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# Modelled on Nature – Biological Processes in Waste Management

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## 1. Introduction

Biological degradation and transformation of organic substances under aerobic or anaerobic conditions are key processes within the natural metabolism of an equilibrated circulation system in order to handle the accumulating biomass. These fundamental processes are the basis for management strategies focusing on the biological treatment of organic waste materials. They are subjected to the biochemical metabolism using the capability of microbial populations to degrade, transform and stabilise organic matter. Stabilisation comprises biological as well as abiotic chemical and physical processes and their interaction. Avoiding greenhouse gases and shortening the after care period stabilisation is the key target for safe waste disposal in landfills. Biogenic waste materials are a source of secondary products: biogas obtained by anaerobic digestion and composts produced under aerobic conditions. For composts stabilisation is a relevant process to achieve plant compatibility and persistent organic substances for soil amelioration. Biological processes additionally contribute to landfill remediation, e.g. by methane oxidation.

Nevertheless, biological degradation of waste materials is ambivalent and can lead to harmful effects if microbial activities take place under uncontrolled conditions in imbalanced systems. Abandoned landfills from the past demonstrate this fact. Anthropogenic organic wastes differ from “natural” organic waste by their amount, their heterogeneity and the content of xenobiotics. Therefore it is necessary to support and optimise biological degradation of waste organic matter by adequate process operation and technical devices. The equilibrium of necessary mineralisation and accessible humification is a topic of high interest in the context of carbon fixation.

“Optimisation” is no aspect in the context with natural degradation processes. Additionally they are not harmless a priori. They take place under the current conditions, but it can be assumed that an equilibrium is reached over longer periods of time. Changes of environmental conditions by anthropogenic activities can accelerate biological degradation. Peat bogs that were drained and amended with carbonates lose organic matter due to mineralisation (Küster, 1990). The pH value, water and air supply and temperature mainly influence the transformation rate. This fact indicates that biodegradability is not only an inherent property that depends on chemical and physical features of the material. The behaviour of biodegradable substances is affected by the interaction of both material characteristics and environmental conditions.

This chapter provides an overview of biological processes in waste management, targets and benefits, weak points and optimisation potential, process and product control by modern analytical tools such as FT-IR spectroscopy and thermal analysis.

## **2. Composting and anaerobic digestion - Environmental benefits of resource recovery**

The biological treatment of waste materials primarily focuses on stabilisation of organic matter in order to avoid gaseous emissions after waste disposal. The aspect of resource recovery has gained in importance during the last two decades. Although resource recovery has been practiced in the past, e.g. by composting of organic residues, this idea is currently going through a renaissance, primarily due to the necessity of energy supply and increase of soil organic matter by compost application. The retrieval of chemical products from waste materials is also under discussion.

The knowledge about the biodegradability and microbial processes is a prerequisite for the optimum use of biogenic waste. The heterogeneous composition of the incoming material additionally demands a certain flexibility and adaptation according to basic requirements. In many cases there is a potential for process optimisation.

Soil improvement by compost application and its relevance to carbon storage and climate change

The benefits of compost application have been known for long time. According to historical traditions clever farmers recognised the value of “rotted” and “putrefying” organic waste for soil amelioration (Bruchhausen 1790, cited by Eckelmann, 1980). Compost management for many centuries has led to the formation of anthropogenic soils in several north-western European countries and in Russia (Hubbe et al., 2007). These so called “Plaggensoils” represent an impressive example of organic matter increase by compost application. “Terra preta” in the Amazon region also attests to the long-term effect of organic matter brought into soil by anthropogenic activities and organic waste (Sohi et al., 2009). Long-term experiments that have been initiated in the 19<sup>th</sup> century provide useful data on the effects of organic matter amendments and their long-term behaviour (Jenkinson & Rayner, 1977).

Agricultural activities, tillage and the application of mineral fertilisers have promoted losses of organic matter in soils that have caused their degradation to a certain degree. “Desertification” has become a keyword in this context (Montanarella, 2003). The current issue of climate change has additionally attracted notice to carbon losses. The maintenance of organic matter and organic carbon is an effective measure to reduce CO<sub>2</sub> emissions. Besides technical approaches of carbon sequestration, prevention of carbon losses in soils by adequate tillage and compost application, which seems an effective measure should be given priority. Composts with high humic substance contents play a crucial role as they favour the fixation of carbon and minimise the losses.

How compost organic matter is integrated in different soil carbon pools is a topic of high interest in order to evaluate the stability and the long-term behaviour. Different approaches have been applied to identify and describe the carbon pools in soils (Six et al., 2000a; Six et al., 2000b; Pulleman & Marinissen, 2004). These methods can be applied to amended soils in order to trace the fate of compost organic matter and to quantify the contribution of composts to the stable carbon pool.

## **2.1 Composting**

Composting is a biotechnological process that can be operated at different technical levels. Due to this fact composting is an appropriate technique for developing countries to handle biogenic resources for soil amelioration. Besides the environmental aspect resource recovery is a crucial issue. The application of composts on agricultural soils has gained in importance in view of the considerable losses of organic matter and soil degradation in many countries.

### **2.1.1 Regulations for compost quality - European and American situation**

No European directive or regulation on compost quality determination has been put into force to date. A first step to establish such regulations was done by the Commission of the European Community in December 2008 by a green paper called "On the management of bio-waste in the European Union" (COM(2008) 811 final) (Commission of the European Communities, 2008). In this green paper national compost standards and legislations of the Member States are summarised. Compost policies and regulations differ substantially between the Member States. In Bulgaria, Cyprus, the Czech Republic, Denmark, Estonia, Hungary, Malta, Poland, Romania, Sweden and the United Kingdom no specific compost legislation exists. In Lithuania, France and Slovakia compost regulations were integrated in the waste and environmental legislation or only simple registration schemes were established. In Belgium, Finland, Germany and Austria specific compost standards are available. Austria, Belgium and Finland have an obligatory and Germany a voluntary quality assurance system. But only in Austria compost reaches the level of a product.

In Austria the "Compost Ordinance" (BMLFUW, 2001) was put into force in 2001. These rules defined limit values for pollutants (especially for heavy metals), foreign matter (plastics, glass, metals) and plant compatibility (maturity, toxic components). The Austrian Compost Ordinance provides three compost classes that are distinguished by both the input materials (e.g. kitchen, yard and market waste, sewage sludge) and the specific limit values for heavy metals. The compliance with the Austrian Compost Ordinance is supported by the „Ordinance for the separate collection of biogenic waste from households“ (BMLFUW, 1992) which was enacted in 1992. It includes the obligation for the separate collection of biogenic waste from households, the recycling and use of these materials.

In America no directive or regulation on compost quality determination has been established up to date. The 50 federal states of America can rule compost quality by themselves. If there is any regulation available it only sets limit values for pollutants, especially for heavy metals.

### **2.1.2 Adequate ingredients and process operation**

A wide range of organic waste materials is available. There are several synonymic terms to describe the waste fraction that serves as input material for anaerobic digestion and composting: organic waste, biogenic waste and biowaste are the most common ones. Besides yard and kitchen waste that have always been a basic component of composts, residues from food industry (Grigatti et al.; Bustamante et al., 2011) and biotechnological processes, agriculture, sewage sludge (Doublet et al., 2010), digestates from anaerobic processes and mixtures of these materials extend the list of ingredients for composting. Agricultural waste comprises crop residues and manure (Shen et al., 2011). Due to increasing amounts of food waste in industrial countries the separate collection for different treatment strategies is under discussion (Levis et al., 2010). Nevertheless, prevention of food waste should be given

the highest priority. Regarding biogenic waste there is also a high potential in developing countries, especially for market waste, crop residues and manure. Two aspects suggest the use of these materials: the minimisation of the environmental risk due to uncontrolled emissions and resource recovery. This purpose is paralleled by adequate measures in terms of waste separation and collection. The separation of biogenic waste from municipal solid waste is not taken for granted in all European countries. In some cases biogenic waste is treated with municipal solid waste and only separated after the biological treatment. In Austria the source separation of biogenic materials was stipulated in the nineties by a corresponding ordinance (BMLFUW, 1992) in order to avoid diffuse contamination that can not be removed *ex post*. The Austrian Compost Ordinance (BMLFUW, 2001) provides a list of possible ingredients for composting in the first annex.

Composting processes are operated in open windrow or closed systems. The geometry of the windrow should allow efficient aeration by convection. Mechanical rotating supports air supply and the removal of volatile metabolic products which is very important during the most reactive phase of degradation. In closed systems forced aeration is necessary. The biological treatment consists of specific phases that are clearly distinguished from each other in well operated processes. The most obvious degradation with the highest transformation rate takes place in the intensive rotting phase that is characterised by increasing temperature due to exothermic reactions. Early metabolic products such as volatile fatty acids and ammonium are parameters that are usually applied to describe this stage of decomposition. The pH value allows a rough estimation. The early stage features low pH values of 5 to 6. In the mature compost the pH ranges from 7 to 8.5. Appropriate process operation in the first phase is relevant to reduce odour emissions by efficient air and water supply. Anaerobic conditions in the windrow lead to methane formation that should be avoided. Nevertheless, temporarily or locally limited aeration also supports humic substance formation that is improved by a moderate degradation to moieties of bio-molecules. Very strong aeration favours mineralisation. After the intensive rotting process metabolic activities slow down and change into the curing and the maturation phase. This stage is characterised by decreasing temperature, low respiration activity, a C/N ratio of about 12 and the oxidation of ammonium to nitrate. The stable stage is indicated by a nearly constant level of organic matter and total organic carbon contents respectively. The remaining organic matter consists of hardly degradable enriched substances, of organic substances stabilised by mineral compounds and of humic substances that are synthesised during composting. This process still takes place in the maturation phase. The continuous degradation process until the measured parameters reach a nearly constant level and indicate a stable product, is only achieved if the conditions for microbial activities are adhered to. A lack of water often gives the appearance of a “stable” state because it leads to a standstill of the microbial metabolism. Due to degradation of organic matter mineral compounds are enriched and show a relative increase. They mainly contribute to the stabilisation of the remaining organic matter fraction. Due to the portion in biogenic waste and the geological background carbonates and clay minerals play the most important role. Fig. 1 illustrates the development of the CO<sub>2</sub> concentration, temperature, respiration activity (RA<sub>4</sub>) and humic acid contents in two composting processes in plant BC1 and plant BC2. Although process kinetics are individual according to the input material and operation conditions, principles of biological degradation are clearly visible. The respiration activities start at different levels and decrease continuously to a low value. The high temperature for several weeks

guarantees favourable conditions regarding hygienic requirements. The CO<sub>2</sub> concentration in the windrow of plant BC2 is maintained for a longer time at a high level. The curves of humic acid formation are still increasing and indicate that the synthesis process has not yet been finished.

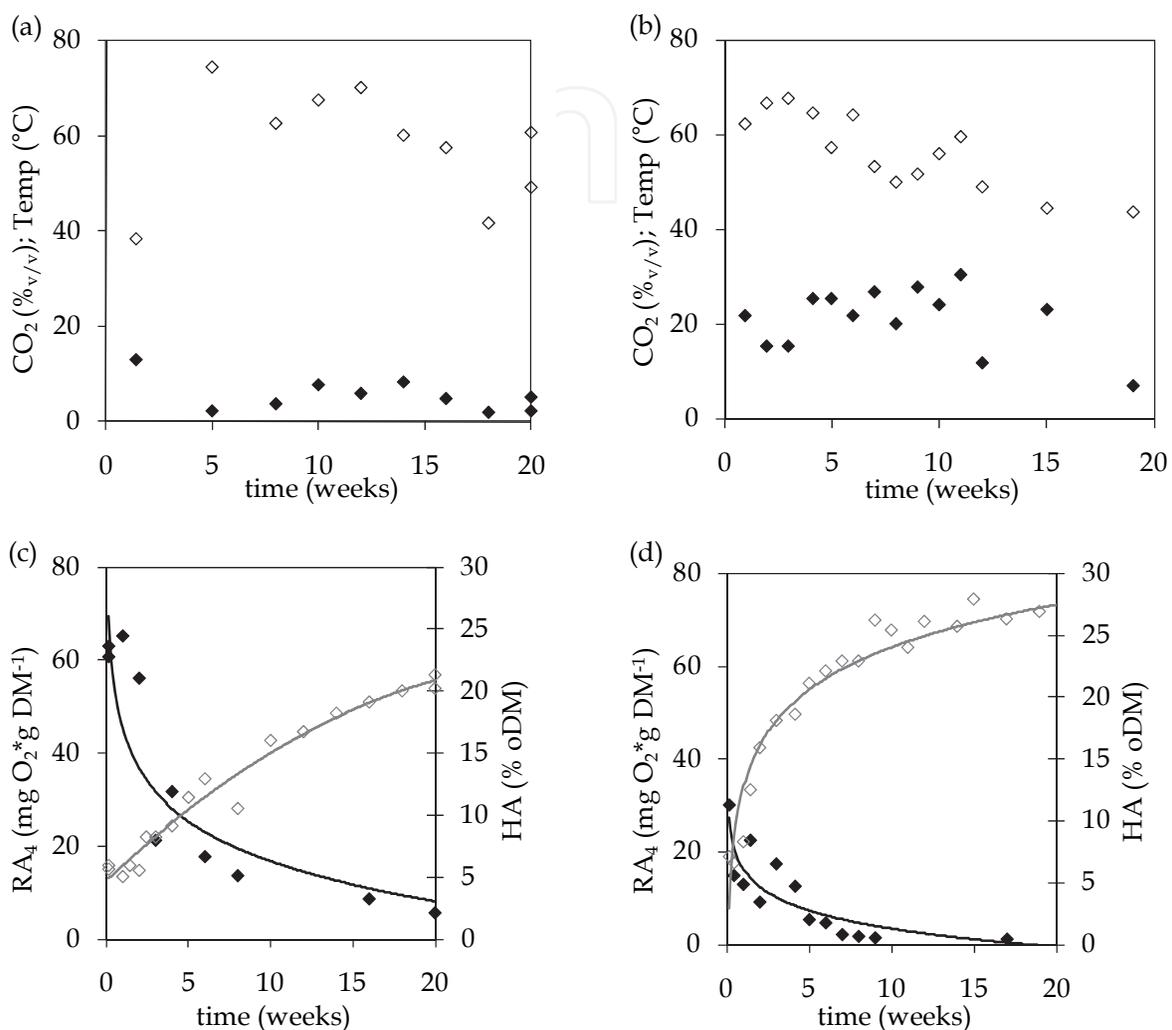


Fig. 1. Development of the parameters in the windrows: (a and b) CO<sub>2</sub> content (black dots) and temperature (grey symbols), (c and d) respiration activity (RA<sub>4</sub>, black symbols), humic acids (HA, grey symbols); a and c = plant BC1, b and d = plant BC2

### 2.1.3 Influence of substrates on microbial communities

The composition of the organic waste mainly influences the turnover rates and the final product. Easily degradable ingredients such as sugars are quickly metabolised which can lead to strong acidification and cause the metabolism to stop. The addition of pH increasing agents such as calcite supports the regulation of the biological process. Fundamental requirements of the microbial metabolism affect the quality of the composting process (Schlegel, 1992). It mainly depends on the experience of the operator in the composting plant. Besides a lack of water and air, the pH values, the C/N ratio and the concentration of metabolic products are relevant parameters that can improve or reduce the microbial

activity. If easily degradable materials are mineralised too fast hardly degradable substances are not attacked at all. This fact suggests that a well-balanced mixture of easily, middle and hardly degradable input materials is necessary to maintain the microbial activity, to regulate the velocity of transformation and to crack recalcitrant substances as well. Additionally it is a prerequisite for humic substance synthesis. A moderate progress of degradation provides the necessary molecule moieties and the opportunity to affect hardly degradable molecules such as lignin that is known to be a relevant compound of humic substances. Fig. 2 shows the respiration activity for 7 days ( $RA_7$ ) and humic substance formation during two composting processes PI and PII, both operating biogenic waste, but considerably differing in the mixtures, especially in the fraction of medium degradable components such as grass clippings and leaves. The high microbial activity of process PI declined very fast due to an imbalanced mixture of easily and hardly degradable substances and humic acid contents remained at a low level. The microbial activity of process PII decreased more slowly. A constant increase of humic acid contents was observed. This fact underlines the assumption that moderate decrease of microbial activity supports humic acid formation in biowaste compost.

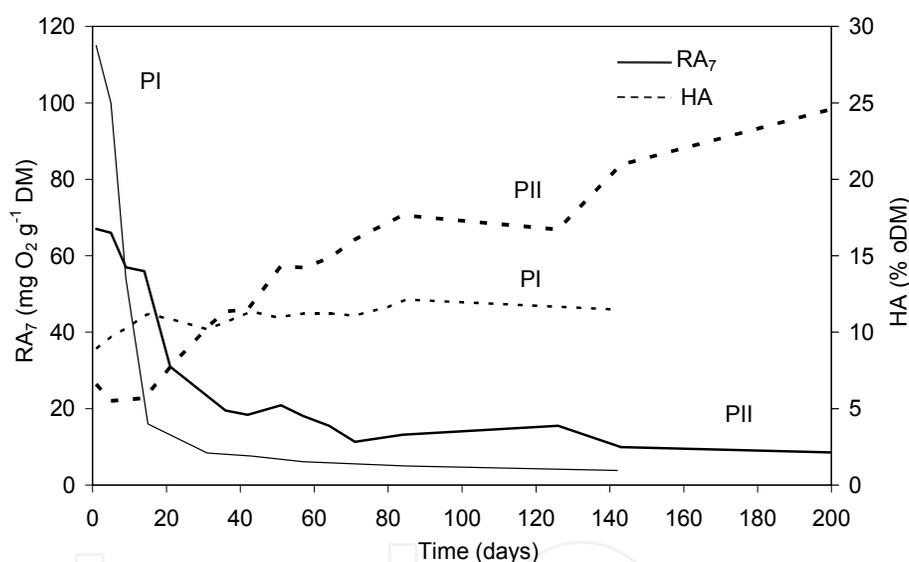


Fig. 2. Development of respiration activity ( $RA_7$ ) and humic acid (HA) contents in two composting processes PI and PII (DM = dry matter; oDM = organic dry matter)

Due to the complexity of the material composition a large variety of microbial communities are involved in the metabolism of biogenic materials. A succession of different species is observed during the composting process (Franke-Whittle et al., 2009).

#### 2.1.4 Process and product control by FT-IR spectroscopy and thermal analysis

The progress of composting processes can be monitored by means of near- and mid-infrared spectroscopy and thermal analysis. Both methods reveal the chemical changes during the biological degradation process by the characteristic spectral or thermal pattern. Several publications in the field of infrared spectroscopic investigations have focused on prediction models for parameters commonly used in waste management to describe compost quality (Michel et al., 2006; Böhm, 2009; Tandy et al., 2010). Fig. 3 illustrates a biowaste composting

process using mid-infrared spectroscopy (Fig. 3a) and thermal analysis (Fig. 3b). It is evident that the progressing degradation process is reflected by both the spectral and the thermal pattern. The bands that are assigned to organic components tend to decrease corresponding to the biological degradation of the molecules. The transformation of organic substances causes some bands of metabolic products to emerge and disappear. The bands that can be attributed to inorganic compounds, e.g. carbonates and clay minerals, gain in height due to their relative increase. More detailed information on band assignment in waste materials were provided by Smidt and Schwanninger (2005) and Smidt and Meissl (2007). The aliphatic methylene bands labelled by arrows in Fig. 3a are relevant indicators of mineralisation that is revealed by decreasing band intensities. Fig. 3b illustrates the degradation of organic matter by the diminishing heat flow. After 14 days those substances primarily were degraded that contribute to the first exothermic peak at 320 °C. Besides the weaker intensities of both peaks after 120 days of composting a shift of the second exothermic peak by 10 degrees to higher temperature (490 °C) is observed. This behaviour is related to increasing stabilisation.

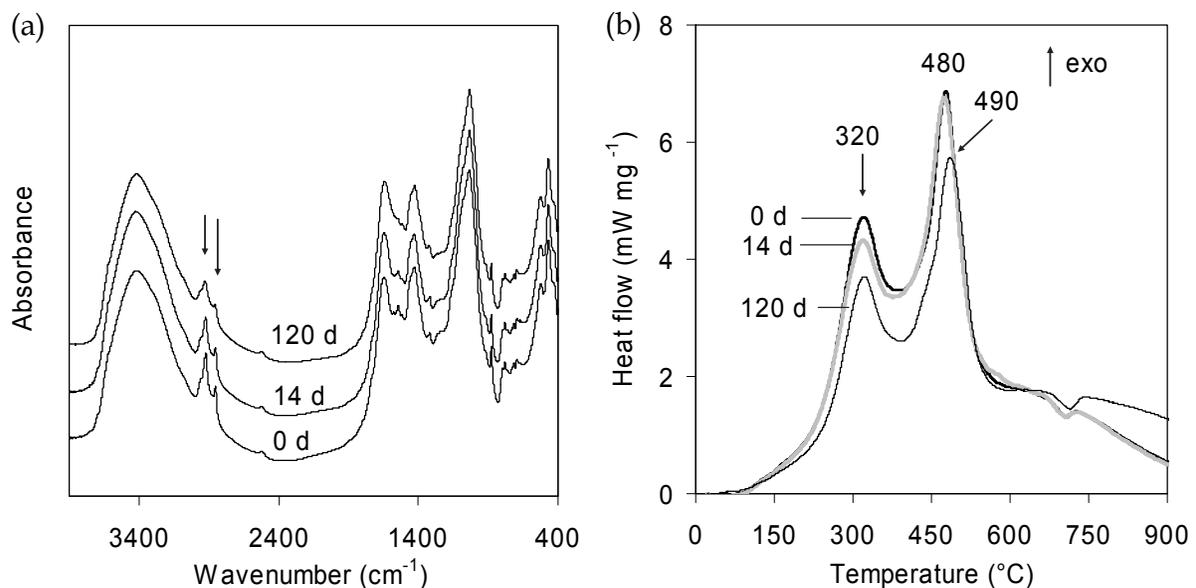


Fig. 3. Development of (a) infrared spectral and (b) thermal characteristics (heat flow profile) of biogenic waste during a composting process (selected stages: 0, 14 and 120 days)

The principal component analysis in Fig. 4 leads to the grouping of five composted materials due to spectral differences caused by the individual chemical composition. The materials of the Austrian biowaste composting processes Bio1, Bio2 and Bio3 can be distinguished as they differ in detail, but they are more similar to one another than the African biowaste (Bio4) composting process that is operated with locally available herbaceous materials. The difference of the sewage sludge compost (SSL) regarding the ingredients causes a large distance to biowaste composts in the scores plot of the principal component analysis (Fig. 4a). The biological degradation of different mixtures of biowaste and sewage sludge and biowaste and manure lead to a specific spectral pattern that is dominated by one of these components. In the biowaste/sewage sludge mixture the biogenic fraction is less resistant to microbial degradation than the anaerobically stabilised sewage sludge with a high portion of mineral compounds. By contrast, manure is faster degraded in the mixture biowaste/

manure and the spectral pattern becomes similar to the pure biowaste compost. The development with time is indicated by the arrows (Fig. 4b).

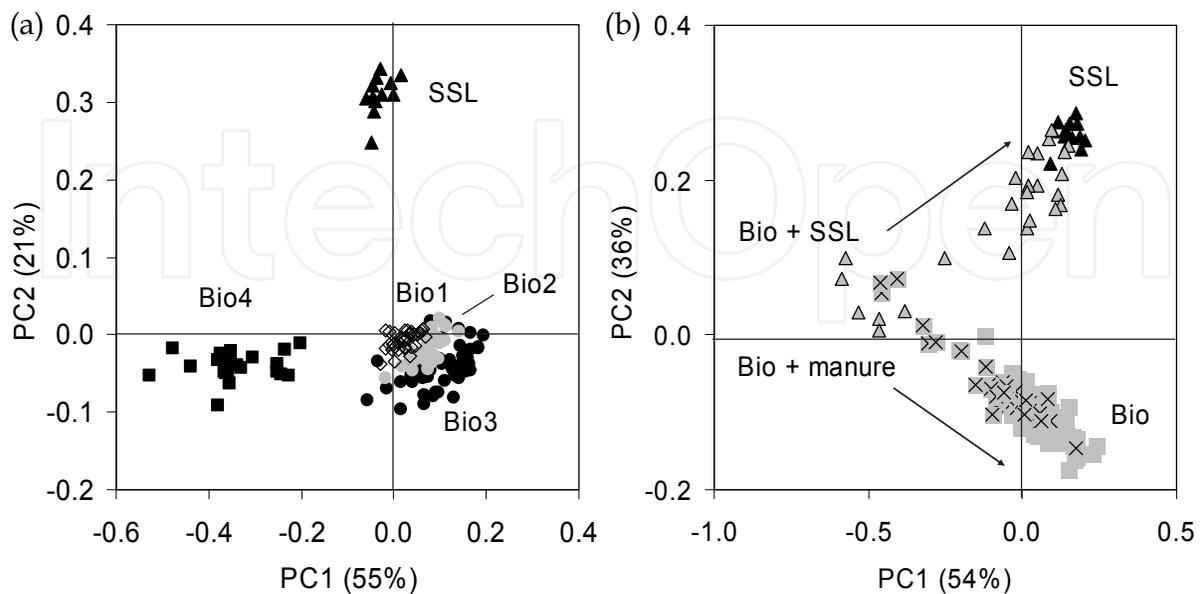


Fig. 4. (a) Principal component analysis of different composts based on their infrared spectral pattern (Bio1 – Bio4 = biowaste composts, SSL = sewage sludge compost); (b) different mixtures of biowaste/manure and biowaste/sewage sludge and their development during composting indicated by arrows

### 2.1.5 Quality criteria for composts

Due to practical reasons the description of compost organic matter is limited to quantitative determination of sum-parameters such as loss of ignition (LOI) and total organic carbon (TOC). Furthermore the nutrient content can be measured by the total nitrogen content (TN), phosphorous (P) and potassium (K) or mineralisation products such as ammonium nitrogen ( $\text{NH}_4\text{-N}$ ) and nitrate nitrogen ( $\text{NO}_3\text{-N}$ ). Information on stability can be given by the carbon to nitrogen ratio (C/N). A wide C/N ratio is typical for not degraded input materials. A C/N ratio of about 12 reflects stable compost matter. Stability also can be detected by other parameters such as degradable organic substance (AOS), “fractionation according to van Soest (1963)”, biological (e.g. respiration activity, oxygen uptake rate) and plant compatibility tests. The parameters “degradable organic substance (AOS)” and the fractionation according to van Soest (1963)” focus on the specific degradability of organic matter fractions under different chemical conditions. Biological tests describe the behaviour of organic matter and therefore provide indirect information on reactivity and stability. The mentioned parameters do not provide any information on organic matter quality. Information on organic matter quality is provided by humic substance determination. More detailed insight into the chemical composition is available by sophisticated analytical tools. Fourier Transform infrared (FT-IR) spectroscopy, nuclear magnetic resonance (NMR) spectroscopy, eco-toxicity tests and thermal analysis are currently applied in research, and apart from NMR spectroscopy these tools are intended for future practical application. The mentioned parameters and analytical tools, the information they provide and related references are compiled in table 1 and table 2 (Böhm, 2009). The parameters and methods

mainly focus on process control and the determination of maturity. Therefore they are related to organic matter and the mineralisation products.

Parameter	Information on	Related references
Loss of ignition (LOI)	Quantity of organic matter	(Austrian Standard Institute, 1993)
Total organic carbon (TOC)	Quantity of organic matter	(Austrian Standard Institute, 1993)
Kjeldahl nitrogen (N <sub>kjel</sub> )	(potential) Nutrient content	(Austrian Standard Institute, 1993)
Mineralisation products (NH <sub>4</sub> -N, NO <sub>3</sub> -N)	Nutrient content	(Austrian Standard Institute, 1993; Haug, 1993)
Low molecular weight carboxylic acids (C-2 to C-5)	Reactivity, Odour index	(Haug, 1993; Binner & Nöhbauer, 1994; Lechner & Binner, 1995)
C/N	Stability	(Austrian Standard Institute, 1993; Haug, 1993; Barberis & Nappi, 1996; Ouattmane et al., 2000)
Degradable organic substance (AOS)	Degradation behaviour	(Austrian Standard Institute, 1993)
Fractionation of organic matter according to van Soest	Degradation behaviour	(van Soest, 1963)
Biological tests e.g. oxygen uptake rate, respiration activity, enzymatic tests	Degradation behaviour, Stability	(Haug, 1993; Barberis & Nappi, 1996; Lasaridi & Stentiford, 1996; Lasaridi & Stentiford, 1998; Chica et al., 2003; Adani et al., 2004; Barrena Gómez et al., 2006)
Plant compatibility	Stability, Maturity	(Zuconci et al., 1981a; Zuconci et al., 1981b; Austrian Standard Institute, 1993; Haug, 1993; Commission of the European Communities, 2008)
Humic substances	Quality of organic matter	(Adani et al., 1995; Barberis & Nappi, 1996; Senesi & Brunetti, 1996; Ouattmane et al., 2000; Tomati et al., 2000; Zaccheo et al., 2002; Smidt & Lechner, 2005; Meissl et al., 2007)

Table 1. Parameters used for the characterisation of compost organic matter, the information they provide and related references (adapted from Böhm, 2009)

Besides maturity the content of toxic compounds plays a crucial role. Especially in countries where the application of pesticides in yards and gardens is very common, the contamination of biogenic input materials with organic pollutants can be relevant. Saito et al. (2010) reported on the concentration of clopyralid in composts. With regard to inorganic pollutants heavy metals are in the focus of interest. They remain in the cycle and are accumulated with

repeated compost application. Therefore their content in the compost is limited. The classification of compost quality according to the Austrian Compost Ordinance (BMLFUW, 2001) is based on limit values of several heavy metal contents.

Besides the standard quality parameters that mainly focus on the reduction of negative impacts, additional quality criteria are useful that emphasise the positive effects of composts and underline the value as marketable products. Nutrients and their availability (Gil et al., 2011), the content of humic substances (Tan, 2003; Böhm et al., 2010) and phytosanitary effects (Pane et al., 2011) might be appropriate parameters to meet this purpose.

Parameter	Information on	Related references
Spectroscopic methods Infrared spectroscopy (IR) Nuclear magnetic resonance (NMR)	Information on a molecular level. Identification of specific molecules and molecule groups Stability, Quality	FT-IR spectroscopy: (Ouatmane et al., 2000; Chen, 2003; Smidt et al., 2005; Smidt & Schwanninger, 2005) NMR spectroscopy: (Kögel-Knabner, 2000; Zaccheo et al., 2002; Chen, 2003; Tang et al., 2006)
Ecotoxicity tests	Indirect information on toxic compounds and therefore on compost quality	(Barberis & Nappi, 1996; Kapanen & Itävaara, 2001; Alvarenga et al., 2007)
Thermal analysis Thermogravimetry (TG) and Differential scanning calorimetry (DSC) Pyrolysis field ionisation mass spectrometry (Py-FIMS) Pyrolysis gas chromatography mass spectrometry (Py-GC/MS)	Stability (TG and DSC) Information on the molecular level with coupled MS	(Dell'Abate et al., 2000; Ouatmane et al., 2000; Otero et al., 2002; Melis & Castaldi, 2004; Dignac et al., 2005; Smidt et al., 2005; Smidt & Lechner, 2005; Franke et al., 2007)

Table 2. Analytical tools used for the characterisation of compost organic matter, the information they provide and related references (adapted from Böhm, 2009)

Compost teas that are fermented aqueous extracts from composts are suggested by several authors as an alternative to mineral fertilisers and pesticides (Koné et al., 2010; Naidu et al., 2010).

## 2.2 Anaerobic digestion

Anaerobic digestion of biogenic materials is a booming technology as it combines organic matter stabilisation and energy recovery. The high interest in this technology is paralleled by the question how to handle the increasing amounts of digestates. Due to a limited retention time in the reactor digestates still feature a considerable reactivity. Therefore open systems for their storage such as lagoons, can lead to uncontrolled emissions of methane or

N<sub>2</sub>O. The quantification of these relevant greenhouse gas compounds from these sources has not been done yet. The useful application of digestates becomes an important question in terms of available areas and transport distances. Digestates are directly used in agriculture or subjected to further treatment such as composting. Eco-balances are necessary to oppose the advantages to the disadvantages and to evaluate the benefits. Increasing pH values during the subsequent composting process lead to ammonia losses. Their determination is an additional question to be answered (Whelan et al., 2010). Nitrogen recovery can be provided by ammonia stripping (De la Rubia et al., 2010; Zhang & Jahng, 2010).

### 2.2.1 Adequate ingredients and process operation

Basically most of the biogenic waste materials are appropriate for anaerobic digestion and only restricted by natural limitations of biodegradability. Lignin for instance is not degradable under anaerobic conditions. Steam explosion of lignocellulosics is a kind of pre-treatment of wooden materials in order to remove cellulosic compounds from the composite lignin and to make them available to microorganisms. Kitchen and market waste from the separate collection, mainly consisting of easily degradable components also serve as input materials for composting processes. By contrast, leftovers originating from public institutions, hospitals, hotels and schools are appropriate ingredients for anaerobic processes and do not compete with other ways of utilisation. Besides organic wastes from urban areas agricultural wastes such as liquid and solid manure and crop residues are processed locally in biogas plants. Industrial waste from the food industry and biotechnological processes, slaughterhouse waste and sewage sludge complete the wide range of organic substances that are processed in anaerobic digesters (Lee et al., 2010). The anaerobic treatment of sewage sludge is more a part of the waste water treatment. Anaerobically stabilised sludge that undergoes a composting process, comes within the limits of waste management. In Austria slaughterhouse waste is subject to restrictions in order to guarantee hygienic standards (Europäische Union, 2009).

Anaerobic digestion is usually carried out under mesophilic (~37°C) or thermophilic (~55°C) conditions (Madigan et al., 2003). Depending on the water content “wet” (5-25% dry matter) and “dry” (>25-55% dry matter) processes are distinguished. The water content also determines to a certain degree the fate of digestates. Very low contents of dry matter suggest an immediate application on fields by irrigation. If an additional composting process is planned, solid residues are in general separated by centrifugation or by a filter press. Anaerobic digestion at relatively low water contents allows a subsequent composting process. Whereas methanogenesis in a liquid process takes place in a temporal sequence, the dry process is dominated by the spatial sequence, depending on the motion of the bulk along the reactor. Anaerobic digestion plays a certain role as pre-treatment of municipal solid waste in several countries (Fdez.-Güelfo et al., 2011; Lesteur et al., 2011) in order to yield biogas before aerobic treatment and final disposal. Improvement of biogas production is a main target and many investigations focus on this issue. The organic fraction of municipal solid waste underwent a dry thermophilic anaerobic digestion process to find out the optimum solid retention time in the reactor regarding the gas production (Fdez.-Güelfo et al., 2011). Co-digestion of press water from municipal solid waste and food waste could improve the gas yield according to Nayono et al. (2010). Besides the substrate process conditions play an important role in terms of gas yields.

Different procedures and technologies are suggested to upgrade the resulting biogas regarding the purity degree of methane (Dubois & Thomas, 2010; Poloncarzova et al., 2011).

### 2.2.2 Microbial communities in anaerobic processes

Molecular identification of microbial communities depending on substrates and process operation and their dynamics during anaerobic digestion were reported by several authors. Organic waste and household waste were used as substrates in these studies (Ye et al., 2007; Hoffmann et al., 2008; Montero et al., 2008; Cardinali-Rezende et al., 2009; Sasaki et al., 2011). Shin et al (2010) reported on characteristic microbial species that dominate specific phases of a food waste-recycling wastewater digestion process and therefore provide information on the performance of the reactor. Hydrolysis efficiency in a similar substrate and the related microbial communities were investigated by Kim et al. (2010). Wagner et al (2011) reported on diverse fatty acids such as acetic, propionic and butyric acid that inhibited methanogenesis coupled with an increase of hydrogen. Abouelenien et al. (2010) could improve the methane production by removal of ammonia that had a negative impact on methanogenesis. By contrast, elevated ammonia contents did not inhibit methanogenesis in a co-digestion process of dairy and poultry manure (Zhang et al., 2011). Although basic mechanisms of the anaerobic metabolism are well-known it should be emphasised that the results obtained are divergent according to the wide range of different experiments regarding individual feeding materials and process conditions. The identification of various microbial communities reflects the complexity of interactions in these processes.

### 2.2.3 Residues from anaerobic digestion

Chemical characteristics of digestates are mainly influenced by the input material, process conditions and the retention time in the reactor. High salt concentrations caused by leftovers do not pose a problem for the subsequent composting process as they are removed with the waste water. By contrast, heavy metals primarily remain in the solid residue. As mentioned above the water content usually determines the further treatment or immediate application on fields. Quality criteria of the liquid residue that is directly applied on the field are mainly determined by the quality of the input material. The nitrogen content is the limiting compound according to the Water Act (Wasserrechtsgesetz BGBl. Nr. 215/1959, in der Fassung BGBl. I Nr. 142/2000) that regulates the output quantity. Composting is a suitable measure to stabilise digestates and to produce a valuable soil conditioner. Disaggregation of the wet, cloggy and tight material is a main issue to ensure the porosity and the efficient air supply. Wood particles and yard waste are appropriate bulking agents for this purpose.

### 2.2.4 Process control by FT-IR spectroscopy and thermal analysis

Parameters usually applied in waste management such as the loss on ignition, total organic carbon contents and total nitrogen describe degradation and changes of organic matter during anaerobic digestion and composting. The reactivity of the material is measured using biological tests. The oxygen uptake during a period of 4 days reflects the current microbial activity ( $RA_4$ ), whereas the gas sum ( $GS_{21}$ ) indicates the gas forming potential under anaerobic conditions during a period of 21 days. Compared to time-consuming biological tests modern analytical tools provide fast information on reactivity and material characteristics. Near infrared spectroscopy was used by Lesteur et al (2011) to predict the biochemical methane potential of municipal solid waste. Fig. 5a demonstrates the development of the mid-infrared spectral pattern from the reactor feeding mixture (FM) to the digestate (D) and the composted digestate (DC). The samples originate from the Viennese biogas plant that processes 17,000 tons a year of biogenic waste from the separate

collection, market waste and leftovers. The thermograms in Fig. 5b illustrate the mass losses of these samples. The degradation of organic matter becomes evident by decreasing mass losses.

The spectrum of the feeding mixture features a variety of distinct bands in the fingerprint region ( $1800\text{--}800\text{ cm}^{-1}$ ) and high intensities of the aliphatic methylene bands. The breakdown of biomolecules due to degradation is paralleled by their decrease. Distinct bands in waste materials indicate a variety of not degraded substances. With increasing degradation bands tend to broaden in the complex waste matrix. The band at  $1740\text{ cm}^{-1}$  can be attributed to the C=O vibration of carboxylic acids, esters, aldehydes and ketones, indicating an early stage of degradation. The bands at  $1640$ ,  $1540$  and  $1240\text{ cm}^{-1}$  represent different vibrations of amides (C=O, N-H, C-N). Typical absorption bands of carboxylates (C=O) and alkenes (C=C) are also found at  $1640\text{ cm}^{-1}$ . More detailed information on band assignment is provided by Smidt and Schwanninger (2005) and Smidt and Meissl (2007). Digestates are still reactive after a retention time of 21 days in the reactor. The remaining gas sum over a period of 21 days ( $GS_{21}$ ) was 80 to 120 L per kg dry matter. The total nitrogen content was found to be between 4 and 5% referring to dry matter (DM). The total nitrogen content in digestate composts was about 2.5% (DM). The nitrogen content is higher than in biowaste composts that feature 1-2% of total nitrogen (DM). Nevertheless, the losses during composting are considerable and need more attention in the future. Apart from the losses of this nutrient compound the volatilisation of ammonia that is formed at higher pH-values leads to odour nuisance in open windrow systems and represents one of the relevant problems in this type of composting plants.

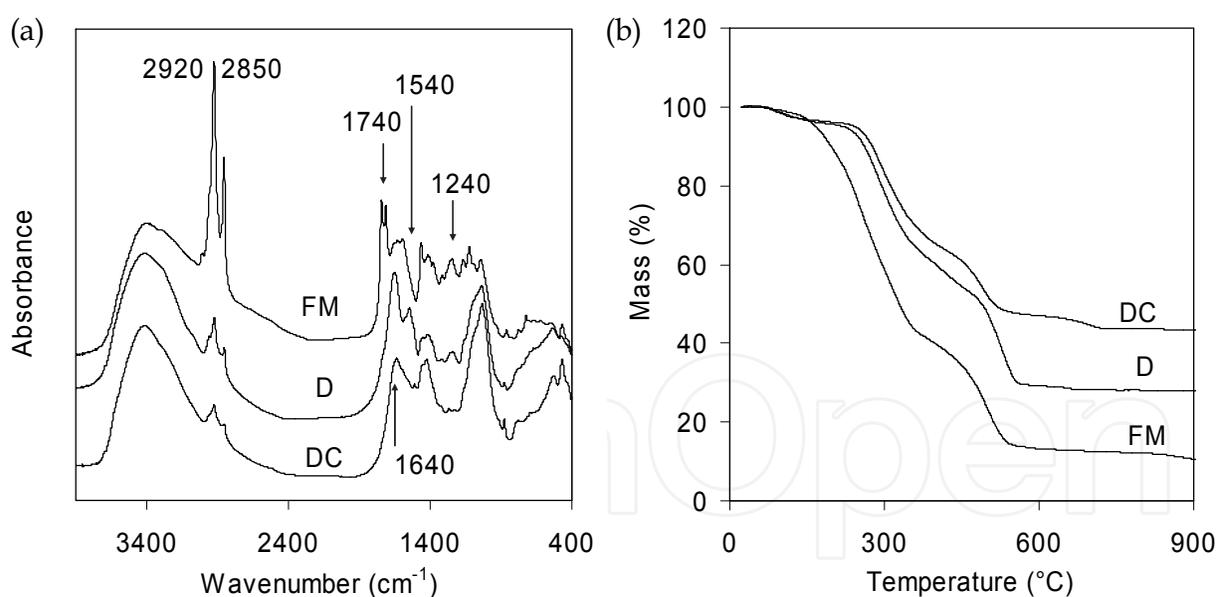


Fig. 5. Development of (a) the spectral and (b) the thermal (mass loss) pattern during anaerobic digestion and subsequent composting of digestates (FM = feeding mixture for the reactor, D = digestate, DC = digestate compost)

Depending on the input materials digestates keep a specific pattern. A principal component analysis based on FT-IR spectra reveals the similarity of residues that originate from thermophilic processes with a 2 to 3 week-retention time in the reactor (Fig. 6a). Three groups of digestates according to the input materials can be distinguished: manure,

biowaste comprising yard waste, fruits and vegetables from households and markets and leftovers that had been mixed with different amounts of glycerol. The 1<sup>st</sup> principal component explains 85% of the variance, the 2<sup>nd</sup> one 7%. The loading plots indicate the spectral regions that are responsible for the discrimination of the materials: the aliphatic methylene bands at 2920 and 2850  $\text{cm}^{-1}$ , and nitrogen containing compounds such as amides at 1640 and 1540  $\text{cm}^{-1}$  and nitrate at 1384  $\text{cm}^{-1}$  (Fig. 6b).

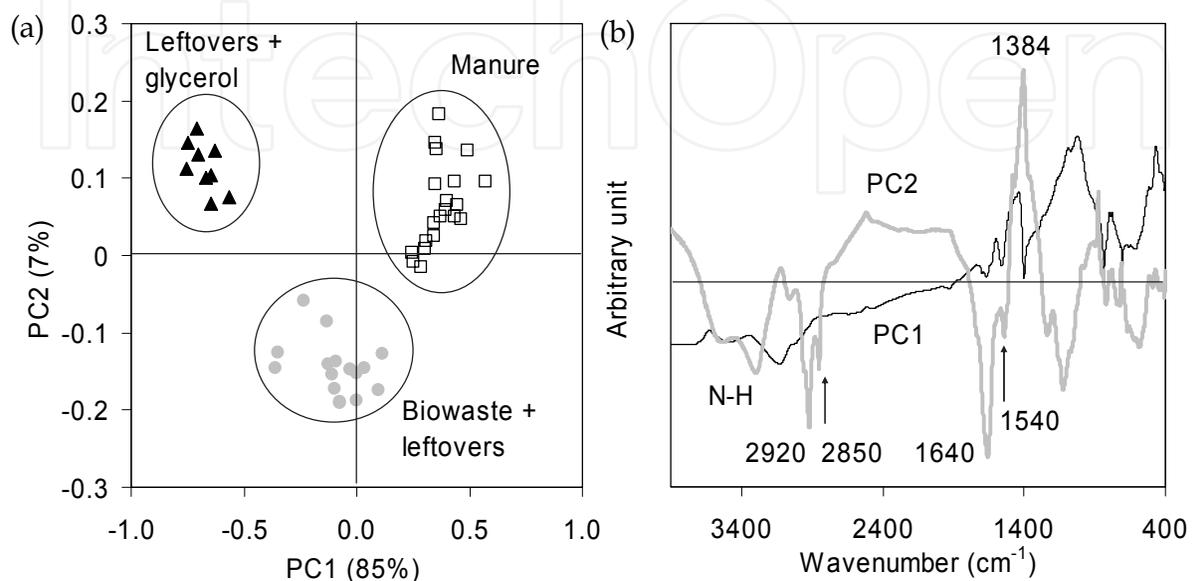


Fig. 6. (a) Principal component analysis based on infrared spectra of digestates from different input materials that underwent thermophilic processes; (b) corresponding loadings plot of the first two principal components

### 3. Biological treatment of municipal solid waste for safe final disposal

Biological processes always deal with both aspects: resource recovery and the avoidance of negative emissions. The history of waste management started with harmful emissions. Waste was disposed in open dumps and was used to level off depressions in the landscape or to fill and dry wet hollows. This strategy has caused severe problems with increasing amounts of waste. The dumped waste was degraded anaerobically, metabolic products of early degradation stages were leached and washed out to the groundwater. Gaseous emissions leaked from the dumps to the top and into the atmosphere or migrated into nearby cellars which can cause an explosion if the critical mixture of methane with air is reached. These environmental problems have led to regulations about the technical demands on landfill sites. The idea was to prevent the emissions by closing the landfills with dense layers at the bottom and on the top to cut them from the environment. Actually the degradation processes continued and the emissions were sealed and preserved, but not prevented. It can be assumed that the life time of the technical barriers is over after some decades. The emissions, leachate at the bottom and landfill gas on the top, become relevant as soon as the density of the layers fails. This fact has promoted the latest changes in European regulations. The stabilisation of waste organic matter prior to landfilling was proclaimed and with regard to the biological treatment the natural stabilisation processes served as a paradigm.

### 3.1 Mechanical-biological treatment (MBT) of municipal solid waste

Besides incineration mechanical-biological treatment is one option to stabilise municipal solid waste prior to final disposal. The mechanical-biological treatment of waste combines material recovery and stabilisation before landfilling. Big particles, especially plastics with a high calorific value, are separated by the mechanical treatment and used as refused derived fuels. The residual material features a relatively low calorific value, a high water content and a high biological reactivity. The calorific value is mainly influenced by the content of organic matter. The biological treatment abates all three parameters. Organic matter is degraded by microbes which leads to gaseous and liquid emissions. Due to the exothermic aerobic biological process the temperature rises. Water evaporates due to the generated heat and the material tends to run dry. The decrease of organic matter that is paralleled by the relative increase of inorganic compounds causes the calorific value to decrease. The degradation process is dominated by mineralisation. Depending on the input material humification takes place to a certain extent. Mineral components contribute to organic matter stabilisation. In practice MBT processes vary in many details. Apart from stabilisation of the output material for landfilling the biological process can focus on the evaporation of water to produce dry material for incineration. Another modification of the process provides anaerobic digestion prior to aerobic stabilisation in order to yield biogas in addition. Most of the MBT plants are situated in Germany and Austria. In France the biogenic fraction is not source separated and thus treated together with municipal solid waste. The output material is used as waste compost and applied on soils. In Germany and Austria this procedure is prohibited by national rules. In this section the MBT technology is described as it is implemented in Germany and Austria. The system configuration of the plants is described in Table 3.

plant	input material	system	mesh size/ treatment
A	MSW	4 w cs, 8-14 w rp	80 mm cs, 60 mm rp, 45 mm lf
B	MSW, SS	2 w cs, 6-8 w rp	80 mm cs, rp, 25 mm lf
C	MSW	4 w cs, 8 w rp	80 mm cs, rp, 25 mm lf
D	MSW	3-4 w cs, 7-9 w rp	160 mm cs, 20 mm rp, lf
E	MSW	4 w cs, 8 w rp	80 mm cs, rp, 40 mm lf
F	MSW	5 w cs, 10-30 w rp	25 mm cs, rp, lf
G	MSW	60-80 w cs+rp	80 mm
H	MSW	30 w cs+rp	25 mm
J	MSW, ISW	20 w cs+rp	70 mm cs+rp, 25 mm lf
K	MSW	4 w cs, 10 w rp	70 mm cs, rp, 30 mm lf
L	MSW	4 w cs, 20 w rp	50 mm cs, rp, lf
M	MSW, SS, BW	10 w cs, 40-60 w rp	60 mm cs, rp, 12 mm rp, 9 mm cp
N	MSW	4 w cs, 12 w rp	80 mm cs, 10 mm rp, lf
O	MSW	3 w bd	40 mm bd, ~25 mm lf
P	MSW, BW	9 w + 6 w rp	not sieved, 20 mm rp, 10 mm cp
R	MSW	6-8 w bd	100 mm bd
S	MSW	1-2 w bd	80 mm bd

Table 3. Austrian MBT plants, input materials and systems applied (MSW: municipal solid waste; SS: sewage sludge; BW: biowaste; ISW: industrial solid waste; cp: compost, cs: closed system; bd: biological drying; rp: ripening phase; lf: landfilled; w = week)

This table displays the diversity of the Austrian mechanical biological treatment processes regarding input materials, mesh size and the duration of rotting and ripening phases in open or closed systems (adapted from Tintner et al., 2010). In Germany about 50 plants are in operation, in Austria 17. Two Austrian plants produce exclusively refuse derived fuels. Anaerobic digestion prior to the aerobic treatment is currently not performed in Austrian MBT plants.

### 3.2 Stabilisation of waste organic matter

The aerobic biological stabilisation process comprises in general two main phases. The first intensive rotting phase takes place in a closed box with forced aeration. The ripening phase proceeds in open windrows, sometimes covered with membranes. The respiration activity that reflects the reactivity of the material summarises the oxygen uptake ( $\text{mg O}_2 \text{ g}^{-1} \text{ DM}$ ) by the microbial community over a period of four days. The respiration activity of input and output, 4-week-old and already landfilled material originating from different Austrian plants was measured. In two plants also waste compost was produced which has ceased in the meantime. Results for mean values and the confidence intervals are given in Table 4.

Respiration activity ( $\text{mg O}_2 \cdot \text{g}^{-1} \text{ DM}$ )			
	mean	$c_l$	$c_u$
Input material $n=34$	44.4	38.3	50.4
After 4 weeks $n=19$	24.1	15.8	32.4
Output material $n=53$	6.9	5.3	8.5
Waste compost $n=9$	7.8	2.6	13.0
Landfilled material $n=13$	6.4	2.7	10.1

Table 4. Respiration activity over four days in  $\text{mg O}_2 \cdot \text{g}^{-1} \text{ DM}$ ;  $c_l$ : lower bound of confidence interval,  $c_u$ : upper bound of confidence interval,  $\alpha = 0.05$

Depending on the system process kinetics can considerably differ regarding the decrease of reactivity. Fig. 7 presents the degradation of organic matter in three different plants (plants D, O, and P according to Table 3). The input material in plant P consists of municipal solid waste and biowaste that had not been separated. This mixture results in a highly reactive input material compared to the other plants. Plant O provides a wind cyclone for the separation of the heavy fraction after a three-week treatment. Plant D represents the classical MBT-type with a three-week intensive rotting phase in a closed system and a seven to nine-week ripening phase in an open windrow system (Tintner et al., 2010). The biological degradation of MBT materials corresponds to the biological degradation in composting processes.

In Fig. 8 the degradation processes in plants M and H are presented in more detail. The  $\text{CO}_2$  concentration and the temperature in the windrows are compared to the water content and the respiration activity of the material. In both plants the respiration activity decreases continuously according to organic matter mineralisation. The  $\text{CO}_2$  concentration depends on the system configuration. In the closed system of plant M the material is aerated actively for 10 weeks. Thereby the oxygen supply is ensured most of the time. In plant H no forced aeration is provided. The  $\text{CO}_2$  content increases up to 60 %. However, these temporarily anaerobic conditions in some sections do not inhibit the biological degradation as the material is turned regularly. The efficient aerobic degradation is verified by the high temperature. It is remarkable that the temperature of the windrow remained at a high level

for a long time. The high temperature supports sanitation of the material which plays a secondary role for MBT output that is landfilled, compared to compost. Although the respiration activity decreased considerably further microbial activities took place, indicated by the constant high level of CO<sub>2</sub> contents in the windrow. Inefficient turning might have been the reason for the CO<sub>2</sub> contents and the high temperature.

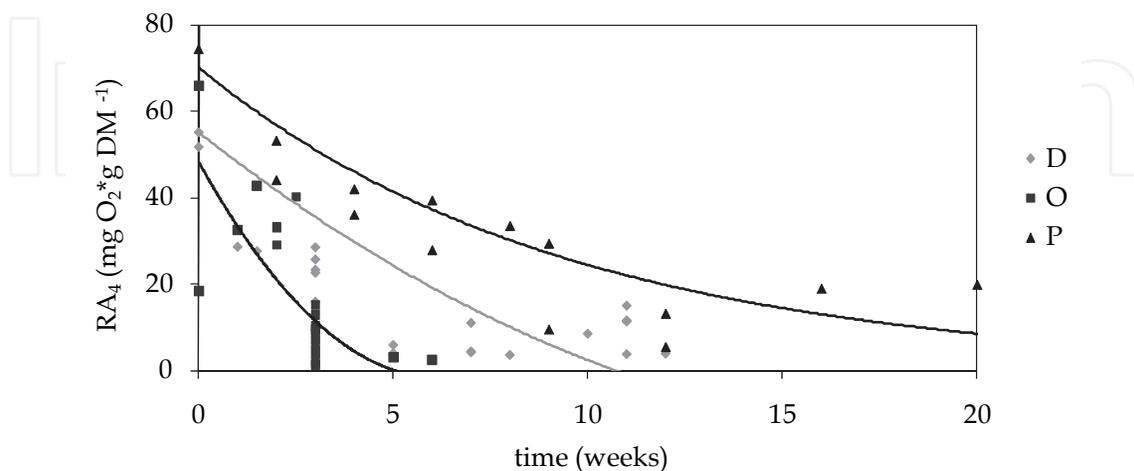


Fig. 7. Decrease of the respiration activity (RA<sub>4</sub>) in three different MBT-plants with different operation systems

The data reflect process kinetics by the specific pattern of organic matter degradation during the biological treatment of MBT materials. The principles of the metabolism are the same as in composting processes. However, the individual mixtures of input materials and system configuration strongly influence the transformation rate. The period of time that is necessary to comply with the limit values of the Landfill Ordinance (BMLFUW, 2008) is a main factor for successful process operation. It should be emphasised that water and air supply play a key role in this context and the retardation of organic matter degradation can in general be attributed to a deficiency of air and water. A homogenous distribution of air in the windrow and the removal of metabolic products is only guaranteed by regular mechanical turning.

### 3.3 Landfilling

When the legal requirements are reached the treated output material is landfilled. The most relevant parameters are the respiration activity with limit values of 7 mg \* g DM<sup>-1</sup> in Austria and 5 mg \* kg DM<sup>-1</sup> in Germany and the gas generation sum that provides information on the behaviour of waste materials under anaerobic conditions. The determination of the gas generation sum is obligatory in Austria and facultative in Germany. In both countries the limit value is 20 NL \* kg DM<sup>-1</sup>.

Landfilling is usually performed in layers of about 20 to 30 cm. The material is rolled by a compactor. In some cases a 40-centimetre drainage layer of gravel is integrated every 2 metres between the waste material. The degree of compaction depends on the water content. At the end of the biological process the material is often dried out. This advantage for the sieving process counteracts the optimal compaction because the water content is lower than the necessary proctor water content. However, a satisfactory coefficient of permeability of about 10<sup>-8</sup> m/s is usually achieved. The efficient compaction can be one of the main reasons why further degradation processes in the landfill are reduced to a minimum. As indicated in

Table 4 the reactivity (mean value) of the landfilled material and of the MBT-output material is similar.

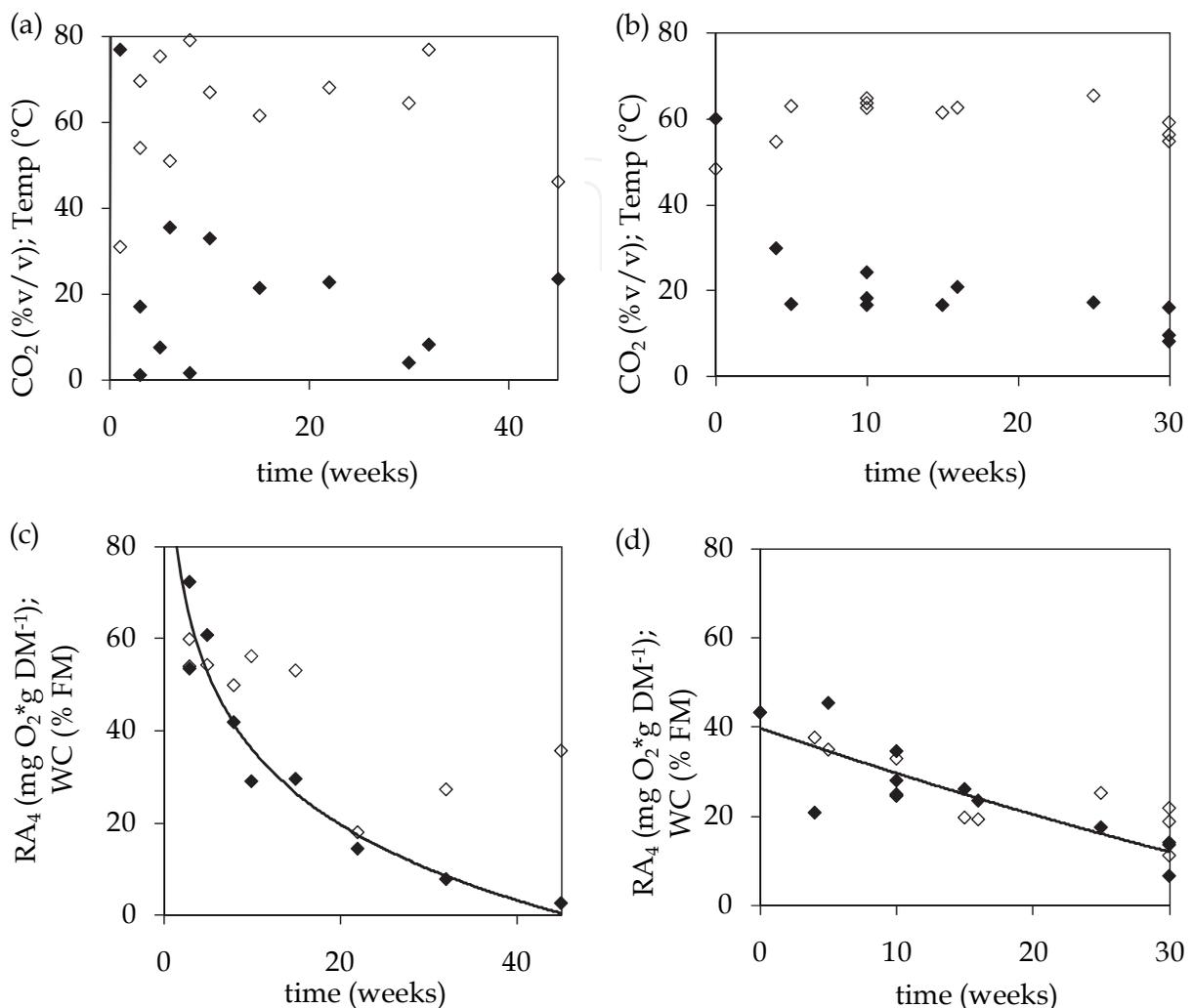


Fig. 8. (a and b) Development of the parameters in the windrow: CO<sub>2</sub> content (black symbol) and temperature (circle), (c and d) respiration activity (RA<sub>4</sub>, black symbol), water content (WC, circle); a and c = plant M, b and d = plant H

In six different MBT plants one to four year-old landfilled materials were compared to the typical output material of these plants after the biological treatment. The comparison of the respiration activity confirmed that no significant degradation took place in the landfill.

Biological degradation after landfilling is minimised and the remaining organic matter is quite stable which is the main target of the pre-treatment of municipal solid waste. However, low methane emissions can be expected. These emissions are mitigated by means of methane oxidation layers where methanotrophic bacteria transform methane into CO<sub>2</sub> (Jäckel et al., 2005; Nikiema et al., 2005). Several publications have focused on the identification of the involved methanotrophs (Gebert et al., 2004; Stralis-Pavese et al., 2006). Regarding the discussion about landfills as carbon sinks the question arises, how much carbon can finally be stored in MBT landfills. The remaining carbon content in MBT landfills can be considered as a stable pool, taken out of the fast carbon cycle. The mean content of

organic carbon of the landfilled materials was 15.6 % DM at a 95 %-confidence interval from 13.3 to 17.8 % DM. The fitting model of the final degradation phase is a topic of current research.

### **3.4 Process control by FT-IR spectroscopy and thermal analysis**

Besides the time consuming conventional approaches for the determination of the biological reactivity in MBT materials FT-IR spectroscopy was proven to be an adequate alternative. The prediction model for the respiration activity ( $RA_4$ ) and the gas generation sum ( $GS_{21}$ ) presented in Böhm et al. (2010) are based on all degradation stages and types of MBT materials existing in Austria.

The second relevant parameter to be measured prior to landfilling is the calorific value. This parameter is usually determined by means of the bomb calorimeter. An alternative method of determination is thermal analysis. The prediction model described by Smidt et al. (2010) is also based on all stages and types of MBT materials existing in Austria.

## **4. Abandoned landfills from the past and related problems**

Although microbial processes lead to mineralisation of waste organic matter and finally to the stabilisation by mineralisation, interactions with mineral compounds or humification, degradation is paralleled by harmful emissions if it is not managed under controlled conditions. The amount and the particular composition of municipal solid waste lead to the imbalance of the system. Careless disposal of municipal solid waste and industrial waste in the past has caused considerable problems in the environment. Due to anaerobic degradation of waste organic matter groundwater and soils were contaminated. The discussions on climate change have attracted much attention on relevant greenhouse gas emissions in this context, especially on methane. Emissions of nitrous oxide from landfills have not been quantified yet. This awareness has led to adequate measures in waste management. As mentioned in the previous section the treatment of municipal solid waste before final disposal is a legal demand in order to have biological processes taken place under controlled conditions.

### **4.1 Risk assessment and remediation measures of contaminated sites**

Despite national rules risk assessment of old landfills and dumps is still a current topic. In countries without an adequate legal frame for waste disposal it will be for a long time. Landfill assessment usually comprises the measurement of gaseous emissions on the surface. Due to inhibiting effects such as drought that prevent mineralisation, the investigation of the solid material is suggested as it reveals the potential of future emissions. Basically the analytical methods FT-IR spectroscopy and thermal analysis are appropriate tools to assess the reactivity of old landfills and dumps (Tesar et al., 2007; Smidt et al., 2011). Biological tests using different organisms provide information on eco-toxicity. The advantage of this approach is the overall view on the effect not on the identification of several selected toxic compounds (Wilke et al., 2008). This procedure is less expensive and in many cases, especially in old landfills containing municipal solid waste, sufficient. Nevertheless, until now the identification and quantification of single organic pollutants and heavy metals is the common approach.

Depending on the degree of contamination specific measures of remediation are required. Excavation of waste materials is the most extreme and expensive way of sanitation. The

presence of hazardous pollutants can necessitate such procedures. In many cases the reactivity of organic matter is the prevalent problem and mitigation of methane by a methane oxidation layer is an adequate measure. In-situ aeration is an additional approach to avoid methane emissions. Due to the forced aeration of the waste matrix in the landfill aerobic conditions replace anaerobic ones. They accelerate and favour the biological degradation of organic matter to CO<sub>2</sub>.

#### 4.2 Re-use and land restoration

As a consequence of the new strategy of waste stabilisation prior to landfilling the possibility of re-use and land restoration for after use becomes evident. Especially the demand for space for the production of renewable energy crops has promoted the awareness of a more economical and considerate exploitation of land. The typical landfill emissions in the past restricted the potential for many after use concepts. Landfill gas minimises the feasibility for agricultural purposes. Therefore most of the old landfill sites are not in use at all. The alternatives for after use concepts range from highly technical facilities or leisure parks to natural conservation areas. Even when the production of food on landfill sites is not taken into account agricultural use for the production of energy crops (maize, wheat, elephant grass, short rotation coppice) has a great potential (Tintner et al., 2009). There are some constraints such as climatic conditions, soil properties, soil depth, compaction, water availability and drought, waterlogging, aeration, and the nutrient status. Provided that no or just negligible landfill gas emissions are present in the root zone, careful site management including a correct soil placement and handling, soil amelioration, irrigation respectively drainage depending on precipitation, fertilisation, choice of adequate species, can accomplish the necessary environmental conditions (Nixon et al., 2001). Remediation of the sites is just a prerequisite for a successful land use management.

### 5. Conclusion

The biological treatment of organic waste materials is state of the art in Austria. Two main strategies are in the focus of interest: stabilisation of organic matter for safe waste disposal or landfill remediation and production of biogas and composts. The biological treatment of waste matter takes place according to the principles of the microbial metabolic pathways. The knowledge of fundamental requirements determines the quality of process operation. Water and air supply is a key factor in aerobic processes and mainly influences the progress of degradation besides the pH value and the nutrient balance. Water and air supply only depend on process operation, the nutrient balance is preset by the incoming waste material mixture. In small treatment plants it can be influenced marginally. The pH value is rather a result of input materials and process operation. Anaerobic digestion for biogas production requires more technical control to maintain a constant gas yield. Microbial processes always take place. It is a matter of anthropogenic activities to avoid the negative impact on the environment, but to use the potential of microbial processes.

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