THE COMPOSTING BIOTECHNOLOGY :
A MICROBIAL AEROBIC SOLID SUBSTRATE FERMENTATION COMPLEX PROCESS

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1. INTRODUCTION

The collection and recycling of biosolids and the organic fraction of municipal solid waste (MSW) is an important factor for the success of the so-called «circle economy» as a component of modern waste management policy.

The last decade has lead to an increasing awareness of the problems associated with the classical methods of waste treatment. It was realized that the elimination of waste materials by burning, or by its dumping in sanitary landfills was not the final solution to all waste problems, but gave sometimes rise to new ones (pollution of air and groundwater, elimination of toxic residues, shortage of suitable sites for landfills). In addition, biodegradable wastes are not very well suited for incineration because of their high water content, and create problems when put in landfills (emanation of gases and leachates). Due to the ongoing dehumification of the soils, the necessity to recycle plant derived wastes to return nutritive minerals to the soil, but also to renew the humus fraction, was recognized.

Initial green and Kitchen waste

Final compost

That's why today, modern waste treatment programs can not be imagined without source separation and composting, either at individual, local or regional level, to treat part of this organic fraction, namely garden and park waste (green waste), kitchen waste, and also agricultural and biodegradable industrial waste.

Composting is a self-heating, aerobic, solid-phase biological accelerated natural process of biodegradation and mineralisation of organic matter.

Industrial composting is a controlled process. The main objectives of this process is to maximize the hygienization and biodegradation/mineralisation.

1.1. ADVANTAGES AND DISADVANTAGES OF COMPOSTING

Composting of the organic fraction of the waste leads to numerous **improvements** in the overall waste treatment process :

- reduction of the amount of waste that has to be incinerated or put in landfills;
- and therefore reduction of incinerator ash to be disposed of, and of landfill space;
- in general lower costs than incineration, although treatment costs in very sophisticated, completely enclosed composting systems are now near those for incineration;
- recycling of humus and nutrients into the soil;
- protecting and improving the microbiological diversity and quality of cultivated soils,
- bog conservation, because compost can be used as peat substitute,
- beneficial role of compost microorganisms in crop protection, in as much as they compete with plant pathogens,
- beneficial role of compost microorganisms in bioremediation (biodegradation of toxic compounds and pollutants).

If composting is not carried out properly, it can also have some **disadvantages** :

- the most common complaint about composting installations are odor nuisances;
- that's why the tendency goes to completely enclosed systems where the outlet air is treated in a biofilter before being emitted. The best way, though, to prevent malodor generation is a composting process with a high degradation rate, in order to remove the putrescible substances as quickly as possible;
- proliferation and dispersion of potentially pathogenic and / or allergenic microorganisms;
- soil pollution if the heavy metal content of the compost is too high. This can be avoided if the starting material is free of these contaminants (source separation of the organic waste; use of sewage sludge only from non-industrial origin);
- groundwater pollution if composting is carried out on a surface that is not made up properly or where the runoff water is not collected.

2. PRINCIPAL SYSTEMS USED

Composting can be carried out at very different levels and in various degrees of complexity: from the simple «dump» in the backyard to fully automated box composting.
The control for contamination with non-biodegradable materials is either carried out visually, or automatically (removing of ferrous materials by a magnet, and possibly of plastic in a wind sifter). Independent of the type of installation used, the composting technical treatment always proceeds in the same manner, as depicted in Figure 1.

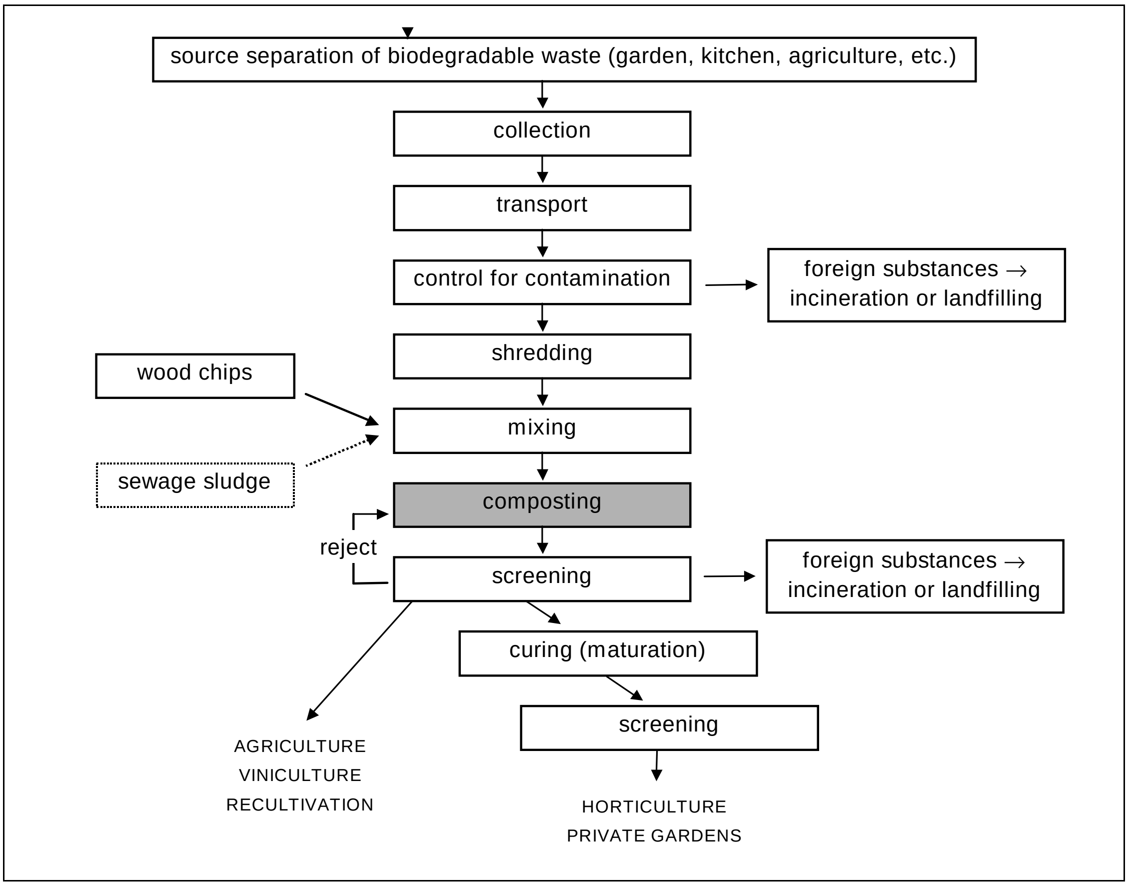


Figure 1: Typical course of a composting process.

2.1. COMPOSTING IN OPEN-AIR (PILES AND WINDROWS)

The composting material is put in piles or long rows (windrows). Depending on the type of turning machine, the windrows have a height of 2-5m, and a width at the base of 4-8m. The turning is carried out with a special machine that drives over the windrows. The «old» method of turning the compost with a front-end loader is fortunately not much employed any more, because this time consuming procedure leads to a infrequent turning frequency, an insufficient mixing of the material, and a bad control of compost moisture.

In pile/windrow composting, the control of compost aeration and humidity is only partially feasible: the former through an appropriate structure of the starting material, the geometry of the windrows and the distance between one row and the other, to allow natural aeration to happen;

the latter through covering of the heaps during rainy periods with a tarpaulin which allows water vapor to escape, but this hinders the passage, and the frequent addition of water during dry periods is further complicated.

Composting in classic compost piles

Composting in windrows

Open-air piles/windrows with no artificial aeration depend mainly on convection-induced mass transfer and gaseous diffusion for oxygenation and the loss of metabolic heat.
Composting windrows tend to vary greatly, both temporally and spatially, in oxygen concentration, temperature, and other physical factors such as moisture, substrate density, and interstitial concentrations of various gases.

2.2. COMPOSTING IN BOXES OR TRENCHES, ROOFED OR IN A CLOSED HALL

Because the composting is carried out in boxes or trenches, natural aeration does not occur. It is though necessary to install an artificial aeration system. Air can either be blown into the compost or sucked through it.
Turnings in boxes or trenches is normally carried out with an automated system that can either run either on the walls that separate the boxes, or is suspended from the roof covering the boxes.

Composting in trenches (System IPS)

Composting in box (System COMPAG)

In some of the installations, compost temperature was controlled by aeration, and the aeration cycle with preset aeration times that change as a function of degree of maturity of the compost. Composting in boxes is usually carried out for a short period of time (6-8 weeks), and a curing stage follows outside the boxes.

2.3. COMPOSTING IN BIOREACTORS

A bioreactor is a completely closed vessel. In order to assume a homogenous composting process, the material either has to be mixed inside the vessel, or has from time to time to be taken out of the vessel, mixed, and refilled. Compost in bioreactors is always aerated.

Composting in closed bioreactors

Composting in closed containers

An interesting concept is the combination of methanization (an anaerobic process) and composting (an aerobic process). Very wet and nutrient rich materials such as kitchen waste or sewage sludge can cause problems during the composting process (clogging of the free air space, and therefore creation of anoxic zones and emission of bad odors). These materials are best methanized in a fermentor under anaerobic conditions. The biogas (methane and CO_2) can be utilized to produce energy (electricity and heat) necessary for the total process. The sludge that comes out of the fermentor (20-30 % total solids) is mixed with shredded wooden waste, and composted optimally in boxes with automatically turning and aeration.

3. COMPOSTING - A MICROBIOLOGICAL PROCESS

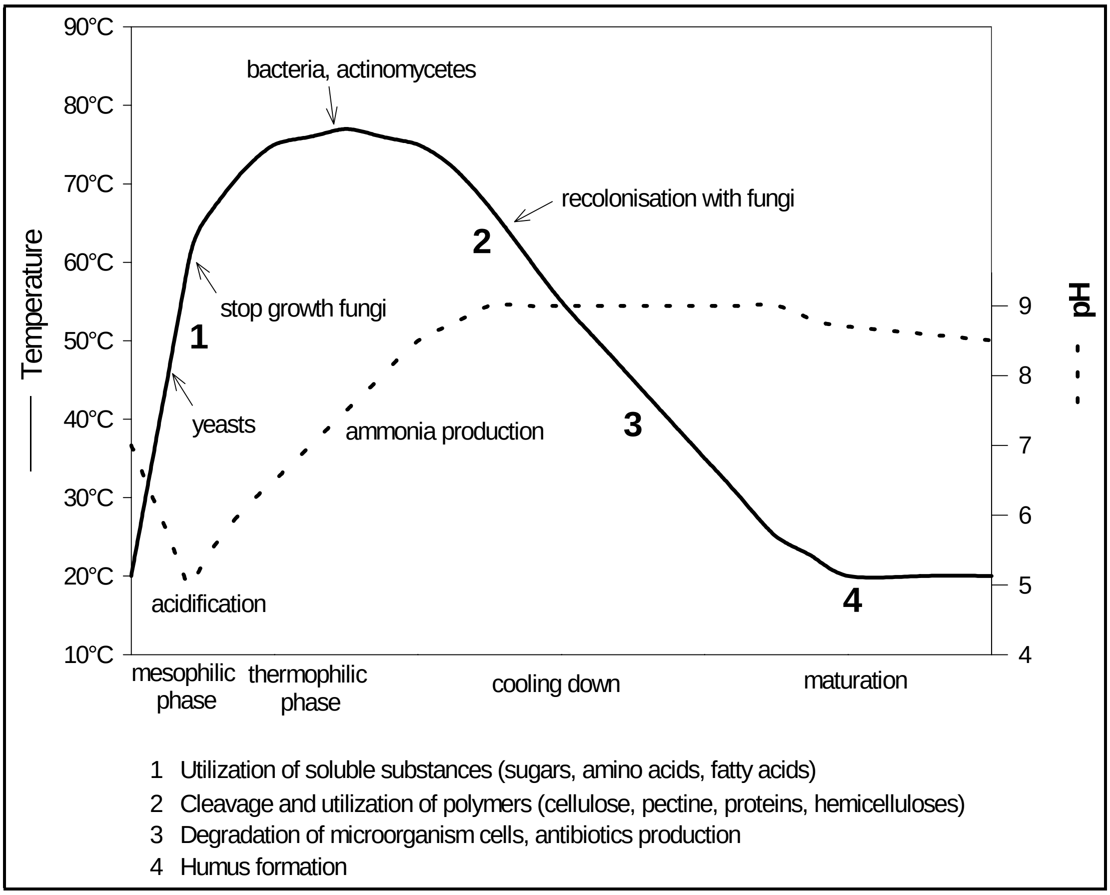
Composting is a microbiological process in which a succession of mixed microbial populations is decomposing heterogeneous organic matter. The description of the microorganisms that participate in the composting process is complex, because the populations and communities change continuously as a function of the evolution of temperature, nutrient availability, oxygen concentration, water content and pH in the course of composting.

The temperature both reflects prior microbial activity and the current rate of activity. The composting ecosystem tends to limit itself due to inhibitory high temperatures resulting from excessive heat accumulation. During this heating stage, various microbial groups succeed each other, each of which being adapted to an environment of relatively limited duration. If a good aeration is provided continuously, the thermophilic stage continues until the heat production becomes lower than heat dissipation, due to the exhaustion of easily metabolizable substrates.

The microbial groups can be classified according to the temperature ranges of their growth activities :

- psychrophilic microorganisms prefer temperatures below 20°C (poorly present during industrial composting)
- mesophilic microorganisms prefer temperatures between 20-40°C
- thermotolerant and moderately thermophilic microorganisms prefer temperatures between 40-60°C
- thermophilic microorganisms prefer temperatures between 60-80°C.

A large diversity and a succession of mixed populations of microorganisms is involved in the composting process; dead and living microorganisms make up 2-20 % of the composting mass. The different populations vary in their growth temperature range, their substrate utilization, their pH tolerance and their oxygen demand (Figure 3). Each population is suited to the environment produced by the previous one.



1 Utilization of soluble substances (sugars, amino acids, fatty acids)
2 Cleavage and utilization of polymers (cellulose, pectine, proteins, hemicelluloses)
3 Degradation of microorganism cells, antibiotics production
4 Humus formation

Figure 2: Schematic depiction of the composting process

A TYPICAL PATTERN OF MICROBIAL POPULATION CHANGES IN FUNCTION OF THE TEMPERATURE WOULD BE AS FOLLOWS :

Stage 1 : Active thermogenic degradation and mineralization

a) Temperature 20-40°C

Fungi, in particular molds and acid producing bacteria are dominant in fresh organic waste, and at the early stage of the composting process (10-100 millions microrganisms/gCDW). Actinomycetes develop far more slowly than most bacteria and fungi and are rather ineffective competitors when nutrient levels are high. The species diversity and the number of the thermophilic / thermotolerant microorganisms are low.

b) Temperature 40-60°C

Mesogenic microorganisms disappear rapidly during the initial thermogenic stage, and the species diversity and the number of the thermophilic / thermotolerant microorganisms increase strongly (100-1’000 millions of microorganisms/gCDW).

The optimal temperature for thermophilic / thermotolerant fungi is 40-50°C. Actinomycetes are generally more tolerant than fungi to moderately high temperatures and their number and species diversity increases markedly at 50-60°C. The number and species diversity of moderately thermophilic bacteria are low at 40-50°C and increase at 50-60°C.

c) Temperature 60-80°C

Only thermophilic bacteria at a moderate species diversity are present, but at high concentrations (1’000-10’000 millions of microrganisms/g CDW). They decompose actively the organic material.

Fungi are reported to be essentially absent at temperatures exceeding 60°C. Actinomycetes could be present at low concentrations, but do not play an active role in degradation and mineralization. Thermophilic bacteria, as well as mesophilic bacteria attack hemicelluloses, decompose a variety of organic compounds such as carbohydrates, sugar alcohols, organic acids, polysaccharides (starch, glycogen...) proteins, lipids, alcohols (methanol, ethanol, phenol..), N-alkenes (acetone..), and oxidize gases (CH_4, H_2, CO...) and reduced inorganic sulfur (H_2S, $S_2O_3^{2-}$, SO_3^{2-}..).

Stage 2 : Active mineralization and maturation

d) Temperature 50-20°C

During the terminal maturation stage the diversity and number of mesophilic / thermotolerant bacteria, actinomycetes and fungi increase strongly (100-1’000 millions of microorganisms/gCDW).

Fungi and actinomycetes are important in cellulose and hemicelloluse attack and decomposition. Lignin decomposition is performed essentially by fungi. The number, species and metabolic functions of mesophilic bacteria also increase markedly. The following bacterial metabolic functions are important for compost maturation and improvement of soil quality :

- decomposition of residual simple or moderately complex organic compounds (proteins, amino acids, lipids, sugars, organic acids...),
- oxidization and mineralization of reduced inorganic nitrogen and sulfur compounds with production of nitrates and sulfate, respectively,
- production of complex humus compounds (exopolysaccharides) by polymerization of simple organic compounds,
- atmospheric nitrogen fixation with the production of ammonia and successively of nitrates by nitrifying bacteria,
- suppression of phytopathogenic fungi,
- mineralization of iron, manganese, and phosphorous,
- metal-binding capacity (Na^+, Mg^{2+}, Cu^{2+}, Ca^{2+}, K^+...) and formation of mineralized aggregates
- toxic heavy metals detoxification by formation of insoluble salts,
- degradation of toxic organic compounds (pesticides).

A great number~~s~~ of scientific papers report the needs during the composting process. Particular attention has been paid to the optimum temperature requirement for the most effective degradation of organic matter. However, there seems to be very little consensus on how to manage the best operating conditions. This is largely associated with conflicting needs of the process, which can be briefly summarized for the different temperature ranges as follows :

- hygienization at > 60°C
- maximum biodegradation at 45-55°C
- maximum microbial diversity at 35-40°C.

High temperatures are often considered to reduce dramatically the functional microbial diversity. A thermogenic phase with temperatures exceeding 60°C was even considered as a **“ microbial suicide** ”. It is therefore generally assumed that to obtain efficient and rapid decomposition temperatures should not be allowed to exceed 55-60°C.
However, the presence and the activities of extremely thermophilic bacteria are essential for biodegradation and mineralisation of organic biowaste at very high temperatures (60-80°C).
Two recent discoveries highlight this point.

- In 1996, it was reported that composts of many different types (garden and kitchen wastes, sewage sludge, industrial composting systems) contain high numbers of bacteria of the genus *Thermus* that grow on organic substrates at temperatures from 50-80^{o}C, with optimum growth between 65 and 75^{o}C. The numbers were as high as 10^{8} to 10^{10} per gram dry weight of compost. Spore-forming *Bacillus* species were also found, but they were unable to grow above 70^{o}C. Thus, it seems that *Thermus* species, previously known only from geothermal sites, have probably adapted to the hot-compost system and play a major role in biodegradation of biowaste in the peak-heating phase. *[T. Beffa* et al.*, 1996.* Applied & Environmental Microbiology ***62****, 1723-1727],*

- In addition, in 1996, a number of **autotrophic** (self-feeding) bacteria were isolated from composts. These non-spore forming bacteria grew at 60-80^{o}C, with optima of 70-75^{o}C, and closely resembled *Hydrogenobacter* strains that previously were know only from geothermal sites. They obtain their energy by oxidizing sulfur or hydrogen, and synthesize their organic matter from CO_{2}. *[T. Beffa* et al.*, 1996.* Archives of Microbiology ***165****, 34-40]*

The morphological, taxonomic (molecular approach), and metabolic/physiological features of these bacteria correspond with the characteristics reported for the following genera or species :

- *Thermus thermophilus,*
- *Hydrogenobacter spp.*
- *Thermus aquaticus*
- *Bacillus schlegelii*
- *Bacillus stearothermophilus*
- *Bacillus thermoglucosidasius*
- *Bacillus thermodenitrificans*

Several of the isolates are probably new strains particularly adapted to the conditions present in the hot composts.

The demonstrated functional bacterial diversity during the thermogenic phase seems to make it possible to compost at high temperatures (65-75°C) for a longer period of time, but not exceeding 80°C. By that, the composting process could be performed very speedy and with a better destruction of potential human pathogens and allergenic molds, as well as phytopathogens and seeds.

4. COMPOSTING - A CHEMICAL PROCESS

Composting can also be regarded as a chemical process, in which the substances present initially in the biodegradable waste are transformed into chemically different ones. Of course, biological and chemical processes are linked, as the enzymes produced by the microflora mainly effect the chemical transformations.

The input of the process is biodegradable waste, consisting mainly of green and kitchen waste, of sewage sludge and other industrial and agricultural waste. Chemically, the main components of these substrates are free sugars, proteins, fats, amino acids and fatty acids, and polymeric substances as cellulose, hemicelluloses and lignin (green waste).

All polymeric substances have to be cleaved by enzymes produced by the degrading microflora in mono- or oligomers, in order to be taken up into the microbial cell. Composting is a solid process, e.g. microorganisms can only utilize those substrates they are in direct contact with, by cleaving of polymers with membrane-bound enzymes, and uptake of monomers. Otherwise, excretion of exoenzymes and uptake of monomers takes place in the water film or the mucilage that surrounds compost particles. **Turning of compost is important** to re-mix microorganisms and/or their enzymes and substrate. In addition, by the mechanical action of the turner, clumps of compost and large wood pieces are broken up, and new surfaces are thus available for microbial attack.

The degradation of the monomers then happens like that of simple sugars, via the Krebs-cycle, yielding, under aerobic conditions, CO_2 and H_2O, under anaerobic conditions (fermentation) volatile fatty acids and alcohols, which serve as substrate for methanogenic organisms, and different gases (CO_2, CO, H_2). Intermediate fermentation metabolites are responsible for bad odors, and can be responsible for the phytotoxic action of composts produced under partially anaerobic conditions. Methane is a very potent "green-house" gas.

4.1. DECOMPOSITION RATE / MATURATION

The goal of composting is the production of a stabilized product that can be stored without further treatment, and can be applied to land without damage to crops. Degree of stabilization is synonymous with **extent of decomposition**, in that putrescible, phytotoxic material is decomposed through aerobic metabolism. Composting at industrial level also aims at maximizing the **rate of decomposition** to reduce the facility space necessary, and to shorten the phase where odor problems could arise. Furthermore, the required maturity depends on the potential utilization: compost that is applied to fields, where it continues the stabilization process, needs to be less mature than compost used in potting mixes.

In order to monitor and control the composting process the following classes of organic substances are tested:

Organic matter (OM), often also denoted volatile solids (VS), is the percent of dry solids or dry weight (DW) lost by ignition at 550°C. Biological activity decreases the OM content of the initial substrate by converting organic waste derived C into CO_2. On the other hand, new OM is formed during the composting process (humus substances, microbial cells). The meaningfulness of the OM content as a maturity indicator is limited, however, because it fails to discriminate among readily metabolizable, putrescible material (sugars, amino acids, fatty acids, etc.), less readily metabolizable material (cellulose, hemicelluloses), and organic material that is only metabolized to a minor degree during any reasonable composting period (lignin).

Total organic carbon (TOC). The test for TOC is basically the same as for OM, only CO_2 production by the combustion of the material is determined, and not ash content. The ratio of OM to TOC for MSW compost was found to be approximately 2.1:1. Therefore, total carbon is often not measured, but calculated by dividing the OM by 2.1 (by 2.3 when testing MSW). Regarding the use of TOC as a maturity indicator, the same critics apply as for OM.

Water-soluble organic carbon (WEOC). Most microorganisms in composts can only take up substances that are solubilized in water. Soluble substances such as sugars, amino acids, fatty acids, etc., are either present initially in the waste, or are obtained by the hydrolyzing of the polymers contained in the solid substrates by the enzymatic activity of the compost microflora. The soluble substances either are utilized immediately by the microorganisms for their metabolism and cell growth, or are accumulated in the water phase. As the composting process progresses, the soluble substances decrease. Various authors confirm the utility of WEOC as an indicator of compost maturity. The water extract of immature MWS compost consisted of sugars, phenolic substances, organic and amino acids, peptides and other easily biodegradable substances, while in the mature compost, most of the soluble organic C was present as humic substances which were resistant to further decomposition. Experiments showed that with progression of the composting process, the proportion of large molecular weight compounds in the water extract increased, indicating the presence of humic substances.

Biological oxygen demand (BOD). Tests for biological oxygen demand are based on aerobic microbial degradation of the readily bioavailable compounds. The standard 5-day BOD test used for sewage sludge has been adapted for compost suspensions: the oxygen decline was followed at 30°C for about 24 h, with inserted periods of aeration. Another method consists in measuring the oxygen concentration in the air space over a solid compost sample placed in a sealed container. After aeration during 16 h, the disappearance of O_2 is followed during 1 h at 37°C. Comparisons of the two methods showed that the respiration rates were highly correlated, but that the test in the compost suspension exhibited up to 6 times higher values.

In the methods book for the analysis of compost published by the German Federal Compost Quality Assurance Organization, a method measuring the oxygen depletion in a respirometer at 20°C in a 6 h rhythm over 4 days is stipulated. One problem encountered with such measurements is the inhomogeneity of the samples, the ideal test temperature and the standardization regarding the water content of the sample. Comparisons between different composts are only possible on the basis of OM, or better WEOC content of the samples.

C/N ratio. The C/N ratio is an important quality parameter when using compost as a soil amendment, because materials with a high C/N ratio can immobilize soil nitrogen by the ongoing decomposition of the carbonaceous substances once the compost has been applied to soil. The ratio decreases as composting progresses because of the conversion of organic C to CO_2 . At the same time, part of the nitrogen can be lost in form of NH_3.

C/N ratio can either be measured in the compost or in an aqueous extract. Normally, a C/N ratio of less than 20 in mature compost is thought to be desirable. However, C/N values measured in sufficiently stabilized composts varied between 5 and 20, depending on the type of raw material.

The C/N ratio in the water extract, on the other hand, showed to be a reliable indicator of compost maturity, as it reached, independently of the composition of the starting material, a final value of C/N_{org} of 5-6.

Others. The **cation exchange capacity (CEC)** of composts is related to the amount of humic substances showed a quite parallel evolution of CEC and humic material in cattle manure compost.

The German Federal Compost Quality Assurance Organization has developed a test for the determination of the **degree of rotting (Rottegrad)** based on self-heating of the compost in an open Dewar vessel (1.5L). Temperature is measured in the lower third of the vessel, for at least 5 days, and the maximum temperature recorded. The rotting degrees are assigned I (T_{max} 60-70°C) to V (T_{max} 20-30°C). Compost with rotting degrees II and III is designated as fresh compost, such with a rotting degree IV and V as finished compost.

The ultimate evaluation of compost has to be based **on bioassays**, e.g. the germination of seeds or growth of plants (cress, barley, ryegrass, tomato or lettuce seedlings, etc.) in compost/soil mixtures.

Considering maturation of compost, it has always to be taken in mind that the end use dictates the level to which the product must be stabilized. For example if compost is to be used in potting mixes, over 50 % of the organic matter has to be degraded, while in composts destined for agriculture, a first stabilization, attained normally after a few weeks of composting, is sufficient.

5. COMPOSTING - A PHYSICAL PROCESS

Composting is also a physical process, in that factors like temperature, humidity, airflow or porosity affect the microbial community, and therefore the degradation process.

5.1. STRUCTURE

The compost matrix is a network of solid particles forming pores of different sizes. Structure is a function of the stiffness of the particles, and their ability to maintain this stiffness also at high water content. It is influenced by the nature of the biodegradable waste. Porosity describes the volume of the free air space, expressed as percentage of the total volume. It is determined by the shape, size and structure of the particles, and the height of the compost pile, as self-loading leads to compression of the material at the base. The pores are filled with air, water or both. For an adequate oxygen supply, the free air pore volume is important, with a minimum free air space of 30 % should be maintained (optimal free air pore volume is 50 %). Water, necessary on the one hand for the nutrient uptake by the microorganisms, hinders on the other hand the diffusion of oxygen into the pores by an increase of the aqueous film thickness around individual particles, and by filling the small pores with water by capillary action. Shredding the material provides an increase of surfaces for microbial attack, but the particles have to be still large enough to maintain a certain porosity. Turning of the compost effects a loosening of the material, thereby decreasing bulk density. With ongoing degradation of organic matter, and mechanical size reduction of woody particles, the porosity of the compost decreases.

5.2. TEMPERATURE

Temperature is a key factor in the composting process. It determines the growth rate, metabolic activity and type of community structure of the compost organisms. Temperature is also the main factor influencing the survival of pathogens present in compost. High composting temperatures also increase degradation, considering that for a given enzyme, activity rates double with a 10°C temperature increase, until the inactivation temperature is reached. Usually, enzymes are more thermostable than the organisms that produce them.

Temperature increases as a function of **metabolic heat evolution** of the degrading microflora and **heat conservation** due to the naturally insulating property of organic waste. Heat storage is an important factor during the initial stage of rising temperature. It is mostly determined by water because of the high specific heat of H_2O. The absolute maximum temperature achievable in composts is 82°C, at which point biological activity and metabolic heat evolution cease.

The temperature that can be measured at any point in a compost heap is a function of the rates of heat evolution and heat transfer (= distribution of heat within the composting mass, and its removal).

Metabolic heat evolution is affected by the following factors:

- the chemical composition of starting material and thus the nutrient content and its availability for microbial metabolisms,
- the moisture content,
- the compost temperature, which effects a feedback control on the activity of different groups of compost microorganisms.
- the turning frequency : stimulation of the microbial activity by redistribution of nutrients and oxygen,
- the oxygen input, because only aerobic metabolisms generate large amounts of heat,
- the particle size; size reduction of particles by shredding leads on the one hand to an enhanced substrate availability through increase of the surface, on the other hand to a reduction of free air space, and therefore to lower rates of activity because of oxygen transfer limitations.

Heat transfer mechanisms are radiation (a minor factor that can be ignored), conduction, convection, evaporative cooling and sensible heating.
Conduction in the bulk compost mass is low, between that of wood ($0.17\ W \cdot m^{-1} \cdot °C^{-1}$) and that of water ($0.56\ W \cdot m^{-1} \cdot °C^{-1}$). In addition, the air-filled pores inhibit conduction. In small composting masses with a large surface area/volume ratio, however, conduction can be a significant factor. Experiments showed lower temperatures in a windrow (4 m wide and 1.2-1.5 m high, with a surface area to volume ratio of 1.6-1.9 m^2/m^3) compared to a pile (radius of 4 m, height of 3 m, area/volume ratio 1 m^2/m^3).

Moving air in a compost heap, either produced by artificial aeration or by convection, or a combination of both, leads to heat removal. About 90 % of the heat is removed by evaporative cooling because of the high heat of evaporation of H_2O; the remaining 10 % by sensible heating of the air passing through the compost. Turning of the compost also leads to significant heat removal through evaporative cooling.

Controlled removal of heat can only be achieved by artificial aeration, often executed as temperature feedback-controlled ventilation. The often-recommended action of turning to reduce temperature certainly removes heat, but, at least in the active phase of the composting process, stimulates microbial activity, and leads to more heat production. Measures to control compost temperature by inhibiting heat evolution are not advisable because they would interfere with optimal microbial activity, slowing thus the whole composting process down.

By the moving air in a compost heap, either due to convection (in the case of open-air windrows) or artificial aeration (in box or trench composting or in a closed bioreactor), a **temperature gradient** builds up, according to the physical phenomena explained :

- sensible temperature increase along the airflow pathway,
- influx of cold and dry air at the lower part of the windrow due to convection that produces an upwardly curved convective pathway ("chimney effect"), or at the point of air entry of the ventilation system,
- heat conduction at the surface of the heap,
- less important heat storage, due to dryer material at the surface, or in the case of artificial aeration, at the point of air entry.

Thermohygienization, e.g. the reduction or elimination of potential pathogens by the high temperatures of the thermogenic phase, is very important for industrial scale composting, because the maturation phase, during which antagonism and antibiotic production mainly occur, are normally very short.

The thermoresistance of microorganisms is usually tested in the laboratory, with reference strains, and often in a liquid environment. Under these conditions, most of the mesophilic organisms are destroyed in a short time at temperatures exceeding 55-60°C. However, inactivation under field conditions may be much different from that observed in the laboratory due to clumping of solids, irregular temperature distribution, incomplete mixing and microorganism regrowth.

5.3. AERATION (O_2 AND CO_2 CONCENTRATIONS)

Composting is by definition an aerobic process : oxygen or O_2 has to be supplied to the compost in order to compensate for the amount used up by the degrading microorganisms. The O_2 status of a composting mass is therefore determined by its rates of utilization and supply. High or low rates of these two factors can result in similar O_2 levels. Air requirements of the microorganisms are dependent on the type of waste (nutrients; structure, which influences the free air space), process temperature, stage of the process and process conditions (moisture content, compaction). Besides providing oxygen, the provision of air also removes waste gases like CO_2 and NH_3, excess moisture and heat.

Anaerobiosis (absence of oxygen) has to be prevented because it leads to a smaller rate of heat evolution and the production of undesirable intermediate metabolites that are the cause of bad odors (propionic and butyric acid, sulfur compounds and ammonia), phytotoxicity, and the production of greenhouse gases (methane, N_2O).

In unvented composting systems, air is supplied to the compost through convection-induced mass transfer ("chimney effect") and gaseous diffusion driven by concentration differences between the interior of the heap and ambient air. Convection will bring fresh, oxygen-rich air into the large pores of the pile, while diffusion from the interstitial atmosphere through the small pores and the water film surrounding the compost particles is responsible for the oxygen supply of the microorganisms. It is stated that oxygen will not limit composting if 10 % interstitial oxygen is present. Thick water films in overly hydrated composts, and small pore sizes will hinder the oxygen diffusion.

Artificially, air can be introduced into the compost by the action of blowers, who either push (positive pressure) or suck (negative pressure) the air through the compost.

Air is also introduced into the compost during turning, but the oxygenation is only momentary, because the turning normally leads to an enhanced microbial activity, and thus to a faster O_2

utilization. The beneficial effect of windrow turning on aeration is most probably a loosening of the composting mass, bringing about an increase in free air space.

The combination of artificial aeration and turning would be ideal, combining the advantages of a maintenance of oxic conditions with the re-mixing of the composting material in the view of homogenous temperature, nutrient and moisture distribution, and the breaking up of preferential air channels which lead to uneven aeration.

Composting windrows without forced aeration tend to vary greatly, both temporally and spatially, in oxygen concentration. Experiments have demonstrated variations between the inner parts of a compost windrow, and the outer layers. In addition, aerated systems can show oxygen gradients, although to a lesser extent. A uniform oxygenation of heaps that exceed a height of 4-5 m can not be obtained: the lower part of the mass gets over-ventilated with excessive cooling and drying, and the upper layers are insufficiently aerated, because the air, while passing through the composting mass, looses oxygen.

The **control of aeration** in artificially oxygenated systems can be exerted in two ways: by either measuring the **temperature** or the **oxygen content** in the compost or in the outlet air. When temperature is controlled at 60-70°C, as suggested by the group of Beffa, to be in the range of maximal decomposition rate, thorough aeration is believed to be automatically ensured, because about 9 times more air is necessary to remove heat than to supply enough oxygen to maintain aerobic conditions. In the first phase of the composting process, temperature controlled aeration did not supply enough oxygen, and that a combined system with temperature and oxygen control was required.

In any system (windrows or boxes) the point where temperature or oxygen content is measured in the compost heap is of big importance, because of the large temperature and oxygen gradients.

Air is normally not applied continuously, but in short bursts to allow a better distribution of oxygen and temperature to all portions of the pile. There seems to be, however, no "standard aeration cycle", and no literature exists where different modes of aeration are compared.
Comparisons of amount of air used for aeration among different systems from the literature are not easy: compost volume instead of weight is used, and it is often not clear if the total amount of air is indicated, taking into account the moments of the cycle where no aeration occurs, or if the amounts given are that of a single aeration event.

The measurements of O_2 consumption or CO_2 production, respectively, either directly in the composting mass after aeration, or in the outlet air in a closed system, can also be used to determine the rate of microbial activity, and therefore the decomposition rate.

5.4. WATER AND HUMIDITY / A_W

Growth of microorganisms is only possible in an aqueous solution, e.g. in the water film that envelops the compost particles. As well, uptake of nutrients takes mainly place if they are dissolved in water.
However, not only a water deficiency, also a water surplus can impair the composting process, in that the water film surrounding the compost particles increases. The oxygen diffusion through water is 10'000 times slower than through air, explaining why a too high initial moisture content leads to anoxic conditions. The maximum water content a material can hold (up to full capillary saturation) is dependent on the material itself: It is recommended a maximum water content for

composting of 74-90 % for wood (sawdust, mulch, bark), 75-85 % for straw, 55-65 % for paper and MSW, and 50-55 % for biowaste (kitchen waste, grass clippings). But in MSW already at a moisture content of 60-65 % the small air pores become water filled (matrix effect due to capillarity), creating water filled zones between particles.
The initial moisture content of mixed garden and kitchen waste ranges from 60-70 %.

Water is produced in the course of the composting process by the metabolic breakdown of organic matter, but this is largely compensated by the loss of water through evaporation, caused by the self-heating of the material. Temperature-controlled ventilation causes an intensive drying of the composting material, because heat is removed mostly in the form of the latent heat of vaporization of water. The composting process should operate with moisture contents in the 40-60 % band, the addition of water during the process is therefore often necessary. This is not possible without re-mixing the material at the same time. At the end of the composting process, a water content of 40-50°% should be reached, in order to facilitate screening.

In open-air windrows a humidity gradient similar to that of temperature and oxygen was measured. After 2 weeks of composting, the top and the base of the windrow were much wetter (55 % H_2O) than the center or the lateral surfaces (45 % H_2O). The top was more humid because of condensation, the bottom because of the pressure of the material.
In ventilated systems, the material tends to dry at the point of the air entry.

5.5. MIXING / TURNING

Turning of compost heap mixes the compost materials, increases porosity, promotes drying through release of water vapor, and exposes the compost mass to high interior temperatures so that adequate pathogen destruction occurs. The widespread belief that turning oxygenates compost is only partially correct.

Own measurements on site showed that the oxygen introduced into young composts (1-4 weeks old) by turning and/or artificial aeration was used up in less than one hour in the thermogenic phase (60-75°C) of the process (T. BEFFA, not published).

This can be explained by the activation of the microflora by the mixing of the compost material, redistributing microorganisms, exoenzymes produced by them, nutrients and water, as well as augmenting the surface for microbial attack by breaking apart clumps of material or large wood pieces. In addition, the increased porosity and the drying effect have a beneficial effect on aeration, leading to increased microbial activity. Little scientific information is available about turning machines, their mixing efficiency and the effect of turning frequencies.

5.6. GEOMETRY OF COMPOS MASS (HEAP, PILE, WINDROW)

Heap and Pile/windrow size markedly influences the composting process: the heat liberated by the thermophilic decomposition must exceed the heat lost through the exposed surface. Increasing windrow size greatly decreases the rate of heat loss. For each 0.5 m^2 increase in cross-sectional area, there was a 1.2°C increase in temperature. It is proposed a maximum height of 2 m for a temperature-controlled aerated static-pile, in order to restrict the temperature to a upper ceiling of 60°C, having determined an upward temperature gradient of 23°C per meter.
WE examined the compaction of the compost material by its own weight, and the resulting resistance to airflow in compost materials. We concluded that with moist material, e.g. 60 % water content, common in starting material, a height of 2.5 m should not be exceeded, otherwise the free air space gets drastically reduced, leading to a loss of free air space, and therefore to anoxic conditions. Drier material (below 55 % moisture) was much less subject to compaction due to its lower density and better mechanical resistance, meaning that in the later stages of composting, e.g. during curing, higher heaps can be formed. Compost heap size is also a function of the turning machine used.

6. DOES COMPOSTING REPRESENT A HEALTH HAZARD ?

By its very nature, biodegradable waste can be the vehicle and the breeding ground of a broad spectrum of microorganisms. Most of them are saprophytes, e.g. organisms which live and feed on dead or decaying organic matter, but the presence of obligate (primary) and facultative or opportunistic (secondary) pathogens is possible. Primary pathogens can invade and infect healthy persons, whereas secondary pathogens normally infect debilitated individuals Primary pathogens can get into the waste by spoiled food, contaminated paper handkerchiefs, animal litter, or with animal excrement polluted grass clippings. Another source is sewage sludge, which is sometimes added in small quantities to yard wastes, or water from sewage plants used for humidification.

Since composting is employed on a large scale for the treatment of sewage sludge, many studies were carried about the survival and dispersion of microorganisms pathogenic for man and animal. When composting plant materials, the elimination of phytopathogenic organisms has to be ensured. Saprophytic microorganisms, which are at the same time opportunistic pathogens (fungi, actinomycetes) have found special attention.

The following groups of human pathogens as having the most importance in composting environments :

Bacteria:
Enterobacteraceae
E. coli
Pseudomonas
Staphylococci
Streptococci
thermophilic actinomycetes, especially
Saccharopolyspora rectivirgula and
Saccharomonospora viridis

Fungi:
Aspergillus fumigatus
Penicillium

Viruses:
Coxsackie-B-Virus
Echo-Virus

Undoubtedly, the most widespread potential biohazards associated with composting appear to be the mould *Aspergillus fumigatus or AF*. *AF,* a cellulolytic mold, is a normal compost inhabitant at temperatures below 60°C, and can survive at temperature of 55-60°C for a fairly long period. Up to 10^6 spores per m^3 of air were measured at sites where compost was processed
AF is an opportunistic pathogen, which can cause infections (aspergilloma, infectious aspergillosis) in immunodepressed people. It is also a powerful allergen, which provokes immunoallergic diseases, like allergic broncho-pulmonary aspergillosis and allergic alveolitis. Immunoallergic response of individuals depends on their genetic predisposition, on the frequency of exposure and on the number of inhaled spores.
The precise dose of *AF* required to elicit adverse health effects in either healthy or sensitive individuals has not been determined.

The presence and abundance of AF in compost and in the air can be taken as an indicator of the potential presence and dispersal of other microorganisms and particles.

Adverse health effects may also result from aerosol exposure to metabolic products of microorganisms. Some fungi produce mycotoxins. β,1,3-D-Glucan and galactomannans, both polyglucose structures in fungal cell walls, have been associated with inflammatory responses. Fever, cough, headache and respiratory impairment can be caused by endotoxins, which are lipopolysaccharides found in the outer membrane of Gram$^-$ bacteria. Furthermore, the constant exposition to dust can provoke an unspecific irritation of the mucous membranes of the respiratory tract (Mucous membrane irritation (MMI)), leading to chronic bronchitis. It is suspected, as in the Organic Dust Toxic Syndrome (ODTS, that often not a single agent, but the combination of fungi, bacteria, and inorganic dust particles, leads to the development of a disease.

Hygiene biorisks need to be identified and solutions need to be found to avoid and eliminate these risks as they may pose a grave danger with respect to:

- Employees of composting operations (though direct contact with the compost or through inhalation of the aerosols),

- The inhabitants in the vicinity of the composting installations (by inhalation of the aerosols),
- The users of the finished compost product (though direct contact),
- The soil and the animals (pathogens can survive after application onto the earth during many months.

6.1. POSSIBLE DISEASES CAUSED BY MICROORGANISMS OCCURRING IN COMPOST

Mycoses

Aspergilli, primarily *AF*, but also *A. flavus* and *A. niger* can provoke a disease called aspergillosis, if the spores get to the lung by inhalation. A benign form is the so-called fungus ball, where the fungus grows in preformed cavities, either in the lung or in the paranasal sinus.

Complications only arise if blood vessels are perforated.

Invasive aspergillosis, where the fungus penetrates from the lung into the blood stream and attacks other organs, has often a lethal outcome. It requires a considerable immune deficiency through an underlying disease like AIDS or leukemia, but also diabetes or hepatitis can favor the development of a mycosis. Patients with a suppressed immune system after organ transplantation or in the course of a cancer therapy are especially at risk. Invasive aspergillosis was observed in aged persons presenting no other risk factors. Aspergillosis has also been observed in animals: young pigs, lambs, cattle (mycotic placentitis, leading to abortion of the fetus), and chicks.

Molds of the order *Mucorales* cause the so-called mucormycosis, which can manifest itself as a lung, a gastrointestinal or a cutaneous disease.

Cryptococcus neoformans, a fungus found in soil, bird excrement, but also in compost, causes cryptococcosis, which can lead to a meningitis.

Mycotoxicoses

Mycotoxicoses are normally provoked by the ingestion of moldy foods, but it has been demonstrated that the spores of various fungi (amongst others *AF* and *A. flavus*) contain mycotoxins. An author discussed the significance of inhaled Aflatoxin B1, produced by *A. flavus*, in the pathology of lung tumors.. One author isolated several potentially mycotoxigenic strains *(A. flavus, A. parasiticus, A. sidowii)* from MSW compost. From 5 strains, three produced mycotoxins after incubation in a liquid medium. No aflatoxins could be extracted from the compost ; a possible interaction between toxins and humic acids was suspected.
The quantities of aflatoxins in the air, and the necessary doses to elicit tumors are not known to date.

Allergies

Because fungal spores can only cause infections in the case of reduced host resistance, the main risk of exposure to high concentrations of fungal or actinomycetal spores is the appearance of allergies.
If the hypersensitivity is caused by the inhalation of spores, one speaks of an extrinsic disease, if hyphae are growing in the air passages, it is called intrinsic.

Fungal allergies are of type I (immediate type); the reaction is triggered by the immunoglobulin E (IgE), which can be found in large quantities in the serum of affected persons. The clinical manifestations are rhinitis, edema of the nasal mucous membrane, and in later stages asthma bronchial. About 10-20 % of the population are thought to be atopic. Population studies of the prevalence of IgE antibodies against *AF* gave results of 0-1 %, increasing to 20 % in allergic subsets.

Actinomycetes but also fungal antigens can provoke exogen allergic alveolitis (EEA), often also called hypersensitivity pneumonitis (HP), which manifests itself in the form of a pneumonia with severe general reactions such as high fever and shivering attacks which occur 6 to 8 hours after contact with the sensitizing agent. Milder courses of the disease can resemble viral infections. The disease is known under the name of Farmer's Lung and constitutes an acknowledged occupational illness.

Allergic Bronchopulmonary Aspergillosis (ABPA) is a characteristic intrinsic condition in atopic, asthmatic patients that can lead to chronic pulmonary damage.

Exposition to bacterial endotoxins

Gram^{-} bacteria produce lipopolysaccharides (LPS) as part of the outer layer of their cell wall that have toxic properties. When the cells lyse, the toxins, called endotoxins, are set free. Inhalation of these can lead to fever and flu-like symptoms.

ODTS

Organic Dust Toxic Syndrome (ODTS) is a non-infectious, flu-like illness, characterized by fever, malaise, muscular pain, and inflammation of the lower respiratory tract, and has been observed in persons exposed to dust containing large amounts of fungi and bacteria. Because no correlation between the presence of precipitation antibodies and illness could be established, an unspecific immune mechanism is suspected.

6.2. THERMOTOLERANT/THERMOPHILIC FUNGI

Fungi play an important role in the degradation process of composts. While yeasts could be isolated in the first few days of the composting process during the acidification phase, thermophilic or thermotolerant species of the order Zygomycetes, Ascomycetes, Basidiomycetes and Fungi imperfecti predominated during the rotting and *Ceratocystis*, *Doratomyces*, and *Trichoderma* in the maturation phase. In stored compost, the opportunistic human pathogenic species *Paecilomyces varioti* and *Scopulariopsis brevicaulis* were detected.

Virulence: Both the small size of the conidia and the ability to grow at 37°C contribute to the pathogeneicity (mycosis) of *AF*. However, other virulence factors are presumed to be responsible for the germination of the conidia and the growth of mycelial filaments in the lung tissue. Toxins contained in the conidia are thought to weaken the action of the cilia that cover the surface of the respiratory tract and that are normally mechanically removing all foreign particles. *AF* was also found to produce proteases that inactivate substances, which render microorganisms more susceptible to macrophage attack in the alveoli, as well as a toxin, gliotoxin, which reduces the mobility of phagocytes.

However, none of these substances was proven alone responsible for the pathogeneicity of *AF*, and no difference was seen between strains isolated from patients suffering from mycoses and strains isolated from the environment. Alternatively, authors concluded that any strain of *AF* could become pathogenic if the normal defense reactions of the host are suppressed.

Presence and dispersion in composting operations: already the garden and kitchen waste contained, dependent on the season, up to 10^7 cfu/gDW, the highest concentrations being measured in the spring material. Grass clippings supported higher *AF* levels (10^6) than dead leaves (10^4). Old woodchips were a big source of *AF*, as they contained between 10^6 and 10^7 cfu/gDW. Even undigested sewage sludge had between 10^2 and 10^3 cfu/gDW *AF*.

During the composting process, a reduction of *AF* numbers was observed, especially in the active rotting phase, when temperatures were highest. In the investigations that took compost samples in different depths in compost piles, it was shown that *AF* concentrations were always higher on the surface than in the center, where high temperatures and maybe reduced oxygen content limited fungal survival and growth. Screening of the compost often lead to an increase in *AF* numbers, attributed to a break-up of spore chains. In sewage sludge composts experiments reported the highest *AF* concentrations in composts from static pile facilities.

The percentage of *AF* on the total fungal flora made out between 20 and 100 %, dependent on the stage of the composting process.

In the heating phase, *AF* occurred almost exclusively, while in the maturation phase, due to temperature decrease and thus concurrence by other, mesophilic fungi, as well as the depletion of degradable substances and progressive drying, its percentage was reduced.

6.3. BACTERIA

Among the bacteria, the actinomycetes and the Gram^- bacteria are most important in the context of composting, the former as allergens and opportunistic pathogens, and the latter as indicators of an insufficient thermohygienization (fecal coliforms) and as producers of endotoxins.

A high degree of thermohygienization in the course of the composting process was generally observed with respect to these bacterial groups. Their regrowth at the end of the thermogenic phase was found to be much more influenced by the degree of degradation of the compost than was the case with fungi. This is because they can not metabolize the less bioavailable substrates like lignin or cellulose left at the end of the composting process, in contrast to fungi.

Gram^- bacteria

Gram^- bacteria, defined as bacteria with a cell wall consisting of a thin murein layer and an outer membrane of proteins, phospholipids and LPS, being colored red by the Gram differential coloration method, have their importance in composting in the connection with the release of endotoxins.

Enterobacteraceae

The family of *Enterobacteraceae* (formerly *Enterobacteriaceae*) groups 2-3 µm long, Gram^-, mostly peritrichously flagellated and oxidase-negative bacteria that are rod-shaped. They do not form spores and are facultative anaerobes. Some species have their habitat in the gut of warmblooded animals and man, whereas others occur normally in water or soil or are plant pathogens. Strains affecting human health are either primary (mostly gastrointestinal disorders) or secondary (urinary tract disease, pneumonia, septicemia, meningitis, wound infection) pathogens.

The most important representatives of this group are members of the genera *Escherichia*, *Proteus*, *Enterobacter*, *Serratia*, *Erwinia*, *Klebsiella*, *Salmonella*, and *Vibrio*.

The classification of *Enterobacteraceae* is not always easy: The newly named species *Pantoea agglomerans* , most common in organic dusts, is a synonym of *Enterobacter agglomerans* and *Erwinia herbicola,* which by recent research using DNA hybridization, have been shown to be the same species. Also, proposals were made to transfer the species *Enterobacter aerogenes* to the genus *Klebsiella*.

The percentage of detection of the different species varied from one installation to the other. A recent publication reported the occurrence of *Salmonella* in 50% of the investigated fresh biowaste samples.

Coliforms

Coliforms are lactose-fermenting *Enterobacteraceae*, which can be of either human, animal or plant origin. Species of the genera *Klebsiella*, *Enterobacter* and *Erwinia* are part of the autochthonous flora of plants. Instead of total coliforms, fecal coliforms which are supposed to be only of human or animal origin, are determined by incubation at 44°C. In fresh biowaste, where concentrations up to 10^8 cfu/gDW fecal coliforms were measured, 1-3 times more total coliforms. In a MSW compost, however, where the microorganisms had be exposed to elevated temperatures (maximum 75°C), no difference between total and fecal coliforms was seen.

Total coliforms are monitored during the composting process because the die-off of coliforms should give a good indication of the completeness of the disinfecting process, and because the population of coliforms can be directly related to the population of human pathogens.

The U.S. Environmental Protection Agency (EPA) regulation demands for sewage sludge compost a final concentration of ≤ 1000 cfu coliforms/gDW.

Escherichia coli

The species *Escherichia coli* (*E. coli*) belongs to the family of *Enterobacteraceae,* and because it is lactose positive to the group of coliforms. It is part of the normal intestinal flora of man, where it is present in concentrations of 10^5 to 10^9 cfu/g feces. Some strains are pathogenic. Its presence in water and food is an important indicator for a fecal contamination. Investigations of biowaste have shown its presence in sometimes quite high concentrations (up to 10^7 cfu/gDW), questioning its fecal origin.

6.4. WAYS OF POSSIBLE INFECTION

Pathogenic microorganisms either are attached to the compost material, or are emitted in form of bioaerosols often associated with dust particles. Infections or allergic reactions in compost workers can occur by inhalation or swallowing of aerosols, by oral contact with compost due to insufficient personal hygiene, or by entry through wounds. While the last two possibilities can be avoided by an adequate instruction of the personnel, and technical measures (protective clothing, etc.), the emergence of bioaerosols can not be completely avoided, unless the composting installation is entirely enclosed and automated, and the vitiated air is filtered before emission to the atmosphere. Although effective personnel protection could be given by the wearing of masks, this is, because of reasons of comfort, only feasible in special situation and for a short period, e.g. for control of completely closed installations or biofilters.

Aerosols

A collection of airborne biological particles is called a bioaerosol. Those generated by agitation of moist compost during the rotting phase are a mixture of microorganisms and plant particles associated with inorganic particles, surrounded by a thin layer of moisture and often consist of aggregates of several organisms.

Human exposure to aerosol during turning of a compost pile

Thousands of *A. fumigatus* particles collected on Petri dish (8 cm diameter) from 100L of air aspirated 50m behind the turning machine

Human exposure to aerosolized microorganisms and their metabolites happens mainly by inhalation of aerosols: the average amount of air inhaled is approximately 10 m^3/day; one breath accounts to 0.5 (no activity) to 3 (heavy work, sport) liters, which adds, by 16 breaths/min, to an average air volume of 0.8 m^3/ hour by moderate heavy work.

Large airborne particles are lodged in the upper respiratory tract (nose and nasopharynx), particles < 6 µm are transported to the lung, and the very small fraction (2-3 µm) gets to the alveoli.

Aerosols are released before being transported by air. Their settling is affected by the physical properties of the particles (size, density, shape) and the environmental parameters (air currents, relative humidity, temperature).

7. CONCLUSION – PRACTICAL AND FUNDAMENTAL BASIC RULES

Our practical and fundamental works (1994-2002), financed by Swiss National Scientific Research Fund (priority program and biotechnology, biorisk module) permitted the identification and evaluation of risks present on site at industrial size composting and anaerobic digestion facilities. Technical solutions were proposed and adopted thereby significantly reducing or eliminating hygiene risks and to improve the management of industrial facilities/systems in order to produce rapidly a good quality final compost.

Industrial composting is a controlled process. The main objectives of this process are to maximize the hygienization and biodegradation/mineralisation. As described in chapter 3, the hot composts are populated with literally billions of thermophilic bacteria per gram; present a wide diversity of highly thermophilic (high temperature loving 60-80 degrees C) bacteria, which serve to degrade organic waste at quasi-infernal temperatures. These elevated temperatures are created through the intensive management of the compost, commonly referred to as **thermocomposting.** The **thermocomposting** technique improves and accelerates the degradation of waste, rapidly kills most of the pathogens for man and plants, avoids the repopulation of the finished compost by pathogens, avoids the formation of odors, and permits the production of a compost of excellent quality within just 8 - 12 weeks.

Even without understanding in detail the complex microbial processes, designer, manager and operator of composting installations should consider certain fundamental basic rules in order to produce compost under good conditions. From our practical work on several different industrial composting installations, we consider the following parameters as essential for an optimal thermocomposting :

- The initial nutrient balance (C/N ratio between 25-35), to ensure a good degradation without nutrient limitation.

- The initial structure and the size of the composting mass to ensure an optimized aeration (passive or mechanical) required for an efficient aerobic degradation process. This rate is directly related to the type of waste and to the phase (initial, intermediary and terminal) of the composting process.

- The control of the airflow rate (in high technology systems) to ensure a homogenous and fast microbial degradation rate. This rate is directly related to the type of waste and to the phase (initial, intermediary and terminal) of the composting process.

- The moisture content (45-55%), sufficient to allow optimum activity without releasing leachates.

- The frequency of mixing or turning, to ensure a better homogeneity of the degradation process. The frequent mixing or turning (e.g. 2-3x / week), improves and stimulate :

  - the constant availability of organic and mineral substrate to micro-organisms, sustaining a high degradation rate and thermohygienization,

  - the redistribution of the free enzymes and micro-organisms in the whole mass,

  - the porosity, air diffusion and moisture distribution minimizes air channeling and avoids the formation of large anaerobic zones provoking nauseating odors.

- The duration of the composting process (minimum 6-8 weeks) ~~:~~ to avoid toxic effects of the end product, as well as the recolonisation of pathogens promoted by the presence of residual large amounts of easily biodegradable organic compounds.

This type of management should be applied universally for industrial size composting and aerobic digestion + composting facilities in Switzerland and around the world.
If these basic rules are not respected, the microbial degradation process, the hygienization, and the final compost quality are negatively affected.

8. COMPOSTING WITH COMPAG TECHNOLOGIES

The <Swiss-Made>, COMPAG Technology permits the recycling of all types of biowaste. The process is 100% ecological and is effective for all organic wastes and agro industrial by-products. The technology was developed in the late 1980's evolving significantly in the past decade. Numerous scientific studies have been conducted in view to optimize the technical and biological parameters. In Switzerland today, the COMPAG system is the most commonly used fully automated composting technology.

STRATEGIC ADVANTAGES OF THE COMPAG TECHNOLOGY

Application, technical management and economics

1. **Reliable** system with simplified management, minimum labor input and **optimized economic model** for the treatment of 5,000 to 10,000 or more metric tons of waste per year.

2. **Automated controls** for real time management of the technical parameters (aeration, turning, hydrating, temperatures, duration, stocking and post-maturation of the finished compost,).

3. **Adaptation and instant modification** of the management parameters as a function of the types of biowaste and the optimum conditions for biodegradation.

4. **Highly flexible, easily expandable with a wide range of fields of application :**

    - Biotreatment of all types of urban and industrial biowaste
    - Remediation of contaminated sites with co-composting
    - Biotreatment of contaminated industrial wastes with co-composting technique
    - Dehydration of Municipal Solid Waste (MSW) (50% water reduction in 12 days).

5. **Enhanced economic return** due in part to an accelerated biodegrading/maturation process resulting in excellent quality finished compost in only 8-10 weeks time.

6. **Optimal aerobic maturation** during the storage of the compost.

Biology, biodegradation hygiene and compost quality

7. **Accelerated degradation/maturation** yielding a variety of compost qualities for diverse applications. For example: the period of 4-5 weeks for fresh compost and 10-12 weeks for a high quality potting compost.

8. **Rapid elimination of all pathogens** present in fresh waste (1 - 3 days) via composting, ensuring safety for human, animal and plant life.

9. **Hygiene and biosafety guaranteed for the workers**, the persons living nearby the installations, due to the absence or very limited dispersion in the air of pathogenic microorganisms.

10. **Avoids the formation of troublesome odors** throughout the whole process.

11. **Natural selection of the microorganisms** responsible for the biodegradation **through the control over the principle parameters** (aeration, turning, hydration, temperature, duration, storage and maturation...).

12. **Homogeneous and constant biodegradation** with optimal distribution of microorganisms and enzymes due to lateral and horizontal turning mechanism.

13. **Production of a high agronomic and biological quality compost** comprising a high diversity and elevated quantity of micro-organisms generally regarded as indispensable for the regeneration and fertilization of soil and for the elimination of plant pathogens.

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