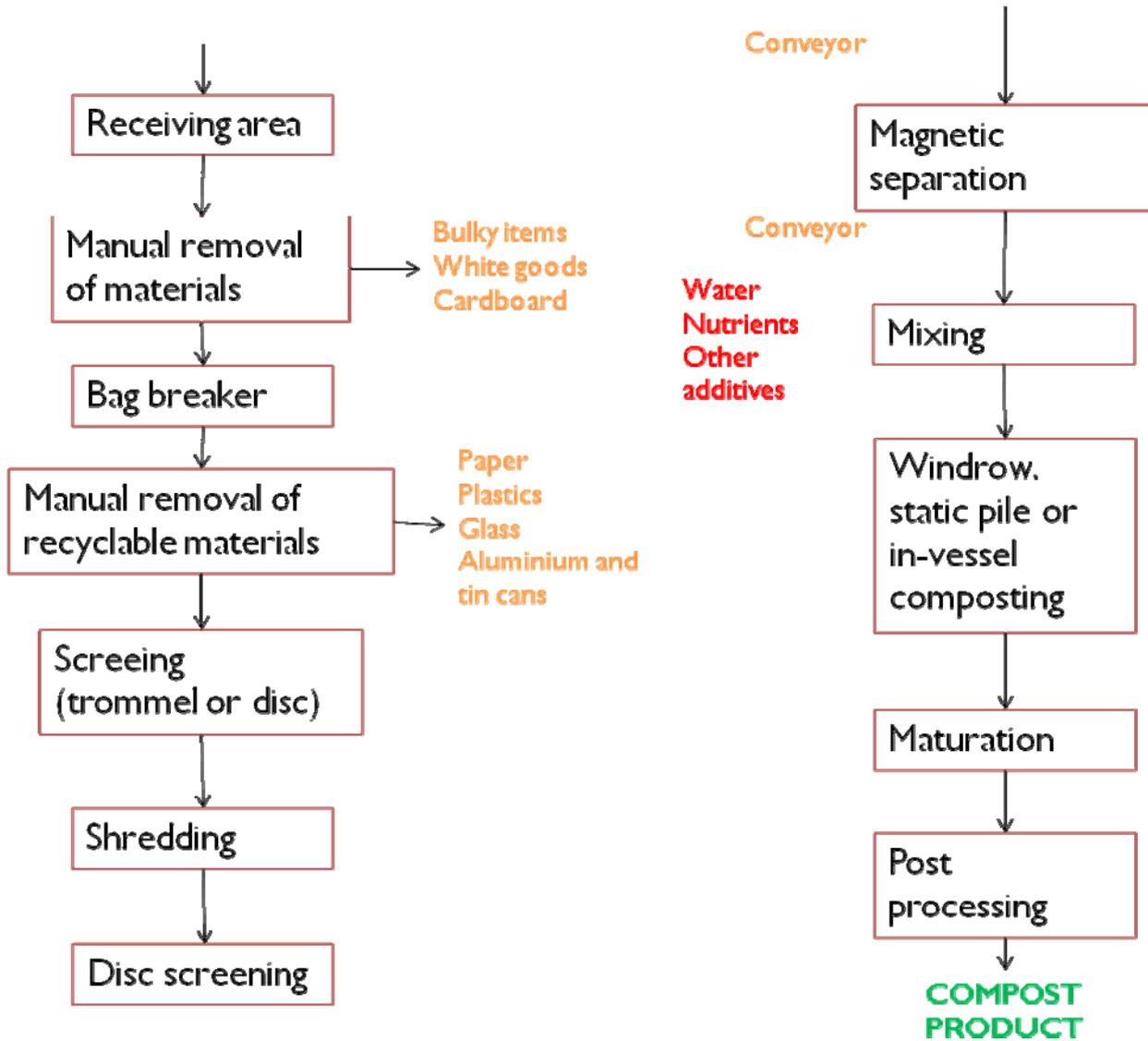
3.1.1 *Process description*

Composting has always occurred in nature. However, the first organized composting operations to be reported in literature were carried out in India in the early 1930 under the direction of Howard and associates. It is known as the Indore process. In its simplest form, the process involves excavating a trench in the ground 2 to 3 ft deep in which successive layer of waste e.g solid wastes, animal manure, earth and straw are placed. The earliest procedure was to turn the material only twice during the composting process, which lasted six months or longer. However, now there are a variety of modern approaches which seek to optimize the process parameters such as temperature, aeration and moisture. There exist a number of commercial composting operations around the world such as the dano process and other and they all consist of three basic steps:

- pre-processing of the substrates
- decomposition of the organic fraction of the wastes
- preparation and marketing of the final compost product.

3.1.2 *Process Microbiology*

- During the aerobic composting process a succession of facultative and obligate aerobic microorganisms is active.
- In the beginning phases of the composting process, mesophilic bacteria are the most prevalent.
- After temperatures in the compost rise, thermophilic bacteria predominate, leading to thermophilic fungi, which appear after 5 to 10 days.
- In the final stages, or curing period, actinomycetes and molds appear.



Microorganisms are commonly classified, on the basis of cell structure and functions, as eucaryotes, eubacteria, and archaebacteria. In some types of biodegradable waste, e.g., newspaper, it may be necessary to add microorganisms as an additive or inoculum..

Group	Cell structure	Characterisation	Representative members
Eucaryotes	Eucaryotic	Multicellular with extensive differentiation of cells and tissue	Plants (seed plants, mosses) Animals (vertebrates, invertebrates)



		Unicellular; little or no tissue differentiation	Protists (algae, fungi, protozoa, actinomycetes)
Eubacteria	Procaryotic	Cell chemistry similar to eucaryotes	Most bacteria
Archaeobacteria	Procaryotic	Distinctive cell chemistry	Methanogens, halophiles, thermacidophiles

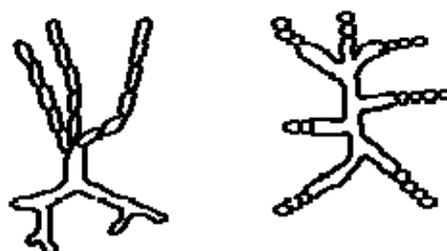
- The procaryotic group (eubacteria & archaeobacteria) are of primary importance in the biological conversion of the organic fraction of solid wastes and are generally referred to simply as bacteria.
- Eucaryotes important in biological conversion of organic wastes include (1) fungi (2) yeasts (3)actinomycetes.
- Bacteria are single cells organisms. Bacteria are the smallest living organisms and the most numerous in compost; they make up 80 to 90% of the billions of microorganisms typically found in a gram of compost. Bacteria are responsible for most of the decomposition and heat generation in compost.

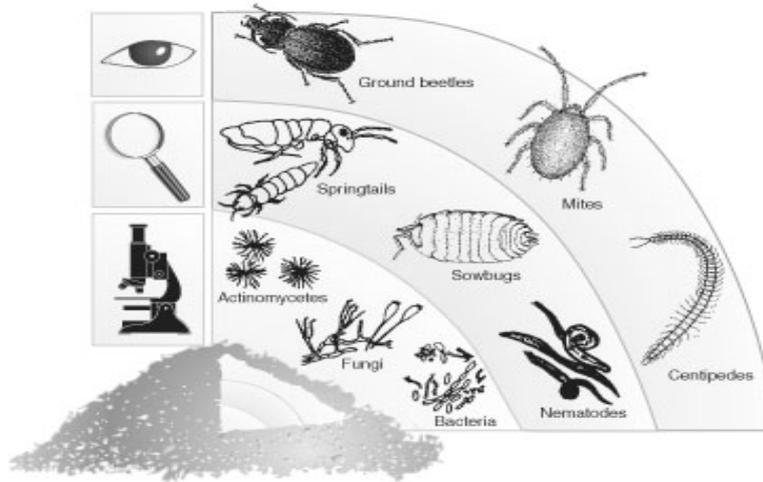


- Fungi are considered to be multicellular, nonphotosynthetic, hereterotrophic protists.



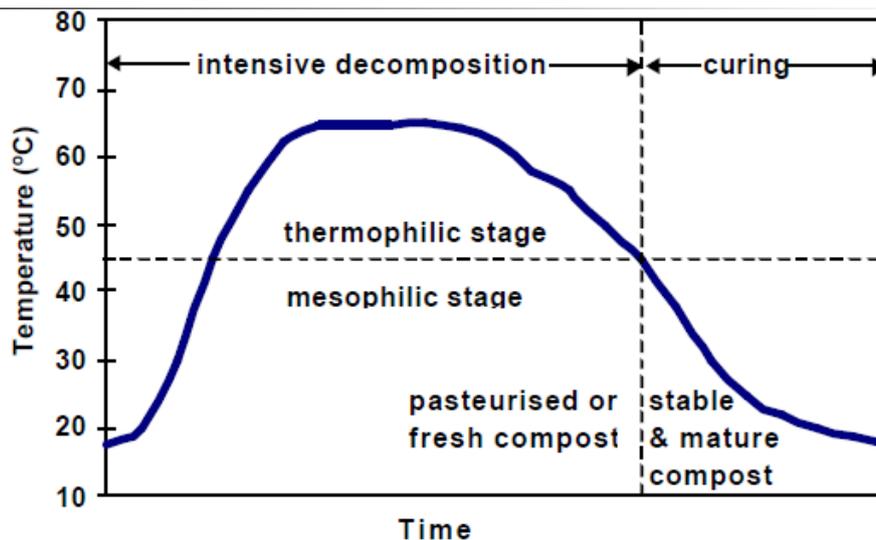
- Actinomycetes are similar in form to fungi, with properties intermediate between fungi and bacteria.





3.1.3 Phases of composting

- Under optimal conditions, composting proceeds through three phases: 1) the mesophilic, or moderate-temperature phase, which lasts for a couple of days, 2) the thermophilic, or high-temperature phase, which can last from a few days to several months, and finally, 3) a several-month cooling and maturation phase.



- Phase I: Initial decomposition is carried out by mesophilic microorganisms, which rapidly break down the soluble, readily degradable compounds. The heat they produce causes the compost temperature to rapidly rise



- **Phase II:** As the temperature rises above about 40°C, the mesophilic microorganisms become less competitive and are replaced by others that are thermophilic. At temperatures of 55°C and above, many microorganisms that are human or plant pathogens are destroyed. Because temperatures over about 65°C kill many forms of microbes and limit the rate of decomposition, compost managers use aeration and mixing to keep the temperature below this point. During the thermophilic phase, high temperatures accelerate the breakdown of proteins, fats, and complex carbohydrates like cellulose and hemicellulose, the major structural molecules in plants (4 to 5 weeks for windrows).
- **Phase III:** As the supply of these high-energy compounds becomes exhausted, the compost temperature gradually decreases and mesophilic microorganisms once again take over for the final phase of "curing" or maturation of the remaining organic matter (2 to 8 weeks in open windrows). Slowly biodegradable materials are converted by bacteria, fungi and actinomycetes.

3.1.4 *Process Design and Control*

Although the composting process is easy to grasp conceptually, the actual design and control of the process are quite complex. Important process variables that must be considered in the design and operation of composting facilities include particle size, and particle size distribution of the material to be composted, seeding and mixing requirements, the required mixing/turning schedule, total oxygen requirements, moisture content, temperature and temperature control, carbon-nitrogen ratio of the waste to be composted, pH, degree of decomposition, respiratory quotient (RQ), and control of pathogens.

3.1.4.1 Particle size

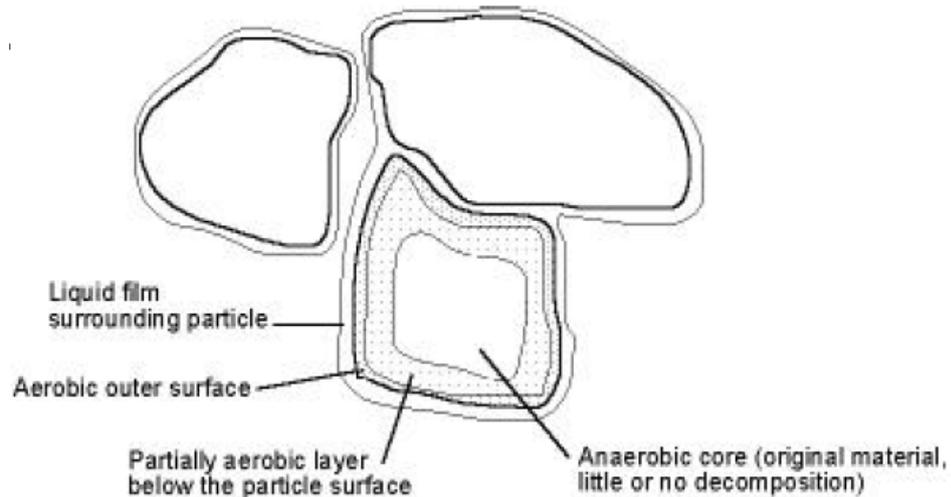
- Porosity, structure and texture relate to the physical properties of the materials such as particle size, shape and consistency.
- They affect the composting process by their influence on aeration.
- The physical properties of a composting mix can be adjusted by selecting suitable raw materials and by grinding or mixing.
- Materials added to adjust these properties are referred to as bulking agents.
- Most materials in MSW are irregular in shape. This irregularity can be reduced substantially by shredding the organic materials before they are composted.
- Particle size influences the bulk density, internal friction and flow characteristics.
- Most important of all, a reduced particle size increases the biochemical reaction rate during aerobic composting.
- The most desirable particle size for composting is less than 5 cm.

For optimum results the size of solid wastes should be between 25 and 75 mm.

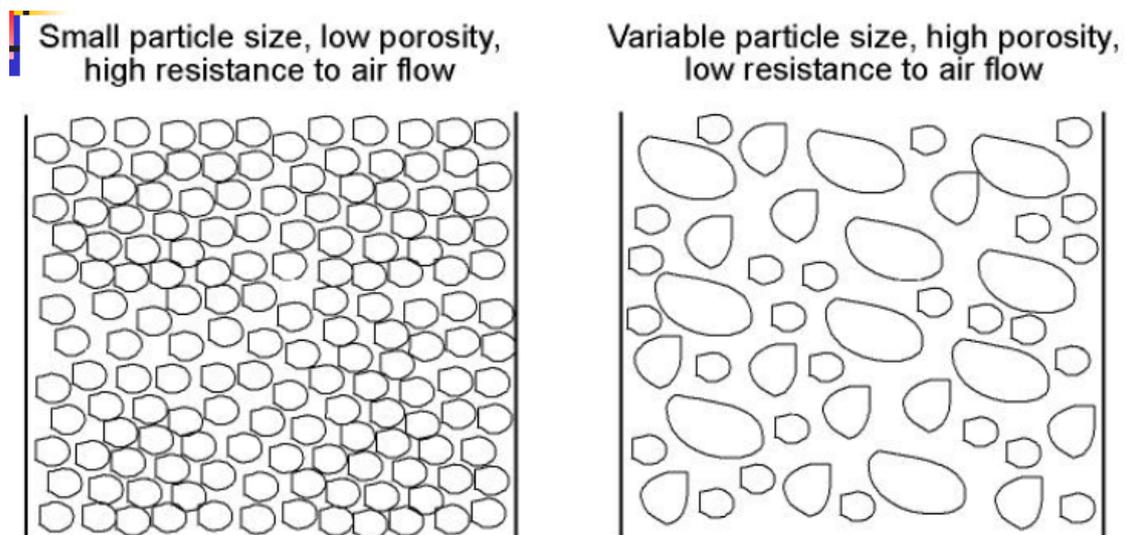


3.1.4.2 Aeration

In aerobic composting, aeration is fundamental to provide oxygen for the microbes to decompose the substrates. The figure below shows the aeration between the pores of the substrates at microscopic level. Decomposition is performed by microorganisms present within the liquid film and on the surface of particles.”



Aeration together with particle size have a key role to play in the supply of proper oxygen within the compost pile as can be seen in the diagram below. Too small a particle size allows circulation of air along specific channels and can lead to the development of anaerobic pockets within the pile.



3.1.4.3 Carbon-to-Nitrogen ratio

- Carbon (C) in organic matter is the energy source and the basic building block for microbial cells.
- Nitrogen (N) is also very important and along with C, is the element most commonly limiting.



- Microorganisms require about 25-30 parts of carbon by weight for each part of nitrogen used for the production of protein (C:N 25-30:1).
- Preparing feedstock to an optimum C:N ratio results in the fastest rate of decomposition- assuming other factors are not limiting.
- It is the most critical environmental factor for composting
- Composting is usually successful when the mixture of organic materials consists of 20-40 parts of carbon to 1 part of nitrogen. However, as the ratio exceed 30, the rate of composting decreases. Further, as the ratio decreases below 25, excess nitrogen is converted to ammonia. This is released into the atmosphere and results in undesirable odor (Pace *et al.* 1995).

Material	C/N ratio
Fruit wastes	34.8
Cow manure	18
Horse manure	25
Poultry manure	15
Raw activated sludge	6.3
sawdust	200 – 500
Mixed paper	173
Yard wastes (grass clippings)	20.1
Yard wastes Leaves (freshly fallen)	40 - 80

Two design factors that may affect the blending of organic fraction of municipal solids waste for composting are C/N ratio and moisture content. Laboratory analyses are required to determine how the various organic materials should be blended for aerobic composting. If the organic fraction of MSW contains significant amounts of paper or other substrates rich in carbon, other organic materials such as yard wastes, manure or sludge from wastewater treatment plants can be blended to optimize the C/N ratio. Similarly, materials too wet and too dry for good composting can be blended in proper proportion to achieve optimum moisture content.



Seeding involves the addition of a volume of microbial culture sufficiently large to effect the decomposition of the receiving material at a faster rate.

3.1.4.4 Moisture Content

- The optimum moisture content for aerobic composting is in the range of 50 to 60 percent. The optimum value appears to be 55 percent.
- Moisture can be adjusted by blending of components or by addition of water.
- When the moisture content falls below 40 percent, the rate of composting will be slowed.
- For higher moisture content, there is the danger that the pile turns anaerobic.

Question 1- Leaves, with a C/N ratio of 50, are to be blended with waste-activated sludge from a wastewater treatment plant, with a C/N ratio of 6.3. Determine the proportions of each component to achieve a blended C/N ratio of 25. Assume that the following conditions apply:

1. Moisture content of sludge = 75%
2. Moisture content of leaves = 50%
3. Nitrogen content of sludge = 5.6%
4. Nitrogen content of leaves = 0.7%

3.1.4.5 Mixing/Turning

- Mixing can be used to achieve a more uniform distribution of nutrients, moisture and microorganisms.
- Turning of the organic material during the composting process is a very important operational factor in maintaining aerobic activity.
- For an organic waste having a maximum moisture of 55 to 60 percent and a composting period of 15 days, the first turn has been suggested at the third day. Thereafter, it should be turned every other day for a total of four to five turns.

3.1.4.6 Control of pathogens

- Destruction of pathogens is an important design element in the compost process.
- The die-off of pathogens is a function of time and temperature. For example, the Salmonella species of bacteria can be destroyed in 15 to 20 minutes when exposed to a temperature of 60°C, or in one hour at 55°C.
- Most pathogens will be destroyed rapidly when all parts of the compost pile are subjected to about 55°C.
- Only a few survive at temperatures up to 67°C for a short period of time.
- Elimination of all pathogens can be accomplished by allowing the composting waste to reach a temperature of 70°C for 1 to 2 hours



Question 2- Determine the amount of air required to compost one ton of solid wastes using an in-vessel composting system with forced aeration. Assume that the composition of the organic fraction of the MSW to be composted is given by C60.0H94.3O37.8N. Assume that the following conditions and data apply:

1. Moisture content of organic fraction of MSW = 25%
2. Volatile solids, VS = 0.93 x TS (total solids)
3. Biodegradable volatile solids, BVS = 0.60 x VS
4. Expected BVS conversion efficiency = 95%
5. Composting time = 5 d
6. Oxygen demand is 20, 35, 25, 15, 5% for the successive days of the 5-day composting period.

3.1.4.7 pH Control

- The pH value, like the temperature, of the compost varies with time during the composting process.
- The initial pH of the organic fraction of MSW is typically between 5 and 7.
- In the first few days of composting, the pH drops to 5 or less. At this stage the organic mass is at ambient temperature, the multiplication of indigenous mesophilic organisms begin, and the temperature rises rapidly. It is the production of organic acids which cause the drop in pH.
- After 3 days, the temperature reaches thermophilic stage and the pH begins to rise to about 8 or 8.5 for the remaining composting process.
- The pH value falls slightly during the cooling stage and reaches to a value of 7 to 8 in the mature compost.

In case of inadequate aeration, anaerobic conditions occur and pH drops to 4.5, affecting the composting process duration.

3.1.4.8 Control of Odour

- In most cases the odour problems are associated with the development of anaerobic conditions within the pile.
- In many large scale systems, pieces of magazines, books or plastics are found, which normally do not decompose in a relatively short time and sufficient oxygen is not available causing anaerobic conditions to develop on the center if such materials.
- Under anaerobic conditions, organic acids will be produced, many of which are odorous.
- To minimise the potential for odour problems, it is important to reduce the particle size, remove plastics and other non-biodegradable materials from the organic material to be composted.

3.1.5 Composting systems

- The selection among alternative composting processes is based on capital and operating costs, land



availability, operational complexity, and potential for nuisance problems.

- Although the composting process is easy to grasp conceptually, the actual design and control of the process are quite complex.
- A number of approaches have been used to categorise composting systems. Perhaps the most basic distinction is between systems in which the composting material is contained in a reactor and those in which it is not.

3.1.5.1 Non-reactor processes

(a) The Windrow Process

Windrow composting is one of the oldest methods.

- In its simplest form, a windrow compost system can be constructed by forming the organic material to be composted into windrows 8 to 10 ft high by 20 to 25 ft wide at the base.
- A minimal system could use a front-end loader to turn the windrow once per year. This process would work, but would take 3 to 5 years for complete degradation. It would also probably emit objectionable odours, as part of the windrow will likely be anaerobic.
- A high-rate windrow composting employs windrow with a smaller cross-section, typically 6 to 7 ft high and 14 to 16 ft wide.
- Before forming windrows, the wastes are shredded and screened to approximately 1 to 3 in and the moisture content adjusted to 50 to 60%.
- High rate systems are turned up to twice per week while the temperature is maintained above 55°C.
- Complete composting can be accomplished in 3 to 4 weeks.
- After the turning period, the compost is allowed to cure for an additional 3 to 4 weeks without turning. During the curing period, the waste is further reduced by fungi and actinomycetes.
- In turned windrows, much of the aeration is achieved by convection and diffusion mechanisms.
- High level of porosity (>20% v/v) is required to assist in 'natural aeration'.

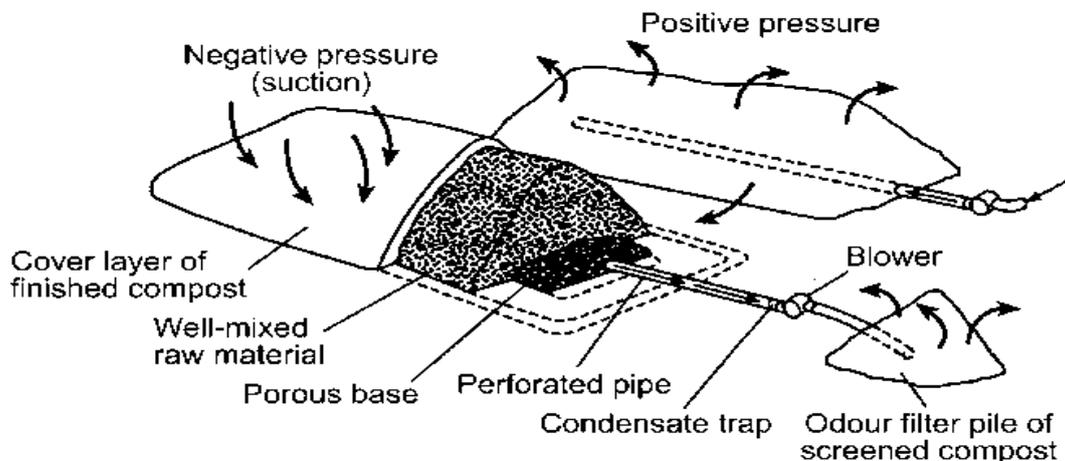




3.1.5.2 Aerated static pile Composting

- Developed by the US Department of Agriculture.
- It consists of a grid of aeration or exhaust piping over which the processed organic fraction of MSW is placed.
- Typical heights are about 2 to 2.5 m. A layer of screened compost is often placed on top of the newly formed pile for insulation and odour control.
- Each pile is usually provided with an individual blower for more effective aeration control.
- Forced aeration is a feature of aerated static pile or in-vessel systems.
- In the case of static piles, forced aeration by blowing also has the advantage of delivering warm air to the cooler outer layers.
- Insulating layer of compost on outside is needed to maintain uniform temperatures.

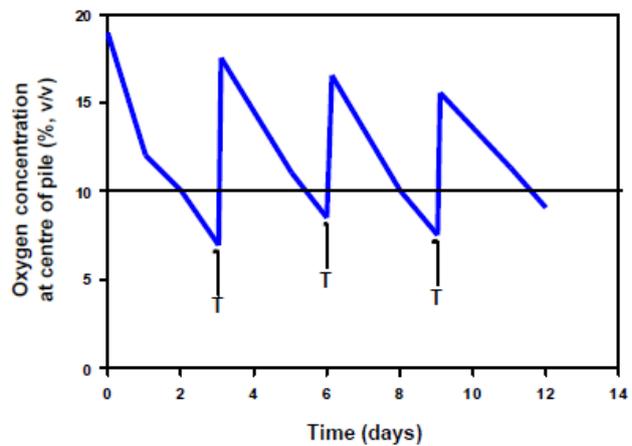
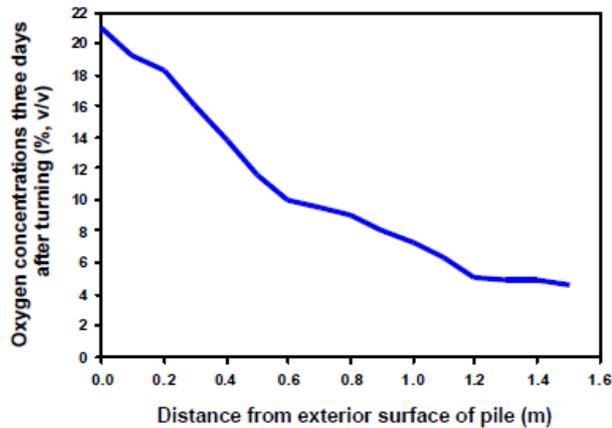
Disposable corrugated plastic drainage pipe is used commonly for air supply.



- Air is introduced to provide oxygen needed for biological conversion and to control temperature within the pile. The blower is usually controlled by a timer.
- Material is composted for a period of 3 to 4 weeks, and cured for an additional 4 weeks.
- Shredding and screening are usually done to improve the quality of the final product.
- For improved odour control, significant portions of the system are covered or enclosed.
- In case of dewatered sludge, some type of bulking agent is required to maintain the porosity of the composting material. Wood chips are commonly used.

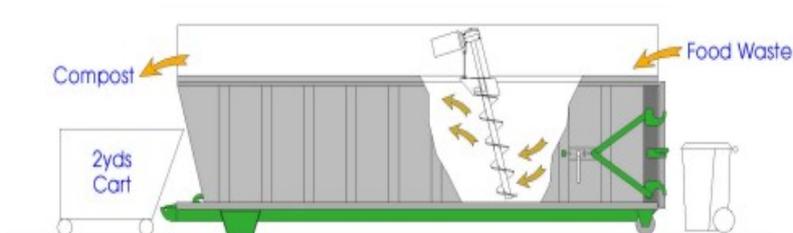


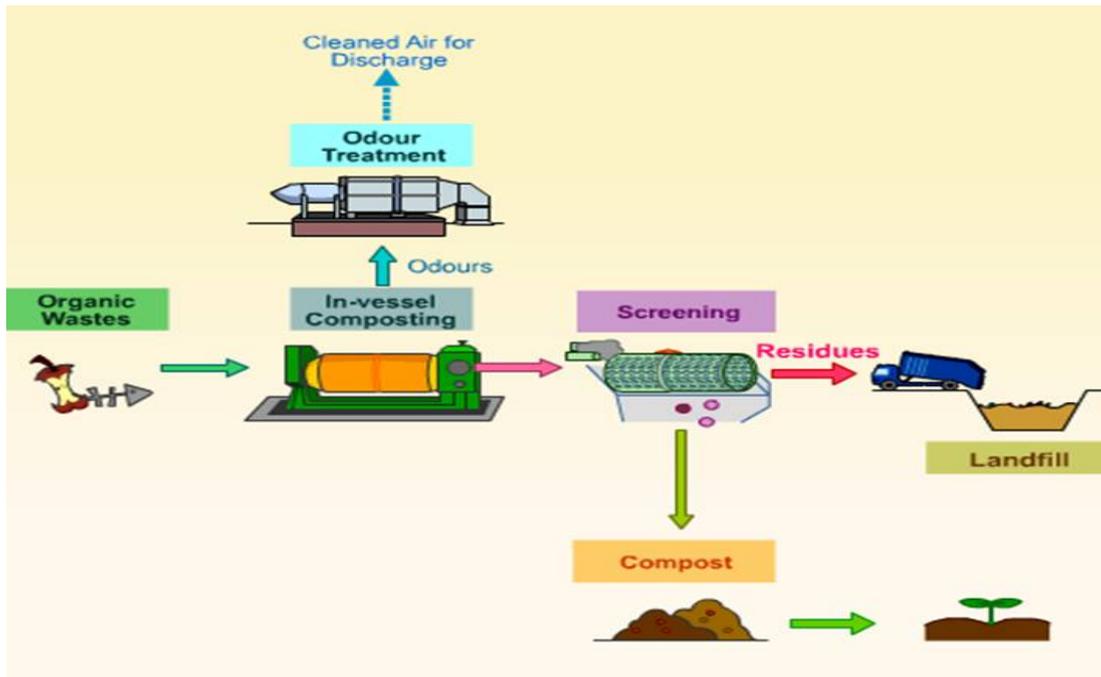
Oxygen profiles - turned windrow



3.1.5.3 In-Vessel Composting systems

- In-vessel composting is accomplished inside an enclosed container or vessel.
- Every imaginable type of vessel has been used as a reactor in these systems, including vertical towers, horizontal rectangular and circular rotating tanks.
- In-vessel composting can be divided into two major categories: plug flow and dynamic (agitated bed).
- In plug-flow systems, the relationship between the particles in the composting mass stays the same throughout the process, and the system operates on a first-in, first-out basis.
- In a dynamic system, the composting material is mixed mechanically during the processing.
- In plug-flow systems, the relationship between the particles in the composting mass stays the same throughout the process, and the system operates on a first-in, first-out basis.





Advantages of In-vessel composting systems:

- Mechanical systems are designed to minimise odours and process time by controlling the environmental conditions such as air-flow, temperature, and oxygen concentration.
- The popularity of in-vessel composting systems has increased in recent years for the following reasons:
 - Process and odour control
 - Faster throughput
 - Lower labor costs
 - Smaller area requirements
- Detention time for in-vessel varies from 1 to 2 weeks, and nearly all systems employ 4- to 12-week curing period after the active composting period.

3.1.5.4 Compost

The final product compost is a dark, earthylike material that is rich in nutrients and without any odour.

3.1.5.5 Properties of compost

In general, the chemical and physical characteristics of compost vary according to the nature of the starting material, the condition under which the composting operation was carried out, and the extent of the decomposition.



Some of the properties that distinguish it from other organic materials are these:

- A brown to very dark colour
- A low carbon to nitrogen ratio
- A continually changing nature due to the activities of the microorganisms
- A high capacity for cation exchange and water absorption

3.1.5.6 Uses of Compost

- As soil substitute
In potting soil or mixing compost in the soil to be planted.
- As mulch
 - Mulch protects the soil, shades out weed seed, and nutrients are washed out slowly into the soil from the compost with each rain to feed the roots of the plants
- As compost tea
 - Compost tea is made by soaking or steeping compost in water. The resulting compost tea is used for either a foliar application (sprayed on the leaves) or applied to the soil. Unlike mulch, compost tea add increased levels of nitrogen, potassium, and other materials all at once.

3.1.5.7 Benefits of Compost

- Compost has been used mostly in horticulture and agriculture to improve soil conditions and enhance plant growth. Compost improves the soil's physical and chemical properties that play an important role in crop production.
- It also enhances the biological properties of the soil by addition of beneficial microorganisms.
- Physical Improvements
 - Soil Structure
 - Compost increases soil aggregation and decreases compaction. Compost also increase soil porosity and favours aeration. All of these conditions aid in plant growth and increase yields.



Soil unamended with compost (left) and soil amended with compost (right)



- Soil Structure
 - Increased soil porosity
 - Reduced soil bulk density
 - Increased gas exchange and water permeability
 - Greater water-holding capacity
- Water Retention

The addition of compost provides greater drought resistance and more efficient water utilisation, therefore, the frequency and intensity of irrigation may be reduced.

Recent research also suggests that the addition of compost in sandy soils facilitate moisture dispersion by allowing water to move laterally more readily from its point of application.



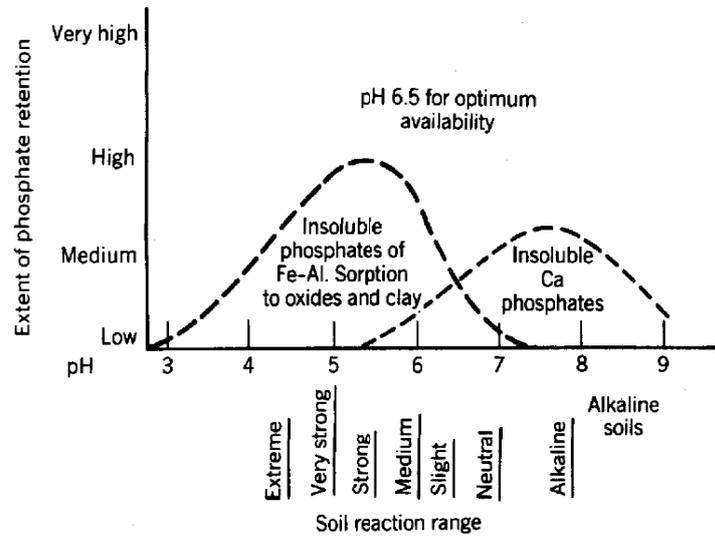
Improved Root Zone



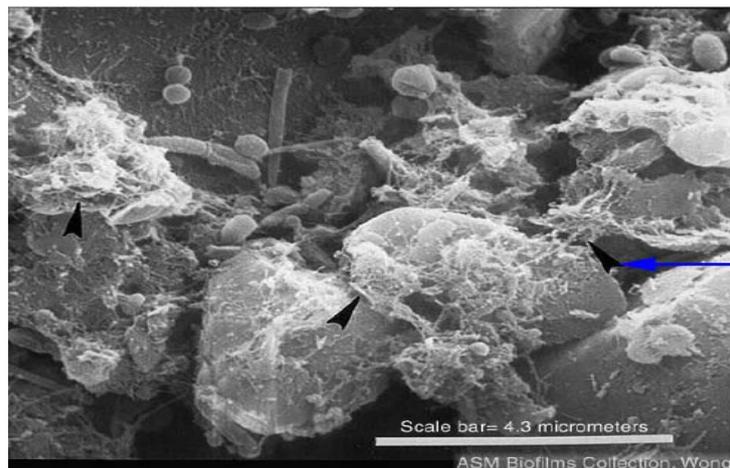
Reduced wind and water erosion

Chemical Improvements

- Cation exchange capacity
Compost improves the cation exchange capacity of soils, enabling them to retain nutrients longer. It also reduces nutrients loss by leaching.
- Soil pH
- The pH of most stable compost is between 6.5 and 7.5.
- Depending on its pH, compost may raise or decrease soil pH
- Organic matter has the ability to buffer pH change



- Provides Nutrients. It is a source of N, P, K and micronutrients
- Effects on Soil Biology
 - Stimulates microbial growth and activity
 - May change species composition in soil
 - Promotes earthworms
 - May suppress plant diseases



3.1.5.8 New and emerging uses of compost

- Bioremediation and pollution prevention
- Disease control for plants and animals
- Erosion control Composting of contaminated soils Reforestation and



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- wetlands restoration Habitat revitalization

3.1.5.9 Plant Disease Suppression

- Numerous studies have shown that organic amendments can reduce or suppress plant pathogens. The control of plant disease is accomplished in two ways. Thermophilic temperatures achieved through composting can destroy many plant disease organisms.
- Disease suppression is accomplished by:
 - 1) antibiosis: the production of fungal inhibitors
 - 2) nutrient competition
 - 3) parasitism: direct attack of pathogens by non-pathogens

3.1.5.10 Bioremediation and Pollution Prevention

Compost bioremediation refers to the use of a biological system of microorganisms in a mature, cured compost to break down contaminants in water or soil. The microorganisms present in compost consume contaminants in soil. The contaminants are digested, metabolised, and transformed into humus and inert byproducts, such as carbon dioxide, water, and salts. Compost bioremediation is effective in degrading many types of contaminants, such as chlorinated and nonchlorinated hydrocarbons, wood-preserving chemicals, solvents, heavy metals (zinc, cadmium, arsenic, nickel, mercury), pesticides, petroleum products, and explosives.

3.1.5.11 Sanitisation attainment – Thermal

The most common test for the quality of compost relates to the exothermic process of composting and to temperature time criteria as follows:

Temperature

The compost product should be brought to a minimum temperature of 55°C for three consecutive days for Aerated static piles or fifteen days with 5 turns for turned windrow in order to fulfill the requirements to further reduce pathogens.

Time

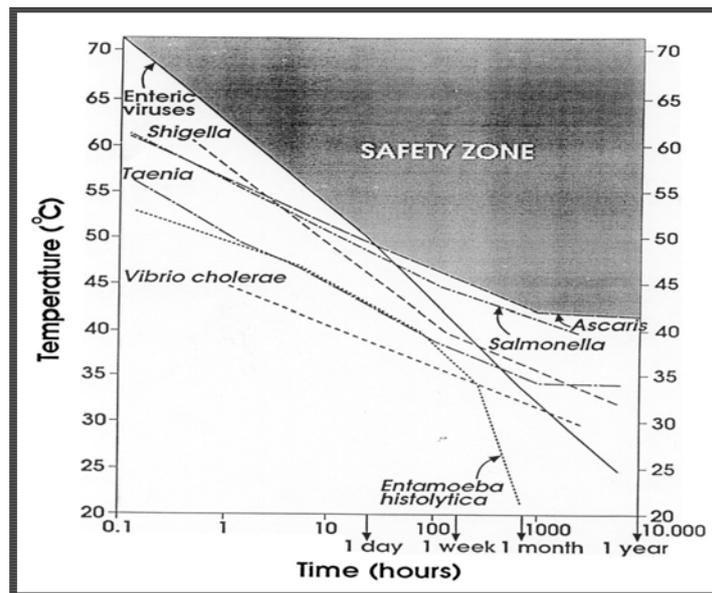
The compost product should be exposed to a minimum composting period of 42 days and a minimum curing period of 30 days prior to distribution

This is based on the fact that when compost is exposed to high temperatures, most of the viruses and pathogens get killed. The table below shows the lethal conditions for each group of organisms. Therefore, except for spore-forming bacteria, sanitization can be achieved at composting temperatures.



Organism type	Lethal Conditions
Viruses	1 to 10 hr, 55 to 70 °C
Non-spore-forming bacteria	5 to 30 min, 50 to 60 °C
Spore-forming bacteria	5 to 10 min, 121 °C
Fungi	
Parasites	1 to 2 hr, 55 °C
Weed seeds	

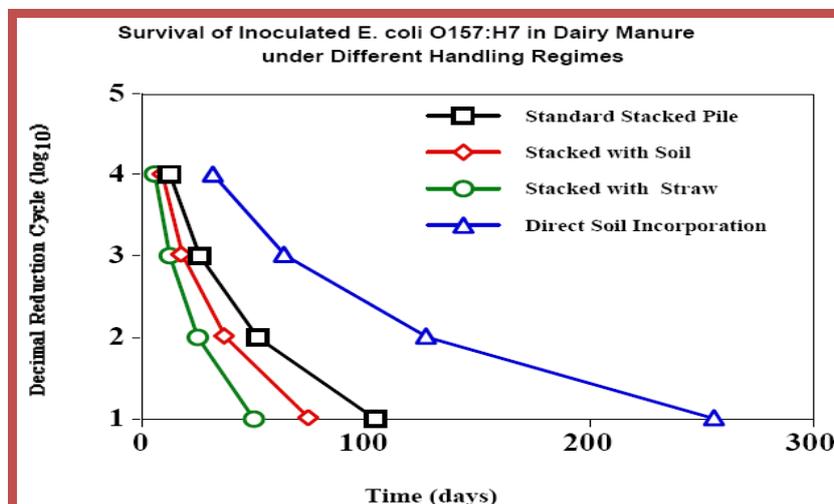
Temperature time inactivation relationships for pathogens



Organisms shall not exceed

- Faecal coliforms <1000 most probable number (MPN) / g of total solids calculated on a dry weight basis, and
- Salmonella species < 3 MPN/ 4 g total solids calculated on a dry weight basis.

Pathogenic E. coli reduction with different amendments





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3.1.5.12 Compost quality parameters

- Maturity
- High organic matter content
- Absence of viable weed and crop seeds, pathogenic organisms and contaminants
- Proper pH for the designated end use
- Available nutrients (nitrogen, phosphorous and potassium)
- Low levels of heavy metals and toxic organic compounds
- Low concentrations of soluble salts
- Uniform particle size
- Dark colour and earthy odour

According to Canadian Standards, compost is deemed mature if it meets 2 of the following requirements:

- a) C/N ratio ≤ 25
- b) Oxygen uptake less than 150 mgO₂/kg organic matter per hour
- c) Germination of cress or radish seeds in compost equal to more than 90% that of control sample, and plant growth rate in soil/compost mix not less than 50% that of control sample

Compost must be cured for a minimum of 21 days and must not reheat upon standing to greater than 20°C

- Compost must be cured a minimum of 21 days and organic matter must be reduced by at least 60% by weight
- Compost must be cured for a six month period
- In the absence of other tests, the six month curing period under proper conditions can be considered sufficient to achieve maturity.

3.1.5.13 Compost quality norms

There are several compost quality norms. The table below shows the norms as per Environmental Protection Agency, USA.



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Quality parameters	Range	Average
pH	6.8-7.3	7.1
Soluble salts	2.5-3.5 mmhos-cm	2.9
Nitrogen	1.0-1.3 ‰	1.1
Phosphorus	0.6-0.9 ‰	0.8
Potassium	0.2-0.5 ‰	0.3
Water holding capacity	100-120 ‰	105
Bulk density	900-1000 lbs cu.yd	945
Moisture content	45-50 ‰	47
Organic matter content	35-45 ‰	38
Particle size	Passes 3/8 inches	

The specifications for compost as per Mauritius standards (Ministry of Environment) are as follows:

Tests to be conducted	Method	Mauritian specifications
Physical characteristics		
Moisture		30-50%
Particle size	Sieving	< 10 mm
Foreign matter		
Glass, metal and rigid plastics > 2 mm		≤ 0.5% (% dry matter by weight)
Plastics-light, flexible or film > 5 mm		≤ 0.05% (dry matter)
Stones and lumps of clay > 5 mm		≤ 5% (dry matter)
Chemical characteristics		
pH		5.5
Electrical Conductivity		≤ 3.5 dS/m
N	Total kjeldahl Nitrogen	≥ 0.8%
P	Total phosphorous by colorimetry	0.63
K	Total potassium by flame photometry	0.10



Tests to be conducted	Method	Mauritian specifications
Heavy metal	Atomic Absorption spectrophotometry	As ≤ 10 mg/kg Cr ≤ 50 mg/kg Cu ≤ 200 mg/kg Pb ≤ 100 mg/kg Hg ≤ 0.15 mg/kg Ni ≤ 50 mg/kg Zn ≤ 300 mg/kg Cd ≤ 3 mg/kg
Biological and Biochemical characteristics		
Biological characteristics	<ul style="list-style-type: none"> • Escherichia coli • Salmonella 	<ul style="list-style-type: none"> • ≤ 1000 CFU/g • nil
Compost maturity	<ul style="list-style-type: none"> • Respiration • Germination • Solvita testing kit 	<ul style="list-style-type: none"> • ≤16 mg CO₂ /g of organic matter per day • ≥80% germination using radish seeds • ≥7 on Solvita maturity index

3.1.5.14 External Quality Assurance & Certification Systems

There are numerous quality labels for the composting process and the compost around the world. These are shown below and each one of them has a set of criteria attached to it that has to be satisfied.



Netherlands



Belgium



Germany Digestion



Austria



Sweden



Germany Compost





ACP-EU Cooperation Programme in Higher Education (EDULINK)
A programme of the ACP Group of States, with the financial assistance of the European Union.



3.2 Biogas

3.2.1 Definition of Biogas

Biogas is a gas mixture of 50-75% methane, which is generated by anaerobic, microbial degradation of organic substrates (anaerobic digestion, fermentation). Besides the valuable component methane, other constituents are 25-45 carbon dioxide (CO₂), as well as traces of hydrogen sulphide (H₂S), Nitrogen (N₂) and carbon monoxide (CO) (Table 1).

Table 1: Average composition of biogas [Kaltschmitt, Hartmann, 2001]

Component	Concentration
Methane (CH ₄)	50-75 Vol.-%
Carbon dioxide (CO ₂)	25-45 Vol.-%
Water (H ₂ O)	2-7 Vol.-% (20-40 °C)
Sulfide hydrogen (H ₂ S)	20-20.000 ppm
Nitrogen (N ₂)	< 2 Vol.-%
Oxygen (O ₂)	< 2 Vol.-%
Hydrogen (H ₂)	< 1 Vol.-%

Biogas can be used for electricity and heat generation. The energy content directly depends on the methane content. One cubic meter of methane has an energy content of about 10 kWh. Therefore the energy content of typical biogas (60% methane) lies in the range of 6 kWh. The average energy content of one m³ biogas is equivalent to 0,6 l fuel oil. Figure 20 shows the general principle of generating electricity and heat from biomass and a few application fields.

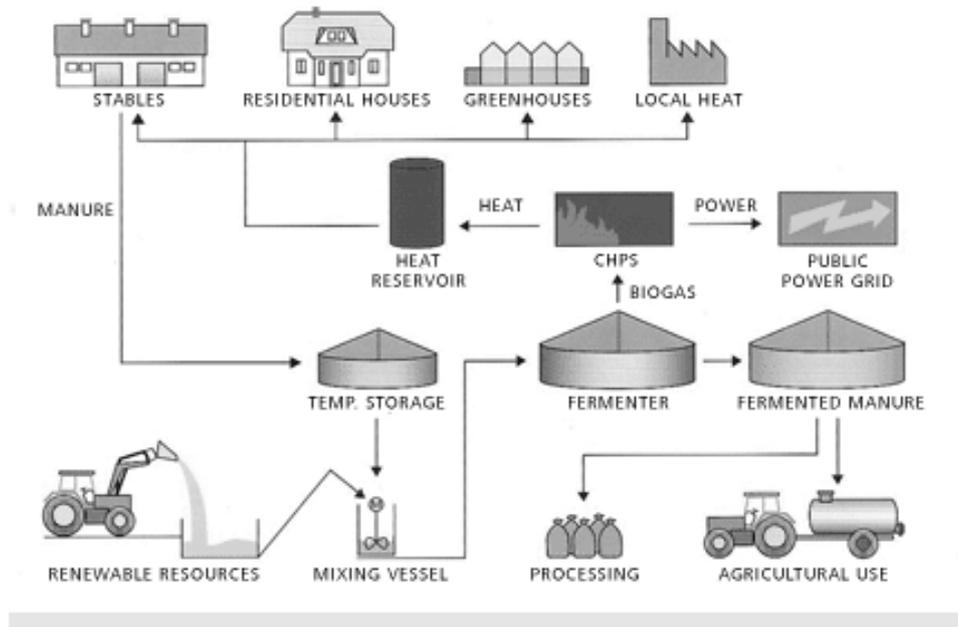


Figure 20: Generating Energy from Biomass – Principle [NawaRo, 2010]

The biological methane generation is a process, which occurs in nature, where wet organic material is available and free oxygen is absent, e.g. in the digestive tract of cows, wet composting plants, landfills or flooded paddy fields.

3.2.2 Basic principle of anaerobic metabolism

Knowledge of the fundamental processes involved in methane fermentation is necessary for planning, building and operating biogas plants. Methane bacteria are obligate anaerobic, which means they are only active under oxygen free conditions. In case too much oxygen penetrates the system, the anaerobic fermentation process can be disrupted or fail. Under anaerobic conditions, the energy generation represents only 1/7 of the aerobic bacteria [Bilitewski et al., 1994]. Therefore anaerobic bacteria have a longer growth rate, respectively. Their metabolism depends on the preparatory steps and symbiosis with other bacteria. The following figure (Figure 21) shows the different phases of the methanogenesis, involving three different bacterial communities.

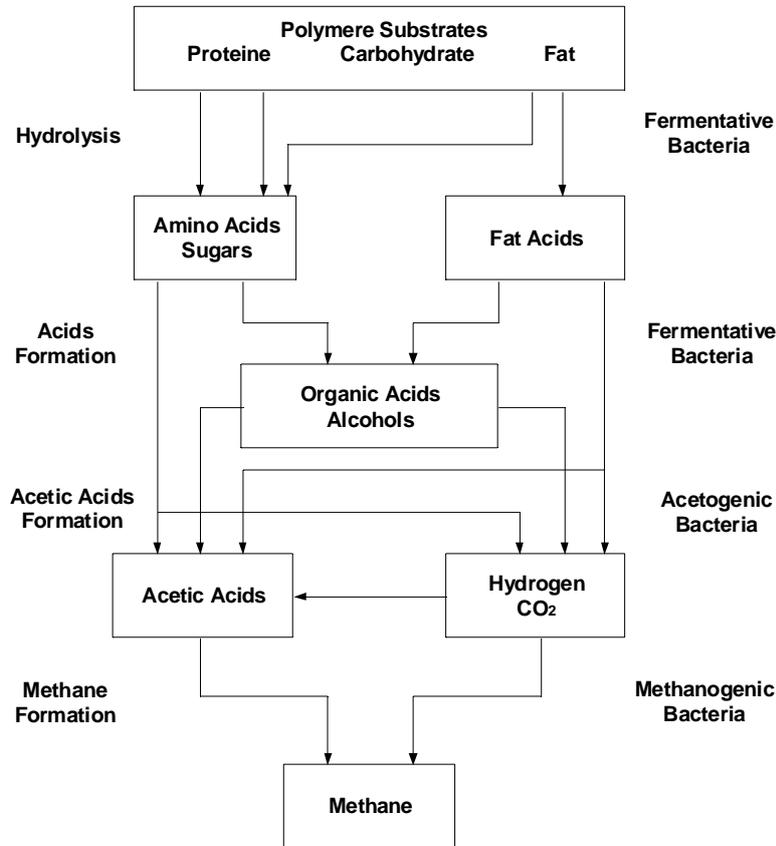


Figure 21: The phases of methane production

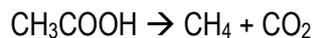
The biogas process consists of three phases:

- **1. Hydrolysis:**
In the first phase, high molecular compounds like carbohydrates, lipids and proteins are degraded into simpler compounds (monomers, like amino acids, peptides, glucose, fatty acids) by fermentative bacteria and solved in water. It's important that the substrate is well degradable, e.g. sugars or hemicellulose. However, Lignin is difficult to break and the process of degradability is slower and less complete. This is called the bioavailability of substrates. The slower the substrate is biodegradable, the slower the entire process runs; therefore, the hydrolysis is the rate-determining step in the biogas process.
- **2. Acidification:**
Acid-producing bacteria convert the solved compounds to organic acids (butyric and propionic acid), alcohol, hydrogen and carbon dioxide. Thereby these bacteria consume the remaining oxygen and create the oxygen-free environment, which is important for the methane formation.
- **3. Acetogenic phase and methane formation:**
In the acetogenic phase the compounds are converted into acetic acids, hydrogen and carbon dioxide. The methane formation is carried out by methane bacteria, which can only utilise C-1 and C-2 compounds. Methane and acetogenic bacteria act in a symbiotic way. The latter create an

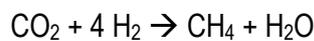


atmosphere with ideal parameters for methane producing bacteria (anaerobic conditions, compounds with a low molecular weight), the former produce the energy for the acetogenic bacteria and use the intermediates of them. Without consuming them, acid would accumulate, resulting in toxic conditions for acid-producing bacteria.

The large part of the formed methane is produced by the utilisation of the acetic acids, built in the acetogenic phase. At this methane and carbon dioxide are formed through the methane-producing bacteria.



Nearly the rest comes from the methanation of carbon dioxide and hydrogen.



In nature as well as in biogas plants, the metabolic actions of the different bacteria act in concert.

3.2.3 Parameters and process optimization

Overall, the methane yield depends on many factors, which relate to the substrate, the pre-treatment or conditions of the substrate and the fermentation process (Figure 22).

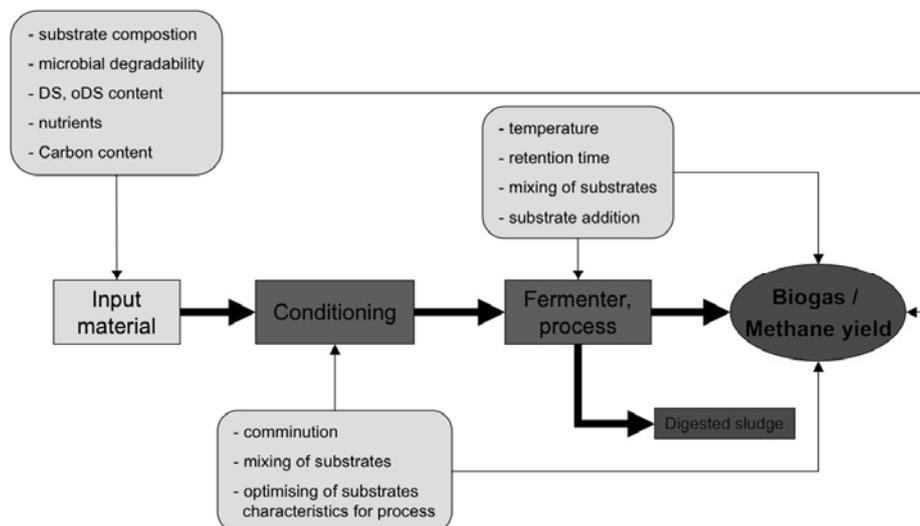


Figure 22: Factors which influence the biogas and methane yield [according to Weiland, 2001]

Substrate requirements

Substrates used for biogas production often are residues, by-products or residues from agricultural, commercial and industrial activities, and also from households. See Table 2 for examples of typical substrates and possible methane yields.



Table 2: Typical substrates and biogas yield

	Methane yield [CH ₄ m ³ /kg oDS]
Cattle manure	0,10-0,35
Pig manure	0,18-0,64
Maize silage	0,22-0,50
Grass silage	0,30-0,60
Food waste	0,30-0,60
Sewage sludge	0,19-0,44

The quantity of biogas and methane produced mainly depends on the composition of the substrate. In practice it is often not possible to calculate the methane yield, as the composition is unknown and the degradation is not complete. Table 3 shows the theoretical, specific biogas yield. The different methane concentrations result from the differences of the relative carbon ratio.

Table 3: Specific biogas yield and methane concentration

	Biogas yield [l/kg oDS]	Methane content [Vol.-%]
Digestible proteine	600-700	70-75
Digestible fat	1.000-1.250	68-73
Digestible carbohydrates	700-800	50-55

Degradability

Suitable substrates for biogas production are basically all kinds of organic matters and biomass containing carbohydrates, proteins, fats, cellulose or hemicellulose. Generally, easily degradable substrates with low molecular compounds, e.g. wet organic kitchen waste can be degraded quicker and more complete. In contrast to this, wooden substrates, containing a lot of lignin, are not suitable.

Inhibiting substances

Inhibiting substances can be toxic to the bacteria involved in anaerobic digestion, so that the processes can be reduced or stopped. Antibiotics or disinfectants in household waste can have these effects. Also, heavy metals or salts from certain concentrations act toxic.

Nutrients

The substrate must contain certain concentrations of nutrients, a certain carbon/nitrogen ratio, as well as trace elements for the bacteria to grow. The demand for nutrients can be estimated according to composition of the microorganisms (Table 4). The optimisation of the nutrient supply must be carried out on an empirical basis, considering the mechanical, chemical and physical framework conditions.



Table 4: Typical Constitution of Biomass [Wittmaier et al. 2009]

Component	Bacteria		Yeasts		Molds	
	Average	Range	Average	Range	Average	Range
Organic Constituents (% dry wt)						
Carbon	48	46 - 52	48	46 - 52	48	45 - 55
Nitrogen	12,5	10 - 14	7,5	6 - 8,5	6	4 - 7
Oxygen		22 - 28				
Hydrogen		5 - 7				
Protein	55	50 - 60	40	35 - 45	32	25 - 40
Carbohydrate	9	6 - 15	38	30 - 45	49	40 - 55
Lipid	7	5 - 10	8	5 - 10	8	5 - 10
Nucleic acid	23 ^a	15 - 25	8	5 - 10	5	2 - 8
Ash	6	4 - 10	6	4 - 10	6	4 - 10
	Bacteria		Fungi		Yeast	
Inorganic Constituents (g/100 g dry wt)						
Phosphorus	2.0	to 3.0	0.4	to 4.5	0.8	to 2.6
Sulfur	0.2	to 1.0	0.1	to 0.5	0.01	to 0.24
Potassium	1.0	to 4.5	0.2	to 2.5	1.0	to 4.0
Magnesium	0.1	to 0.5	0.1	to 0.3	0.1	to 0.5
Sodium	0.5	to 1.0	0.02	to 0.5	0.01	to 0.1
Calcium	0.01	to 1.1	0.1	to 1.4	0.1	to 0.3
Iron	0.02	to 0.2	0.1	to 0.2	0.01	to 0.5
Copper	0.01	to 0.02			0.002	to 0.01
Manganese	0.001	to 0.01			0.0005	to 0.007
Molybdenum					0.0001	to 0.0002
Total ash	7 to 12		2 to 8		5 to 10	

^a Values this high are observed only with rapidly growing cells

Process parameters

A number of parameters have an influence on anaerobic digestion and can be adjusted in technical processes; to optimise the gas production, methane yield, the degradability (disintegration) of substrates, the hygienic situation, and fertilising qualities of the residual digested matter.

Temperature



The temperature is a major factor for the activity of bacterial communities. Three ranges of temperature can be distinguished:

- psychrophile : around 10°C
- mesophile: 32-50 °C
- thermophile: 50-70 °C.

Generally a thermophilic process results in a quicker metabolism and degradation. It is often preferred if the substrate contains high levels of fat, or if pathogenic microorganisms shall be destroyed. However, a process in this temperature range is more sensitive, even daily fluctuations of temperature by 1°C around the average could have a significant adverse effect of the bacteria [KWS, 2009]. Most biogas plants are operated under mesophilic conditions because the process is biologically more stable and energy costs are lower [Bilitewski, 1994]. Furthermore the efforts for control are lesser. On the other hand longer retention times, a lower degradability and a lower gas production have to be accepted. Generally biogas plants can be operated on all temperature levels within 30-55°C.

pH-Value

The pH-value plays an important role for all microbial processes. The pH-values of the first phases (Hydrolysis and acid formation) lie in the range of 4,5 – 6,3 and differences of this value do not inhibit the process that much [FNR, 2004]. In contrast to this, the optimum pH-value for the methanogenesis lies in a close range of 6,8 – 7,5 and the tolerance of the bacteria for small differences is low. Therefore the process needs to be adjusted to their requirements. Generally pH-values, which are too low, should be prevented as they have an inhibitory effect on the microorganisms of the methanogenesis.

The quantity and characteristics of fed substrates has an influence on the pH-value. Substrates which are very quickly and easily degradable, lead to a decreasing pH-value due to the fast acidification. Hence, such substrates may be fed only with caution [KWS, 2009].

Retention time

The duration depends on the temperature, the capacity of the digestion-tank, the concentration of substrate in the reactor, the concentration of active biomass and the desired degree of degradation. The duration period can vary from a few hours (waste water clarification technology) up to 2 months (agricultural biogas plant).

The above mentioned, slow bacteria growth creates the problem that in order to shorten the duration period the active biomass must be retained or enriched. This can be achieved by immobilising the carrying materials in a solid or whirl bed or by adding sludge or processing water. The addition of inert solid fillers or inert particles, which through adhesion can retain the bacteria, is only possible in wastewater clarification. This is because by the addition of solids or sludge type waste, the solid bed can become blocked or the carrying materials in the whirl bed process can also be transported out. In fermentation of clarification sludge, waste or agricultural substrates, with normal duration periods of between 15 and 60 days, continual injection or enriching of microorganisms of the fermentation suspension is not necessary. All known continual processes do not need additional injection after the start up phase. Special types of microorganisms are not required.

3.2.4 Technical application



Development of anaerobic processing technology comes traditionally from wastewater clarification. In reactors suitable for wastewater treatment, industrial organic waste, wet and bio-waste can lead to deposits, blockages and build-up of sediment and floating layers. Therefore this had lead to the development of two principle solutions, which are suitable for other substrates than wastewater:

- Dry fermentation
- Wet fermentation.

With dry fermentation the substrate is fermented to a dry substance content of up to 65%, whilst with wet fermentation it is mashed with water into sludge of approx. 5% to 12 % dry substance content. In two stage wet fermentation the solid substance goes through a hydrolysing stage in which a large part of the organic substance is dissolved in water. This is then treated in a normal anaerobic reactor as is used in waste water clarification. With dry fermentation the advantages of having a lower water requirement and a higher sludge-digestion tank load can be expected. Dry fermentation mostly operates in batch-process with 4-12 fermentation-boxes per plant (Figure 23 and Figure 24).



Figure 23: Loading of a dry fermentation box by a loader



Figure 24: Dry fermentation box with digestate from biowaste

Wet fermentation promises fewer problems in the handling of a homogenous sludge, a possible separation of floating or sinking substances at the liquefying stage and sludge reduction. In two phase wet fermentation it is hoped that higher capacities can be reached by having the possibility to attain optimum conditions for the separate phases and the use of high capacity reactors as used in waste water clarification plants. The biogas generated is of higher value with higher methane content as it is mostly rejected in the carbon dioxide generated in hydrolyses. Figure 25 shows an interior view of a typical agriculture wet fermentation plant.



Figure 25: interior view of wet fermentation plant with heating system and stirring unit

The specific biogas yield in dry and wet fermentation plants varies depending on the duration period, tank capacity etc. In principle, the same level of specific biogas yields can be reached from a substrate in both dry



and wet fermentation plants. Dry fermentation plants can be made very resistant to interfering materials depending on how they are technically equipped.

Substrate handling and storage of biogas substrates is done similar to substrates used for biomass combustion (see below). The storage and transport of liquid substrates are done using agricultural equipment and machines.

Table 5 gives an overview of features of different types of biogas plants for solid and sludge-like substrates.

Table 5: Features of different types of biogas plants for solid and sludge-like substrates [Institut für Energetik gGmbH, quoted in BMU, 2003]

Criterion	Features
DS-content of substrate	<ul style="list-style-type: none"> • Dry fermentation (DS from 15 to 65%) • Wet fermentation (DS up to 15%) • Anaerobic wastewater treatment (for wastewater)
Type and source of substrate	<ul style="list-style-type: none"> • Agricultural mono-fermentation plants (manure fermentation) or Co-fermentation plants (manure plus additional substrates) • Biowaste fermentation plants • wastewater
Temperature of process	<ul style="list-style-type: none"> • Psychrophile (below 20°C) • Mesophile (25 to 43°C) • Thermophile (from 55°C)
Charging clearance	<ul style="list-style-type: none"> • batch • Intermittent • Semi- or quasi continuous
Method implementation	<ul style="list-style-type: none"> • Single-stage - All degradation stages simultaneous • Two-stage - Separation of hydrolysis • Multi-stage - Separation of hydrolysis and formation of acid
Principle of mixture	<ul style="list-style-type: none"> • Mechanical - Propeller agitator • Hydraulic - Pumps • Pneumatic - Gas injection

3.2.5 Biogas utilization

Biogas processing

For the utilisation of biogas in unit power stations, heating boilers etc, it must be treated to varying degrees depending on the energy utilisation system. During the anaerobic microbial transformation processes in a biogas plant, the existing various forms of sulphur (sulphate, organic sulphur compounds etc) will be converted to sulphide (S²⁻). The sulphide will then exist as hydrogen sulphide (H₂S) in the biogas. During the oxidation of



biogas in a unit power station, heating boiler, or other energy conversion plant, H_2S is converted into SO_4^{2-} . In the form of sulphuric acid (e.g. in exhaust gas heat exchanger in a unit power station) it can lead to significant corrosion problems in the condensation zones. The removal of H_2S from the biogas can be achieved through biological or chemical purification.

Chemical de-sulphuring is generally carried out by precipitation of H_2S to bog iron ore (as FeS) or gas purification with sodium hydroxide. In biological treatment, which can take place in the fermenter head itself or in a connecting reactor (gas purifier), the biogas is supplemented with oxygen (O_2). On the surfaces in the fermenter or in external reactors, microorganisms will grow which can oxidise H_2S , S and $\text{S}_2\text{O}_3^{2-}$ to SO_4^{2-} . H_2S is removed from the gas phase (biogas). A significant decrease in pH values on the H_2S oxidising microorganism-growing surfaces will occur; so these should be regenerated from time to time.

If silicon compounds are added (e.g. those used as de-foamers in some lemonade) in the fermentation process, Silan (SiH_4) will be generated by the biological conversion. Silan is gaseous similar to methane. On burning of biogas containing silan, for example in unit power stations, silicone oxide (silica sand) will be generated. This will lead to significant damage in the internal combustion engine. It is assumed that silan causes approx. 50% of damage to unit power stations in German waste water purification plants converting biogas from sludge digestion. Silan can be removed from biogas using various different methods. A process most generally used in biogas plants is adsorption on activated carbon.

In a fermenter the relative humidity of biogas is 100%. The biogas humidity must be reduced in order to protect the unit power stations from high wear and damage. This can be brought about for example by installing a pipeline system between the fermenter and the unit power station (heating boiler etc.). On installing the pipeline it must be ensured that any condensation created in the pipeline can be drained off into condensation collectors and that no pools of condensation can result from lower points in the pipeline caused by settling for example. If the pipeline system is not long enough or the outside temperature is too high for part condensation of the water vapour in the biogas, then external cooling (air conditioning system, water cooling with ground water or cold surface water etc.) must be used to reduce the relative humidity of the biogas.

Depending on the quality of the biogas and its proposed use further specific treatment processes may be necessary. To feed biogas into the natural gas grid, its methane content must be increased. As this and other similar processes are not yet economic and are only individually applied, they do not require to be further discussed here. If required, refer to current specialist literature.

Biogas utilisation

Utilisation of biogas generally takes place in heating boilers (heat utilisation) or in unit power stations. This will briefly be discussed in the following. Other innovative processes for the conversion of biogas into energy using fuel cells, gas turbines, steam engines, organic rankine plants or sterling engines are generally not yet economic and will not be further discussed here.

In the conversion of biogas in heated power stations, depending on the type and size of the plant, electricity will be generated with an efficiency rate of 30 to 40 %. In partial load areas the output is decreased. The rest of the energy is precipitated in the form of heat. Heat in the form of hot water can in be absorbed and used at a temperature of 90°C . The thermal output (usable heat) from unit power stations generally ranges from 20% and around 50% depending on the specification of the individual plant and according to application with or without exhaust heat exchanger. When heat is utilised alongside electricity, the process is referred to as power-heat-coupling.

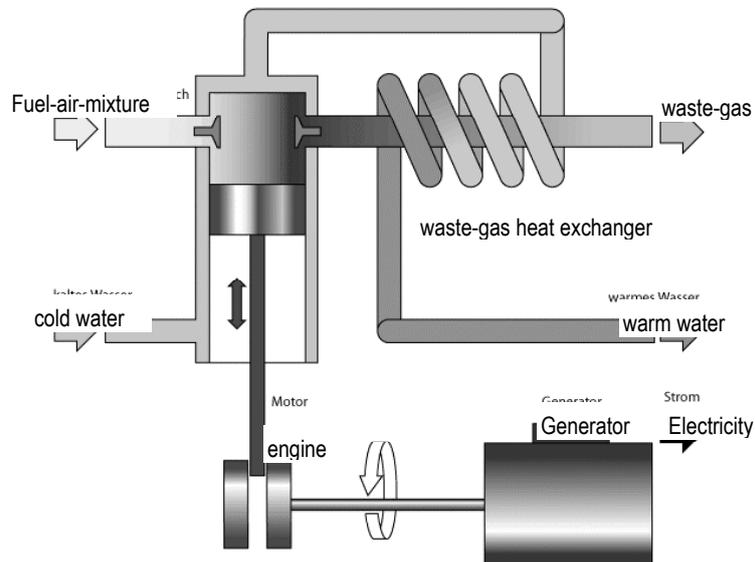


Figure 26: Functional principle of CHP

Unit power stations consist of an internal combustion engine and a generator for the generation of electricity. In Figure 26 the principle function schema of a combined heat and power unit (CHP) is shown. Gas-Otto engines or gas-diesel engines are used for the internal combustion engines. Whilst gas-Otto engines (Figure 27) can be run on biogas alone, with gas-diesel engines (Figure 28) require an oil-ignition part alongside the biogas (e.g. diesel; approx. 10 % the combustion heat output).



Figure 27: Unit power station with gas-Otto engine with an electrical output of 375 kW

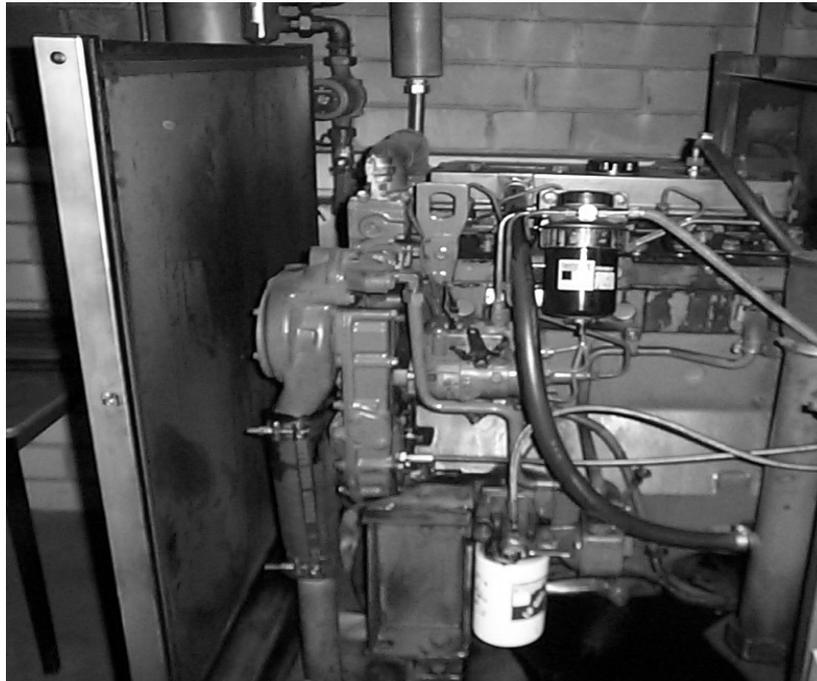


Figure 28: Unit power station with gas-diesel motor within an electrical output of 60 kW

Gas-diesel engines are generally installed in unit power stations with an electrical output of 20 to 300 kW, Gas-Otto engines with an electrical output of between 100 kW and 2 MW. Gas-Otto engines normally have better exhaust values and a longer serviceable life.

Gas-diesel engines are suitable for operation at lower outputs and can be purchased more inexpensively. On selecting a suitable aggregate, the economic and investment costs in each individual case as well as the availability of spare parts, serviceability etc. must be taken into account.

3.2.6 *Benefits*

The development and operation of biogas plants opens up a variety of developmental perspectives, particularly also in rural areas. Alongside the reduction of GHG emission, the focus is on the provision of infrastructures for the disposal of waste and substrates from wastewater clarification, and agriculture in certain aspects and adds new values to life in rural areas.

Biogas plants create jobs, increase economic power, and produce decentralised fertiliser and energy in the form of electricity and heat, thereby making a region less dependent on external resources. Besides this the anaerobic fermentation as well as composting, serves to stabilise, sanitise, and reduce the mass of organic waste [Stegmann et al. 2006].

The positive perspectives of biogas plants have been well discussed. For this reason, only a table of some of the advantages have been listed below (Table 6).



Table 6: Benefits of Biogas plants

Area	Benefits
Waste treatment	<ul style="list-style-type: none"> • Natural waste treatment process • Infrastructure for waste treatment • Reduces disposed waste volume and weight to be landfilled • Reduces the long term hazards of landfills • Sanitation of waste and substrates from waste, waste water treatment or agriculture
Energy	<ul style="list-style-type: none"> • Generates biogas which can be used for the production of electricity, heat or cooling (heat exchange) • Net energy producing process • Proven in numerous end-use applications
Environmental	<ul style="list-style-type: none"> • Significantly reduces carbon dioxide and methane emissions (Greenhouse effect) • Eliminates odour • Produces a sanitised compost and nutrient fertiliser • Maximises recycling benefits, reduces resource depletion
Other benefits	<ul style="list-style-type: none"> • Cost-efficient • Decentralised applicable • Flexible process for a wide range of substrates • New value creation chain for the waste management sector and agricultural sector • Generates jobs, tax revenue, revenues • Reduces the dependency from external energy supply

4 Thermal waste Treatment

Thermal treatment of waste is an appropriate and important method for the management of waste. It comprises waste incineration, pyrolysis, hydration and drying. The most important process is incineration. The various types and methods of drying, which are mainly linked to drying of sewage sludge (waste water treatment), are not further discussed in this context. The goals or objectives of thermal waste treatment are first of all (primary principles):

- Inertization of the residual waste (no polluting effect on the environment)
- Volume reduction

Other objectives, but of secondary importance, are:

- Energy recovery
- Production of marketable secondary raw material



4.1 Incineration of municipal solid waste and commercial waste

The incineration of waste is used to treat non-recyclable and non-reusable materials. The result of incineration (thermal treatment) in modern waste management should be [Bilitewski, 1994]:

- Inertization of any hazard waste residues while minimizing the emissions into the environment
- Destroying organic contaminants
- Concentrating inorganic contaminants
- Minimizing the quantity of waste requiring disposal, especially its volume
- Recovering the waste's heat value to conserve energy resources by producing heat and power (energy cycle)
- Transforming the residues into usable secondary products to conserve raw materials and resources (resource cycle)

4.1.1 Design of a MSW incinerator

The principle design of a waste incineration plant could be described with a few basic components and units. It is shown in Figure 29.

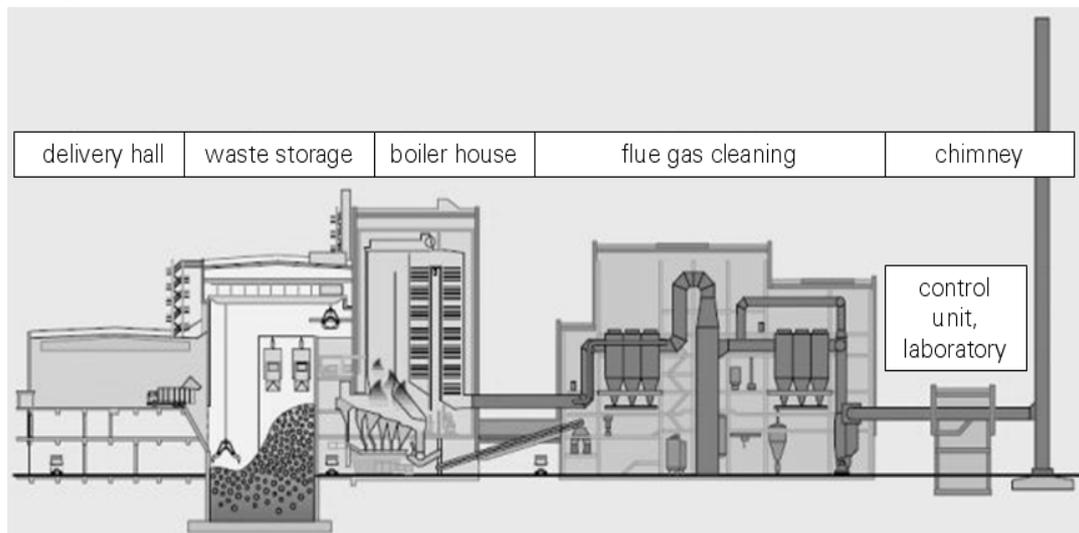


Figure 29: Principle of a combustion plant for MSW [Igelbüscher, 2009]

The basic process of incineration and the material flow at waste incineration plants is usually only slightly different at the various plants. The following functional areas are characteristic for incinerators and are defined below:

- Waste receiving
- Storage, preprocessing
- Charging and incineration unit
- Slag removal, residue treatment, storage
- Boiler with steam recovery
- Air pollution control system
- Stack



Figure 30 shows the disposal pathways of a waste incineration plant.

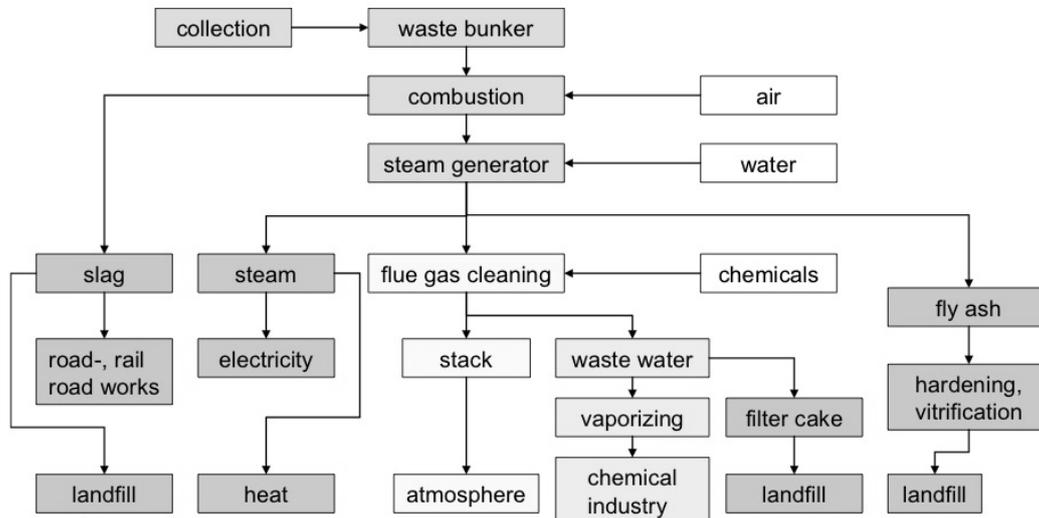


Figure 30: Disposal pathways of a waste incineration plant [Stegmann et. al. 2006]

4.1.2 Waste receiving

First of all waste receiving happens in an incineration plant. For this purpose weighing and classification of the incoming waste in terms of quantity and quality takes place.

The incoming waste quantity is documented at weighing for cost sheet. In addition, the collected data could be used for waste statistics and operational performance calculation.

The classification of the incoming waste serves the ejection of non-combustible waste (extraneous material), which would possibly interrupt the process. In addition, bulky waste has to be reduced in size before incineration [Wittmaier et al. 2009].

4.1.3 Storage, Preprocessing and Charging

The delivery of waste happens discontinuously. On the other hand the process of incineration and the feed into the incinerator happens continuously. Thus, storage of waste is necessary. The bunker serves several purposes:

- Buffering of the waste
- Recognizing of incompatible material and removing or conveying for pre-processing
- Homogenization of the waste

Three different bunker types can be distinguished: deep bunker, plate conveyor bunker and shallow bunker.

Deep bunkers have a small area need. Even the cranes for waste rearrangement (homogenization) and



loading have short distances. There is a risk of anaerobic processes.

Plate conveyor bunkers are used principally for receiving and charging. They consist of a conveyor belt which is reinforced with steel plates to minimize damage. It is located at the bottom of a pit with funnel-shaped cross section. At this bunker type there is only a small mixing of the waste.

For shallow bunkers, with the same volume as deep bunkers, larger areas are needed. This can be problematic at construction in urban areas. The costs for construction are lower than for construction of deep bunkers but there are operational disadvantages (e.g. larger crane operating distances).

If waste stays in a bunker a long time, self heat processes and gas production (methane production under anaerobic conditions) happens. This can lead to fire or explosion. Therefore sensor or detection systems as well as good aeration and fire extinguishing systems should be installed in the bunker.

Since bulky waste must be crushed for incineration, pre-processing is necessary. The size reduction leads to a volume reduction and thus to a better use of bunker space. Furthermore the specific surface is increased, which in turn has a positive effect on combustion. In addition, blockage of the charging funnel can be prevented. For the task of size reduction and removal of incompatible material shearing mills, impact crushers, or jaw mills can be used. Moreover the crane is used for this also.

Due to the continuous operation of incinerators, the funnels are constructed in a way that an appropriate hourly throughput can be ensured. The waste in the funnel tubes reaches the charging mechanism through the filler shaft. The shaft can be closed with a flap to prevent a backfire of flames. The stress of the charging units is high, from thermal (position near the grate) as well as mechanical (transportation of waste) encumbrances [Bilitewski, 1994].

4.1.4 Combustion Process

The basic design of the combustion chamber is always similar. It is limited by the grate below, through the combustion chamber walls and a ceiling or a boiler on the top. To start the waste incinerator, the combustion chamber should be pre-heated. This is necessary because of possible national legal regulations regarding pollution control. The pre-heating is done by an auxiliary burner, which operates by gas or oil. Generally the combustion process itself can be divided into different phases. These phases can not be strictly separated from each other. The phases are:

- Drying
- Degasification
- Gasification
- Combustion
- Post-combustion

At the drying phase the waste is heated by heat radiation or convection in the upper area of the grate to about 100 °C. The water is evaporated from the waste. In the degasification the volatile components are expelled at temperatures of 250 °C and higher. These include water and other smoulder gases. A pure degasification is only possible if no oxidizing agents are present. Subsequently the gasification happens with the implementation of fixed carbon to gaseous products. This process takes place mainly in the temperature range from 500-600 °C. Finally the proper combustion happens (complete combustion), at which the combustible gases from the previous process steps are completely oxidized. In modern waste incinerators the loss by combustion is less than 0.5 wt-%. The afterburning or post-combustion zone is necessary to minimize



unburned and CO in the flue gas. For this purpose air or flue gas is re-added with a residence time of at least 2 sec. and at 850 °C. Figure 31 illustrates the different phases of the combustion process.

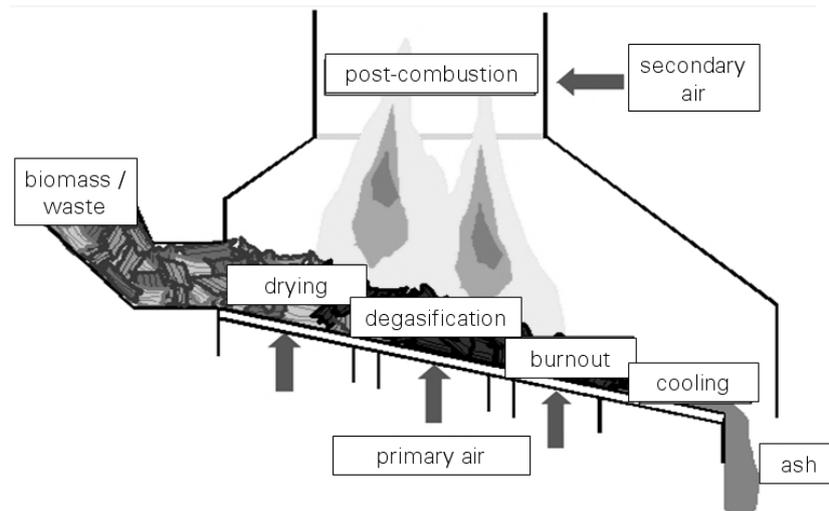


Figure 31: Principle of the combustion process [Wittmaier et. al. 2009]

Grate firing System

At grate firing three different types of grates can be distinguished, which are all used for waste incineration in Germany (see also Figure 32). These are:

- Travelling grates
- Reciprocating grates
- Rotating drum grates

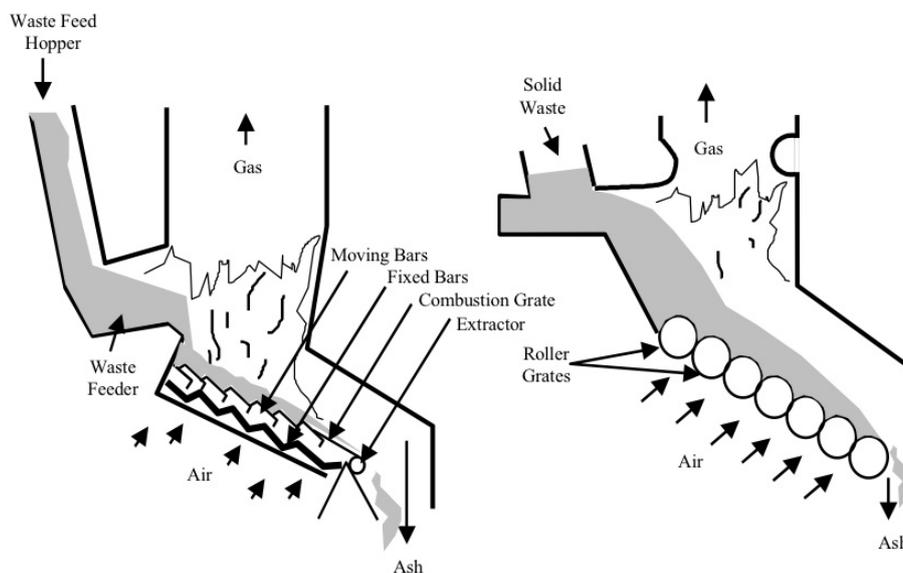


Figure 32: Grate systems [CalRecovery, 2005]



Travelling grates consist of several overlapping rows of fixed and movable grates. The waste is transported through the stroking motion of the grates from the charging end to the outlet. The grates are installed inclined as well as horizontal. A sufficient stoking is also supported by the movement of the grates.

As the travelling grates the reciprocating grates consists of mobile and stationary transverse rows. The grate is inclined to the outlet of the slag, on the other hand the lifting movement of the grate bars is to the charging direction. Overall this type of grate achieves a good stoking. At the end the discharge of combustion residues happens with the help of a roller.

A rotating drum grate consists of 6 side-by-side drums with a diameter of 1,5 m each (see Figure 33). The declination towards the discharger is 30°. The drums are individually controlled (by electric motors). The pockets between the individual drums force a rolling motion of waste, which results in a thorough mixing and stoking [Wittmaier et. al. 2009].

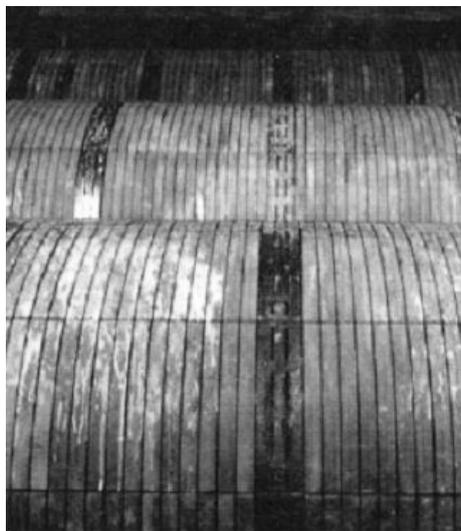


Figure 33: Rotary drum grate [Igelbüscher, 2009]

Beside the optimal combustion the design of the combustion chamber has to ensure a good flue gas mixing. For the directing of flue gases through the combustion chamber, three different types can be distinguished: Direct flow, counter flow and central flow (see Figure 34).

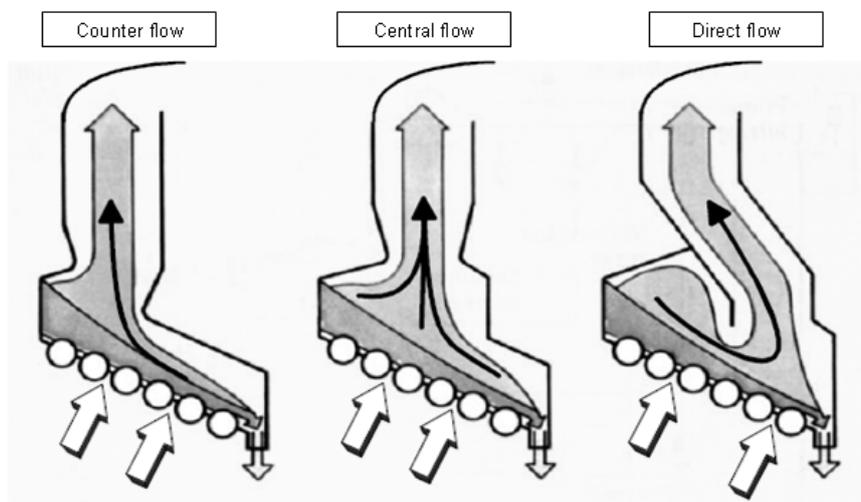


Figure 34: Principles of the air circulation in the combustion chamber [Igelbüscher, 2009]



At direct flow the critical gas (unburned hydrocarbone gases) is lead through the temperature maximum and nearly completely burned. The disadvantage is, that the hottest flue gases are generated at the end of the grate and must be recirculated to the drying and ignition zones. Therefore the method of direct flow is suitable for dry, rapidly igniting materials and for those with high heat value.

In the counter flow the hot combustion gases are recirculated from the end of the grate through the drying and ignition zones. Advantage is that moist and low heat value products can be burned quickly with thus formed pre-drying.

By using central air flow, the first under air blower is installed above the main combustion area. In this way, the flue gases must necessarily pass through the hot combustion zone.

Overall, often a compromise between counter flow and central flow is often made [Bilitewski, 1994].

Fluidized-Bed Incinerators

The fluidized-bed incinerator consists of a lined, cylindrical combustion chamber, with air distribution nozzles on the bottom. These nozzles supply the necessary air for the combustion process, which fluidizes the bed material as well as the waste and which starts to behave like a viscous fluid. This results in a relatively large surface area for heat transfer and substance exchange. The principle schema of a fluidized-bed incinerator can be seen in Figure 35.

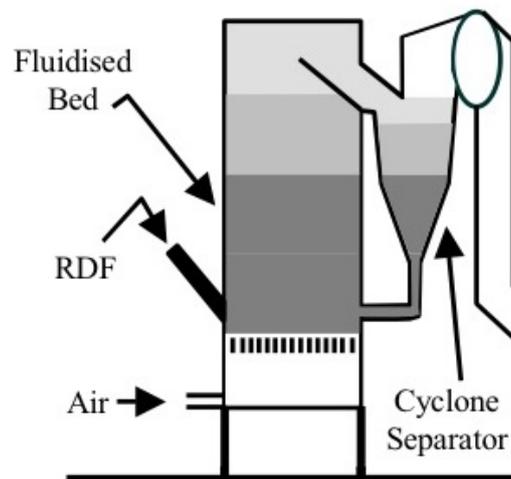


Figure 35: Circulating fluidized bed incinerator [CalRecovery, 2005]

The bed consists of granular material (sand), which rests loosely on the permeable bottom during the resting state. To form a stabled fluidized-bed at a high temperature, the silica sand is filled in the incinerator furnace with optimum quantity. Nozzle floor (see Figure 36 and Figure 37) and material layer are perfused by air, which is also combustion air, in ascending direction. From a certain air speed the individual particles of the material layer are lifted. The movement of the particles leads to an intensive mixing of the whole layer volume, the fluidized-bed is actively formed in the sand layer. The product to be incinerated is supplied on the sand



fluidized-bed and mixed with the sand while the sand particles are actively moving. The water instantly evaporates from the product and the product temperature is increased by the contact with hot air. The product is incinerated through these processes. The ash produced by incineration is crushed into small pieces and discharged out of the system accompanies with the exhaust gas. Finally, the ash is collected with a dust collecting system.

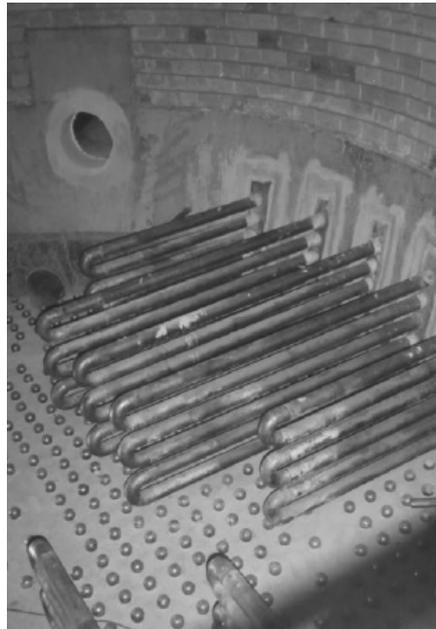


Figure 36: Nozzle floor of a fluidized-bed reactor [Igelbüscher, 2009]



Figure 37: Air distribution nozzles of a stationary fluidized-bed reactor [Igelbüscher, 2009]



This incinerator type has a wide application range. Not only sludge but screen residues and other waste can be incinerated. Furthermore, low air ratio combustion is possible with a fluidized-bed incinerator. Because of the high thermal capacitance of sand and excellent thermal conductance of the fluidized-bed, the water is instantly evaporated from the waste. There is no local overheating area and a consistent temperature is kept in the incinerator furnace, and thus the fear for generation of ash clinker is reduced and energy can be saved, which is required for any type of incinerator. Because of the fact that the bed cannot exceed a certain temperature (the bed sand would soften), only a small amount of heavy metals are retained in the ash. So a fluidized-bed incinerator is only suitable for incineration of waste with low concentrations of heavy metals, for example [Wittmaier et al. 2009]:

- Wood, eventually plastic and paper
- Human waste sludge and sewage sludge
- Industrial wastewater sludge
- Waste less from industrial processes

The main characteristic of fluidized bed incineration is the inert bed which consists of 90 % either sand or other non-combustible substances. Only the remaining residue consists of combustible materials. Since the bed itself possesses considerable heat capacity, it is possible to achieve a homogenous heat distribution in the fluidized bed which is independent of combustion properties of the waste. This leads to an exceptionally clean or odourless burn. To reduce concentration of pollutants in the flue gas, additives such as lime can be used to retain harmful gases. For the incineration process with a fluidized-bed incinerator, it is necessary to pre-sort the waste to remove non-combustible material as well as ferrous metals and also to perform size reduction.

4.1.5 Slag removal

After the combustion process and at the end of the grate the generated slag has to be removed. This is necessary because of different reasons:

- Prevention of blockage during the continuous generation
- Prevention of secondary air leakage

The discharge of slag always happens by gravity, regardless which grate system is in use. The slag falls into a chute and is led to the residue handling equipment. The major problem at discharging the slag is the high temperature of about 600 – 900 °C. If the excess air is too low, temperatures of about 1000°C could be reached (melting point of slag). To quench the slag and to reach an air-lock to the combustion chamber, various wet-systems have been developed and are in use [Bilitewski, 1994].

4.1.6 Boiler and heat recovery

For various reasons, the installation of a boiler at operation a waste incinerator is required, mainly because of the waste heat recovery from MSW incineration, partly because of cooling the flue gases. The flue gases must be cooled down after burning from 1000 - 1200°C to 200 – 300°C for procedural reasons, as flue gas cleaning processes require temperatures below 350 °C.

The heat of the flue gases are transferred by the boiler into a suitable thermal carrier (steam or water). Important elements of a steam boiler are the feed water treatment unit, the feed water line, an air pressure



tank, safety valves, and the steam release pipe with controls for water level and boiler and steam pressure. In waste incineration plants, three different kinds of boilers are in use:

- Hot water boiler
- Saturated steam boiler
- Superheated steam boiler

Also, there are three different designs for the dynamic of steam in steam boilers. These are circulation boilers, forced circulation boilers and force-through flow boilers. The construction of a circulation boiler with three to five flues above the furnace has established. New constructions with a primary boiler and a secondary boiler have been used successfully. Both designs have their specific advantages and disadvantages.

Important for the recovery of combustion heat for generation of steam are the site conditions and requirements. In large facilities mostly high-grade steam (40 bar, 400 °C) is produced for electricity generation, temporarily combined with district heating. Smaller facilities generate steam with lower operating parameters (15-20 bar, 200-250 °C). At this the steam is often used for heating purposes or as process heat for industrial purposes [Wittmaier et al. 2009].

4.1.7 Emission control

Flue gas quantity and composition

At incineration of waste designated quantities of flue gases are produced (about 5000 m³ per Mg). These are in addition to carbon monoxide (CO), carbon dioxide (CO₂) and water steam also sulfur dioxide (SO₂), nitrogen oxide (NO_x), unburned particles, other hydrocarbons, polycyclic aromatic hydrocarbons, dioxins, furans and other pollutants like HCl, HF or heavy metals. These pollutants can occur in both, gaseous form as well as particulate pollution. Flue gas scrubbing is used to remove these particles and gaseous pollutants from the flue gas stream [Bilitewski, 1994]. The arrangement of the flue gas cleaning at a waste incineration plant is shown in Figure 29.

Collection of particles

First, the particulate pollutants have to be removed in the dust removal. This reduces the load on the scrubbers. Particles in the flue gas have a size range of 1 µm bis 1 mm. Various methods can be used for the dust removal, they are described briefly below.

In the dust removal in a cyclone, the mass inertia of the particles is used. The dust-laden gas is given tangentially into a symmetrically rotating centrifugal separator. Particles are carried by inertia to the cylinder wall and exit the cyclone through the conical section on the bottom while the clean gas runs out through the top. The principle of a cyclone is shown in Figure 38

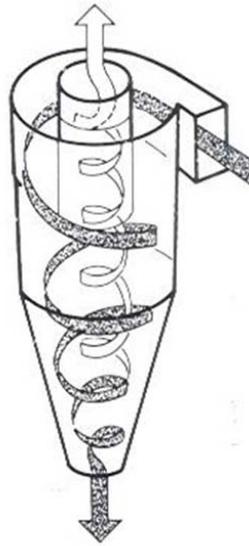


Figure 38: Principle of a cyclone [Wittmaier et al. 2009]

Another option is to clean the flue gas with a fabric filter. In this method, the dust-laden gas is passed through a porous layer, which transmits the gas, but retains the particles on the surface. Fibres are used as filter material made of natural products, plastics, minerals, and others, who are processed into fabric or felt. Figure 39 shows a modern fabric filter with the relevant elements.

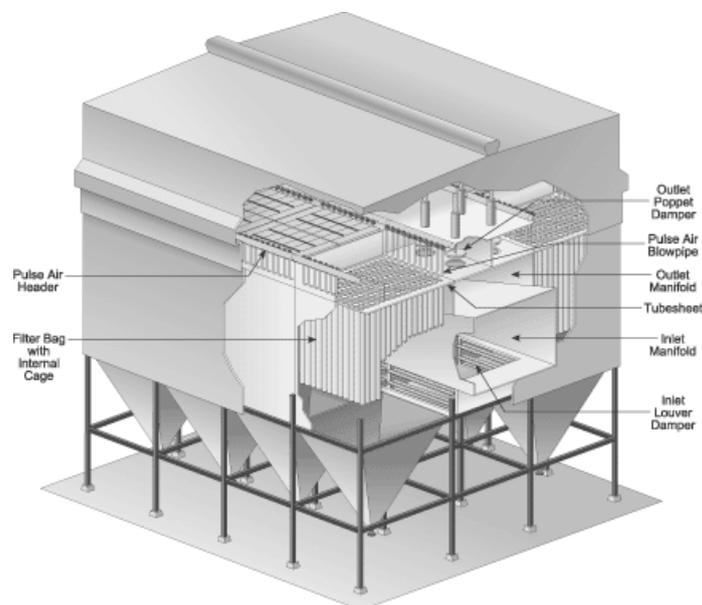


Figure 39: Fabric Filter [Babcock, 2010]

The electrostatic precipitator works on the principle that the dust particles are first charged (release of electrons in a discharge electrode). Then they are moved to the wall surface by the force of a high-voltage field and are separated (collecting electrode) [Wittmaier et al. 2009]. The construction of an electrostatic separator is shown in Figure 40.

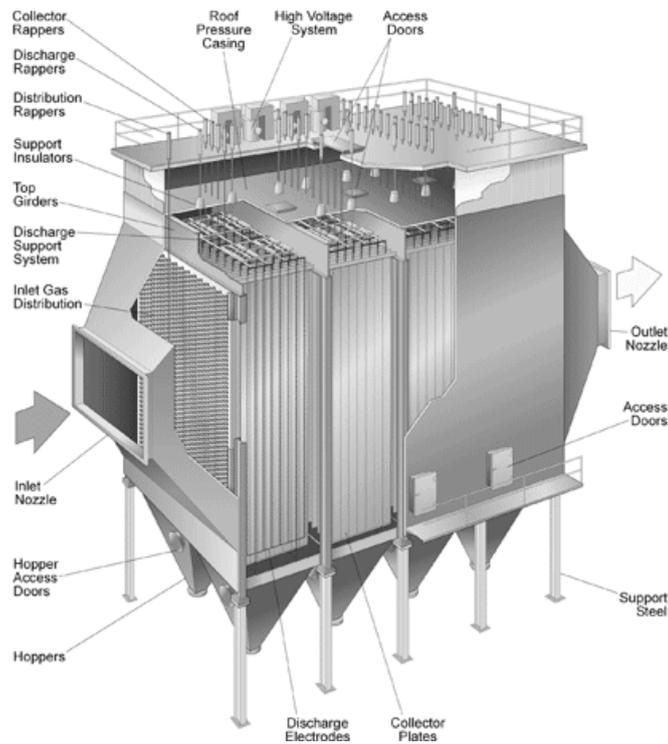


Figure 40: Dry Electrostatic Precipitator [Babcock, 2010]

Physical and chemical principles for the removal of gaseous pollutants

The principles for the removal of gaseous pollutants are based always on either absorption or adsorption. Absorption means the solution of gaseous constituents in suitable liquids (solvents) or solids. The solution can be both, chemically and physically. At the adsorption the compounds of the gases or liquids are adsorbed on surface-active substances such as active carbon or lime, and thus selectively removed. Low temperatures and high pressure are advantageous for this process. The adsorbed amount depends mainly on the specific surface and the surface structure of the adsorber.

Removal of Acidic pollutants

The processes for the removal of acid pollutants can be distinguished between wet, wet-dry and dry-scrubbing. The principle of wet scrubbers based on the absorption of acidic gases in a liquid phase. Often this process is built two-stage. The acid stage is used primarily to cool the flue gases and for the removal of HCl, HF and volatile heavy metals. The subsequent alkaline scrubber serves for the removal of SO₂. The principle of wet scrubbing is shown in Figure 41.

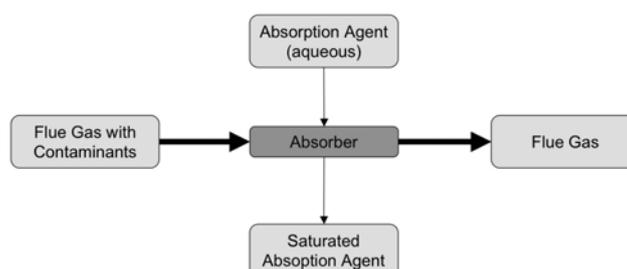


Figure 41: Scheme of the wet scrubbing process [according to Bilitewski, 1994]



Dry-wet scrubbing means a spray absorption, in which a solution or suspension is sprayed as a neutralizing agent in the hot flue gas stream. The crystallized solid products are removed in a downstream solid separator. The amount of heat in the flue gas is used to evaporate the water, the dosage of agent must be in according to the amount of heat. Neutralizing agent is usually $\text{Ca}(\text{OH})_2$ -suspension to react with the components HF, HCl, SO_2 und SO_3 .

In the absorption process of the dry scrubber finely crystalline and alkaline components are blown in the hot flue gas stream. The reaction products are removed from the flue gas stream by a filter. As neutralization agent nearly exclusively $\text{Ca}(\text{OH})_2$ -powder comes into operation. As filter electrostatic precipitators and fabric filters are used [Bilitewski, 1994].

Denitrification

During the incineration of waste nitrogen oxides are formed at higher temperatures. The denitrification can be distinguished into primary and secondary processes.

The formation of nitrogen oxides can already be prevented in the combustion chamber. For this purpose several methods are possible. The first method is air staging, in which in the waste is burned incompletely in the first stage. By the addition of more combustion air the waste is burned completely in the following phases. The content of nitrogen oxides in the flue gas could be reduced by up to 20% by flue gas recirculation. Cooled and dedusted flue gas is recirculated to the combustion chamber in this process. Finally a method, which is not in use for the incineration and flue gas scrubbing of waste, is staging of fuel.

Already formed nitrogen oxides are destroyed in the secondary denitrification by reduction. There are two processes for the purpose: catalytic reduction and non-catalytic reduction. With the non-catalytic reduction (SNCR, Selective Non Catalytic Reduction) denitrification rates of about 70% can be achieved. Ammonia, urea, liquid manure or similar substances are used as reduction agent and injected into the combustion chamber. At temperatures of about 1000 °C, the reducing agent reacts with the NO_x and forms oxygen and nitrogen (N_2). With the catalytic reduction a higher denitrification rate of up to 85% can be achieved. Flue gases are directed over a catalytic converter in which ammonia or urea is injected. It should be noted that the higher the temperature at denitrification in this process (150-400 °C), the smaller the surface of the catalytic converter has to be dimensioned.

Dioxins and Furans

Treatment of Slag, Ashes and Flue gas cleaning residues

Table 7: Air pollutants from solid waste incineration and methods of control [according to CalRecovery, 2005]

Pollutant	Control Methods	Typical Reduction (%)
Oxides of nitrogen (NO_2)	<ul style="list-style-type: none"> • Selective catalytic reduction • Selective non-catalytic reduction • Flue gas recirculation 	10 to 60



Pollutant	Control Methods	Typical Reduction (%)
	<ul style="list-style-type: none">• Combustion control	
Acid gases (SO ₂ and HCl)	<ul style="list-style-type: none">• Wet scrubber• Dry scrubber• Fabric filter• Electrostatic precipitator	50 to 85 SO ₂ 75 to 90 HCl
Carbon monoxide (CO)	<ul style="list-style-type: none">• Combustion control	50 to 90
Heavy metals	<ul style="list-style-type: none">• Dry scrubber• Fabric filter• Electrostatic precipitator	70 to 95
Particulates	<ul style="list-style-type: none">• Electrostatic precipitator• Fabric filter	95 to 99.9
Toxic organics (including dioxins and furans)	<ul style="list-style-type: none">• Combustion control• Combination of dry scrubber and fabric filter	50 to 99.9

4.1.8 Control and monitoring

A monitoring system is very important to control a waste incineration plant. It provides information about the status of the individual processes and operating conditions. Many sensors at different locations are installed in the plant, including a gas analysis at the boiler outlet (raw gas) and another after the gas cleaning process as well as sensors for temperatures, pressure, throughput and charging gauges. CO and O₂ measurement help to control the combustion process. Particulates emissions are constantly measured for operating the electrostatic precipitator while the contaminant concentrations in the clean gas are monitored and recorded. Similarly, the conductivity and pH value of the boiler water as well as pH value of the scrubber wastewater are generally analyzed.

Another important aspect is to control the combustion process. With the application and help of a precise control reduction of emissions such as CO, NO_x and unburned material can be achieved. The control of heavy metals and inorganic halides by combustion is limited. To reduce the temperature in the combustion chamber and to control the steam temperature, the flue gases are recirculated. For denitrification flue gases are also recirculated into the area of primary denitrification [Wittmaier et al. 2009].

4.2 Incineration of hazardous waste

The treatment of hazardous waste, in this case the thermal treatment, is of special importance to protect or minimize the hazards for nature and human beings and to ensure an appropriate disposal of this waste with no serious effects on the environment.

4.2.1 Storage, pretreatment and charging

Hazardous wastes are delivered to an appropriate treatment facility and are stored in containers or barrels of different shapes and sizes. If the incineration is not possible because of physical, chemical or toxic factors, a pre-treatment is necessary in order to allow combustion. This could be a chemical/physical for detoxification,



neutralization, sludge treatment, emulsion separation, solidification or evaporation. For the trouble free incineration, it is also important to avoid large fluctuations in heat values [Wittmaier et al. 2009].

4.2.2 Incinerator furnaces

Types of hazardous waste incinerators, which should be grateless, are rotary kiln furnace, multi-hearth furnace, fluidized bed furnace and the combustion chamber.

The rotary kiln furnace is the predominant type of furnace for the incineration of hazardous waste. This is founded in the high operating temperatures, the long residence time and the universal firing system. The Principle of a rotary kiln furnace is shown in Figure 42. Different kinds of waste can be treated in a rotary kiln furnace. These are liquid substances like solvents, pumpable material like sludge, pasty material and solid and compound materials that melt below their flash point. Liquid waste is injected at the front end of the rotary kiln, using the pipe pressure (5). Doughy and pasty waste in barrels is brought by a barrel-elevator from an intermediate storage to the feed hopper (2). Solid waste is directly filled by a crane into the feed hopper from the top. Gaseous wastes are injected directly into the afterburning chamber (8).

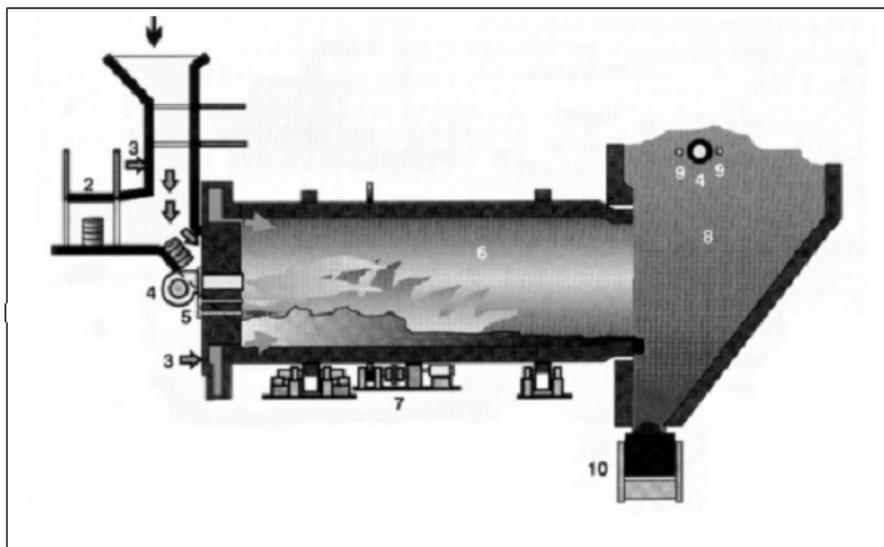


Figure 42: Principle of a rotary kiln [Wittmaier et. al. 2009]

The multi-hearth furnace is suitable for incineration of industrial waste with very high water content. This kind of furnace is rarely used for treatment of hazardous waste though.

Homogenous liquid, pasty and gaseous wastes could be incinerated in fluidized bed furnaces. Because of the low reachable temperatures the use of fluidized bed furnaces for incineration of hazardous waste is limited.

The combustion chamber is a cylinder into which the waste and the combustion air are injected. Therefore this type is the preferred type for the incineration of gaseous and liquid industrial waste [Bilitewski, 1994].

4.3 Incineration of other waste

4.3.1 Sewage sludge

Sewage sludge is burned primarily in multi-hearth furnaces and in fluidized-bed incinerators, especially in the fluidized-bed incinerator. In addition there is also the possibility of co-combustion in waste incineration plants, which is recently taken into account while planning the facilities. So there are two methods for thermal



utilization of sewage sludge:

- Mono-combustion
- Co-combustion in a waste incineration plant

For incineration in a multi-hearth furnace, sewage sludge with a high water content travels first through a drying zone with temperatures below 100°C (first five levels), before it is burned. The principle of the multi-hearth furnace and the temperature chart is shown in Figure 43 and Figure 44.

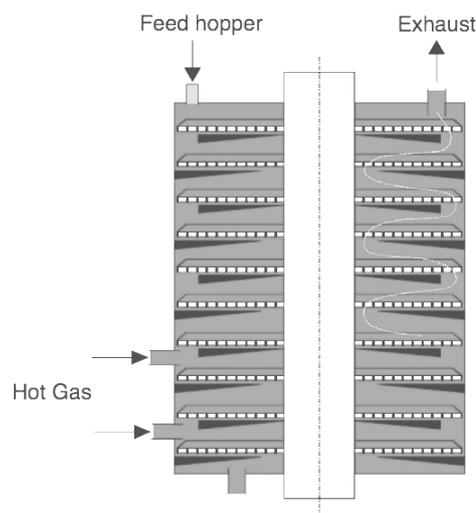


Figure 43: Schematic of a multi-hearth furnace [Igelbüscher, 2009]

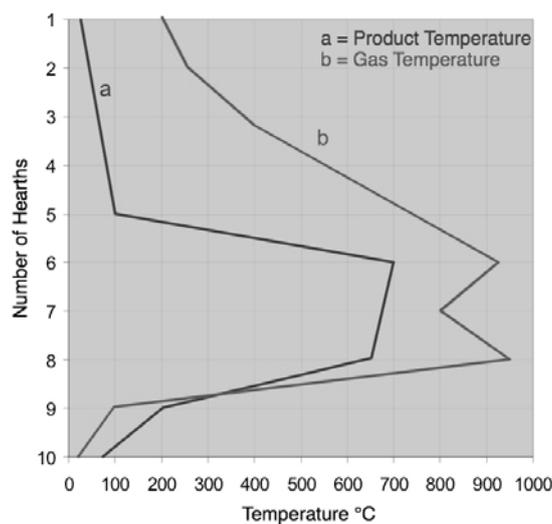


Figure 44: Temperature curve of a multi-hearth furnace [according to Igelbüscher, 2009]

Sewage sludge could also be burned together with coal. Because of the low caloric value of sewage sludge an addition of co-fuel is recommend (e.g. tree bark).



For several reasons the co-combustion of sewage sludge with household waste is beneficial. On the one hand the energy content of waste could be used for drying the sewage sludge. Thus, this heat energy is economically feasible year-round. On the other hand no preprocessing of waste or sewage sludge is necessary for co-combustion in either a multi-hearth furnace or rotary kiln furnace [Wittmaier et al. 2009].

4.3.2 *Straw and wood*

A part of the straw can not be used well (20%). Straw has a water content of about 20% and a low caloric value of about 12 to 14 MJ/kg. A wide transportation is uneconomical because of the low density of about 200 kg/m³, for which reason straw is considered to be burned in local small scale incinerators. Since straw is free of pollutants there are hardly any harmful emissions during the process, except for incomplete oxidized gases (e.g. CO) through incomplete combustion. For this reason, some boilers are equipped with afterburners. The fly ash emissions can be minimized by using more sophisticated firing systems or processing the straw into briquettes or pellets.

The combustion of wood for energy production is only useful if no other recovery (material recovery) is possible (e.g. chipboard). Combustion in small scale plants is only recommend if the wood could be received with low costs or free of charge and if little treatment is necessary. For the combustion in large plants, two principles of wood combustion are in use:

- Complete combustion in the combustion chamber
- Pyrolysis and combustion of pyrolysis gases afterwards

If wood is unconditioned it contains non-environmental substances which makes a treatment of combustion residues necessary. However, even with the burning of wood the disposal of ashes and filter dusts has to be ensured (according the load factor).

4.4 *Pyrolyzation and gasification of waste*

Both pyrolysis and gasification are used to convert solid waste into gaseous, liquid and solid fuels. The principle difference between these two systems is that pyrolysis systems use an external source of heat to drive the endothermic pyrolysis reactions in an oxygen-free environment, whereas gasification systems are self-sustaining and use air or oxygen for the partial combustion of solid waste [McGraw, 1993].

The following advantages of pyrolysis and gasification in comparison to other processes were expected:

- Uncomplicated and cost effective processes
- Energy and resource recovery
- Possibility for storage of recoverable product (energy)
- Flexibility with respect to various wastes and changing waste compositions
- Almost complete prevention of environmental pollutions

The objectives of pyrolysis and gasification are similar to the waste incineration. Waste should be reduced in volume and converted to a physical state whose storage has no serious effects on the environment. Table 8 shows the interrelationship of the different thermal treatment methods.



Table 8: Classification of various thermal treatment methods [Bilitewski, 1994]

Potential Process steps	Treatment Method			
	Drying	Pyrolysis	Gasification	Combustion
Step 1	Drying	Drying	Drying	Drying
Step 2		Pyrolysis	Pyrolysis	Pyrolysis
Step 3			Gasification	Gasification
Step 4				Combustion

4.4.1 Pyrolysis

Pyrolysis is the thermal decomposition of waste in the complete absence of oxygen. Because of the fact, that most organic substances are thermally unstable, they can be split through a combination of thermal cracking and condensation into gaseous, liquid and solid fraction. In contrast to combustion or gasification the process of pyrolysis is endothermic. This requires an external heat source [McGraw, 1993].

In the temperature ranges i.e. 150-900 °C volatile compounds are expelled and complex carbohydrates are converted into simpler compounds. The products of pyrolysis are pyrolysis gas (main product), pyrolysis coke, oil and tar, depending on the input material, heating parameters, pyrolysis temperature and reaction time. The solid residues consist of pyrolysis coke and other materials like metals or sand, which are not converted into gas in the process [Wittmaier et al. 2009].

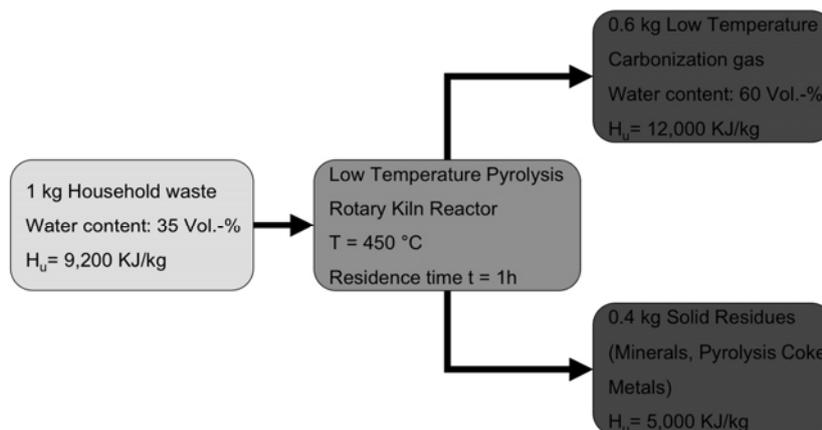


Figure 45: Example of material and energy balance from the low-temperature pyrolysis of MSW [according to Bilitewski, 1994]

4.4.2 Environmental considerations of the pyrolysis process

Regarding the environmental considerations of the pyrolysis process it has to be distinguished between two kinds of contaminants. On the one hand contaminants, which are inherent to the input medium (sulphur, chlorine, heavy metals, etc.), on the other hand contaminants, which are produced depending on the thermal process (type of pyrolysis facility, temperature, etc.).



During the pyrolysis, organic compounds are reduced into simple, low molecular compounds. For example, these are hydrogen (H₂), carbon monoxide (CO) or carbon dioxide (CO₂). In addition, mainly hydrogen compounds are present as ammonia (NH₃), hydrogen sulphide (H₂S) or hydrogen chloride (HCl). At process temperatures of about 500 °C aromatic and phenolic hydrocarbons are formed. When the gas gets cool, these compounds condense as tarry substances and accumulate in condensate and gas washing water as contaminants. Therefore, an immediate combustion of the pyrolysis gases is useful. In this way, the waste water pollution can be avoided. The discharge of heavy metals depends on the process temperature. At temperatures of around 500 °C only a small heavy metal rate is expected in the gas. During the pyrolysis process the extracted sulfur concentration rises from 50-60% at 700-750 °C to about 80% of the input sulphur at temperatures around 950 °C. Even at low temperatures HCl occurs in the gas, coming from PVC. Higher temperatures have only a small further effect on the concentration. Organic contaminants can be reduced by their destruction during the pyrolysis process, whereby the gases are directed through the hottest zone of the reactor. The required temperature is about 1000-1300 °C.

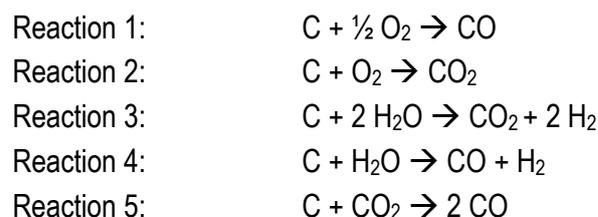
Pyrolysis waste water consists of moisture from waste, decomposition water and water from combustion. The highly contaminated waste water, especially at pyrolysis of household waste with oils, tars, phenols, etc., requires a chemical-physical pre-treatment before further treatment. Water from wet removal of solid residues can extract solvable compounds like water-solvable calcium, chlorides, sulfates and organic compounds.

The low temperature pyrolysis (400-500°C) can help to retain the heavy metals in the pyrolysis residues due to the higher carbon content in the residues and thus the better adsorptive characteristics.

The concentrations of polycyclic aromatic hydrocarbons (PAH) in MSW are much higher than in the solid residues of pyrolysis. This means that the pyrolysis reduces PAHs in the solid phase. In comparison to incineration only small quantities of PCDD and PCDF are generated during the pyrolysis because oxygen is necessary to form dioxins. Oxygen enters the pyrolysis process, which is an oxygen-free process, only as a part of the waste [Bilitewski, 1994].

4.4.3 Gasification

Gasification means the conversion of carbon-containing materials at high temperatures into gaseous fuels, whereby reactive gases are added to oxidize the residual carbon of the pyrolysis coke at temperatures above 800 °C with less than stoichiometric oxygen and further conversion of carbonized residues into additional gaseous products. As reactive gas normal steam, carbon dioxide, oxygen or air are used. The following chemical reactions take place in the gasification of carbon-containing materials, depending on the gasification agents (oxygen, air, steam, hydrogen, carbon dioxide).



From the partial combustion of the carbon in Reaction 1 and 2, the fuel bed becomes glow and reacts with the generated carbon dioxide according the heterogeneous Boudouard reaction (Reaction 5). At higher temperatures in the fuel bed the carbon monoxide production is higher. The interrelationship of CO₂ to CO is



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