Mechanical-Biological Pre-Treatment of Waste – State of the Art and Potentials of Biotechnology

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Summary

Mechanical-biological treatment of waste (MBP) is the processing or conversion of waste from human settlements with biologically degradable components via a combination of mechanical and other physical processes with biological processes. It is a technological alternative to waste incineration. It is applicable for the treatment of waste prior to depositing, but also for the production of refuse derived fuels (RDF). A capacity of about 2 million tons has been established in Europe since 10 years, and a broad technological variety including aerobic and anaerobic bioprocesses is available. The process design is mainly based empirically, but biotechnological information is widely used. The following figures characterise the process results: Up to 95% of the degradable TOC and 94% resp. 86% of non-cellulosic carbohydrates resp. cellulose are metabolised. The stability of the treated waste is defined by a respiratory coefficient (AT_4), or a gas production coefficient (GB 21); typical process results on the technical scale are 5 mg/g dry matter for AT_4 and 20 l/kg dry matter for GB 21. Emissions from the processes include organic compounds metabolised or generated by bioprocesses, as methane and carbon dioxide, as well as volatile organics which are stripped out from the waste. A treatment by biofilters results in a 20% to 50% reduction, after a further treatment by incineration a value < 55 g TOC per ton of waste is achieved. The level of contaminants in both leachate and gas emissions from the landfill is reduced up to 95% compared with untreated waste. One kilogram of treated waste potentially releases a total load of 1–3 g COD, 0.5–1.5 g TOC, and 0.1–0.2 g NH_4-N into the leachate.

Introduction

Sustainable development calls for an environmentally sound, cost effective and socially acceptable management of municipal and industrial waste. It is general consensus, that waste has to be avoided, and non-avoidable waste has to be re-used as far as possible under well balanced economical and ecological conditions. Only the so-called residual waste, which is neither avoidable nor re-useable, should be deposited. In order to avoid any harmful effect on the environment, residual waste has to be pre-treated prior to landfilling. The technology of pretreatment has to be chosen after waste quality, waste management conditions, as well as other economic, ecologic and social aspects.

Because municipal solid waste contains a large portion of organic matter (Fig. 1), it is useful to treat it by biotechnological processes. Thus, biotechnology has been an integral part of waste management technologies since decades. Well established examples are the composting of source separated organic residuals to convert them into an organic fertilizer, the bio-gas technology for the production of a renewable energy source, as well as the cleaning of waste gas by bio-filters, and soil remediation.

As a quite recent option of biotechnology in waste management the so-called mechanical-biological pre-treatment of municipal solid waste (MBP) is applied, especially to residual waste prior to landfilling. MBP is defined as the processing or conversion of waste from human settlements with biologically degradable components via a combination of mechanical and other physical processes (for example, cutting or crushing, sorting) with biological processes (aerobic „rotting“, anaerobic fermentation) [1]. It aims to reduce the mass and the volume of the waste. Another target is a low environmental impact of the waste after its deposition, i.e. low emissions of landfill gas, small amounts of leachate, and a reduced settlement of the landfill body. Furthermore, MBP includes the separation of useful waste components for industrial reuse, such as metals and plastics as well as refuse derived fuel (RDF).

The scientific base of the MBP, especially in biotechnological terms, is to be broadened to improve the performance, to reduce costs and to minimise ecological impacts, thus making MBP even more competitive with other options of waste treatment, as incineration. The paper deals with some aspects of biotechnology, especially on the base of the results of a German Federal Research Project, which was finished after a 5 years investigation period in spring 2001 [2].

State of the Mechanical-Biological Pre-Treatment of Residual Waste

Waste Management Background

Waste incineration has been considered to be the best available technology for MSW treatment in the recent decades, but it requires a high local appearance of waste and big financial resources. These circumstances led to the development of MBP as an adequate technology, especially for rural areas. In the case of a poor management of landfills or a low availability of suitable grounds, MBP can contribute to a rapid improvement of the waste management situation, with respect to landfill gas production, leachate emissions, and settlements. More generally, it is fortunate by its higher flexibility compared to an incineration plant. It can be adopted easily to changes of the waste amount or composition. Nevertheless, its ecological and economical benefits, compared with incineration and direct deposition, depend on a variety of local conditions, and it has to be proven in every single case.

The mechanical-biological treatment of municipal solid waste has been applied since about ten years, especially in Germany, Austria and Switzerland on technical scale, but also in several developing and emerging countries on pilot plant scale. In Germany, where about 35 million tons of municipal solid waste (MSW) are generated every year, about 1,8 million tons are treated in 29 mechanical-biological pre-treatment plants [3]. Compared with actually twelve million tons treated by incineration in 51 facilities, MBP has already become a considerable factor in waste management. It has good chances to succeed as a technology compatible with the European Landfill Directive, which demands for an implementation of waste pre-treatment in all EU member states.

Since March 1st, 2001 in Germany the MBP technology is ruled by a special decree, the German Ordinance on Environmentally Compatible Storage of Waste from Human Settlements

(Abfallablagerungsverordnung, AbfAblV [1]). It defines the quality limits of the pre-treated waste, especially in terms of the reactive organics, as well as the standards of the process emissions (ruled by the 30th Ordinance on Execution of the Federal Immission Control Act: Ordinance on Facilities for Biological Treatment of Waste, 30. BImSchV [1]). Some characteristic parameters are given in Tab. 1.

Tab. 1: Emission standards for MBP and allocation criteria for landfills for MBP-treated waste in Germany [1]

Parameters (selection)	**limit value**
Emission standards for MBP	
Organic substances, expressed as total carbon (monthly mean value)	55 g/Mg
Nitrous oxide (monthly mean value)	100 g/Mg
Odorous substances	500 GE/m^3
Dioxins/furans (sum value)	0,1 ng/m^3
Allocation criteria for MBP-treated waste	
Organic component of dry residue in original substance, determined as TOC[1)]	18% by weight
Biological degradability of dry residue in original substance,	
determined as respiration activity (AT_4) or	5 mg/g[2)]
determined as gas formation in the fermentation test (GB_{21})	20 l/kg[3)]
Upper thermal value (H_o)[1)]	6000 kJ/kg

[1)] Parameters may be applied in equivalence
[2)] mg O_2 with respect to dry weight
[3)] Standard litre of gas with respect to dry weight

Technological Background

MBP technology comprises mechanical and biological process steps and combinations thereof. It can be applied as a stand-alone system or combined with other technologies, especially with incineration. MBP more and more becomes an integral part of a material flow management system, were all re-usable components of the waste are separated to such an extent, which is economically suitable and environmentally sound. A typical process scheme of the process combinations and the material streams comprises as rough numbers a 30% to 40% fraction of material for deposition, 30% to 40% for the production of RDF. The residual 20% to 30% are process losses, biogas in the case of anaerobic fermentation, as well as untreatable material for incineration.

The mechanical step includes the removal of contaminants and components, which impede the technological process. Reusable material is separated. The whole waste is fractionated into two or more fractions defined by material qualities, which are then handled specifically. Mechanical treatment consists mainly of screening and shredding devices. For that, equipment from traditional waste processing is applied. Specialities of residual waste are partly considered, but there is a good potential for further improvements. Most plants aim to separate the components with high calorific value, as plastics, paper, timber, and composites, for energy recovery.

The biological pre-treatment step relies on aerobic rotting, anaerobic fermentation or combined processes. Aerobic systems are in widespread use. These include windrows with or without aeration, containers or boxes, drums, or tunnels. Anaerobic pre-treatment includes a bio-gas production step, so that a net energy gain is possible and minor odour problems occur.

The main advantage of the anaerobic process is the tremendous reduction of the gas needed in the whole process, thus resulting in a much lower expenditure for waste gas cleaning. The anaerobic plants can be operated in one or more stage processes according to the needs and the quality of the waste. An optimal adaptation to the needs of residual waste processing resp. its integration into other waste treatment systems is still under development, offering opportunities for process and system improvement.

Aerobic treatment systems are more homogenous concerning the biological processes, but they show a big variety in both process intensity and duration. Windrow systems operated directly on the landfill site require only a minimal technical outlay. The windrows often are aerated through drainage pipes which act as vents; the process time varies from 5 to 15 months. As a special case of this type, the dome aeration system [4] combines the windrow technology with so-called dome aerators. For the process, the waste material is pre-conditioned, to guarantee best conditions in the windrow. The fraction over 80 mm is separated for use as fuel. The aeration equipment is installed in the centre of the windrow, and the waste material is heaped around the dome. In operation, the air flows into the aeration channel, passes through the waste material and then flows through the dome by the pressure difference. The pressure losses are low, as the dome is constructed as a grid. The number of the aerators can be adapted to the needs over the length of the windrow. Obviously, this is a quite simple technology.

The majority of contemporary plants includes an encapsulated, controlled, intensive biological stage. With respect to the emissions, in most aerobic systems the waste gas is collected and treated by bio-filters and scrubbers. Further improvement is possible by thermal gas treatment. In Germany, this is a need in accordance with the legislation, which calls for emission control at the very high environmental level of 55 g carbon per ton of waste processed, in analogy to the limit in the case of waste incineration. After the intensive stage, in most cases a further process period takes place in windrows without forced aeration.

As a special case, the biological drying technology is to be mentioned. On the contrary to MBP before landfill, the main objective of the biological drying technology is the production of a refuse derived fuel (RDF) called ‘dry-stabilate’. For this purpose, both windrow and box systems are applied. In box systems, the waste is treated aerobically for only one week, but with high aeration rates. The result is a dried material with a slightly reduced organic content. Only the most easily degradable compounds are metabolised, so that the loss of caloric value is low. The dry-stabilate can be fractionated very easily, because adhesive substances were eliminated in the bio-process. Iron and non-ferrous metals, as well as glass and minerals are separated for material recovery. The remaining material has a calorific value of 15–18 MJ/kg, mainly due to the high content of plastics, wood, and paper. It can be used as a substitute for fossil fuels in power stations and cement kilns, but also for the production of process gases. In Germany, this technology is applied in industrial scale at several plants, each with a capacity of 75,000 to 150,000 Mg/a [5].

Investigations into MBP as a bioprocess

For MBP is a process type developed quite recently, the research in terms of biotechnology is still narrow. The focus of research was on (i) process optimisation including emission control, (ii) landfill behaviour of pre-treated material, (iii) screening and balancing as well as processing of toxic waste substances, and (iv) ecological evaluation of the whole technology. Biotechnological items have been studied especially with respect to the degradation of the residual organic material.

Degradation of Organic Matter

The objective of waste pre-treatment is to achieve a material for deposition at low environmental impacts. An elementary pre-condition for that is a low biological activity of the waste after treatment. Thus, it is the aim of the process to reduce the content of organic material as far as possible to form a non-reactive „stabilised“ product.

Like all municipal wastes, the input to MBP contains different parts of non-cellulosic carbohydrates, cellulose, lipids, lignin and other organic substances, as plastics. Residual waste but has a relatively low content of easily degradable components, which are metabolised already during the transportation and storage period.

For the degradation of the organic matter, aerobic as well as anaerobic processes and combinations thereof can be applied.

The typical progress of aerobic residual waste decomposition is given in Fig. 2. The main degradation takes place during the first few weeks. In the case of a windrow system, after a period of 10 weeks, the organic matter reduces to about 40% of the initial mass. During the remaining process time (up to 45 weeks), the degradation continues and results in a residual content of one third of the initial organic matter. The non-cellulosic compounds are degraded at the highest extent. A relative accumulation of the heavily degradable substances occurs. Up to 95% of the degradable TOC and 94% resp. 86% of non-cellulosic carbohydrates resp. cellulose are metabolised.

A main factor for the performance and the rate of the aerobic treatment is the aeration intensity, which has to be estimated after the oxygen needs of the bioprocess and the energy balance, but also reflecting the needs of industrial safety. The specific aeration rate for the bioprocess alone is about 2000 m^3 per ton of waste to achieve a 60% degradation of the biological degradable material. In practise, an aeration of about 10.000 m^3 per ton waste is applied due to the assumption, that a minimal oxygen concentration of about 18% in the process gas is required to prevent limitations and local anaerobic zones. However, recent experiments on the laboratory scale indicate that the process is not limited even with an oxygen content of only 5% [6], as the availability of carbon substrates seems to be the limiting factor for the whole process. This evidence may lead to a more economic use of process air in future aerobic treatment plants, thus requiring significantly less expenditures for waste gas processing and lower influence on the atmospheric household. But high aeration needs for process temperature control especially in the first process steps have to be kept in mind. The application of anaerobic process steps is a possible mean for the minimisation of the oxygen need and the minimisation of the aeration.

As the anaerobic degradation of organic matter comprises several intermediate steps, one approach to the optimisation of anaerobic waste treatment is to be seen in the local or temporal separation of the biological steps, allowing optimal growing conditions for the contributing bacteria. Various experiments proved the benefits of a multi-step anaerobic treatment, including combinations of anaerobic and aerobic process steps. The highest degradation rate of organic dry matter was achieved by a 4-step process (Fig. 3), comprising an intermediate aerobic degradation of lignin-like compounds by higher fungi. The following anaerobic step was applied to accomplish the conversion of organic matter into biogas. About 90% of the theoretical potential were achieved. In this case, a final aerobic process step of the material is dispensable, if not required for safety reasons or odour control.

In Fig. 4 and 5 anaerobic and aerobic processes are compared in terms of the degradation of organic matter and the resulting biological stability of the material (see below).

Stability Characterisation of Pre-Treated Waste

To characterise the mineralisation of the wastes, the ignition loss is used as an integral criteria, which represents the total organic content of the material. Based on the standard of waste incineration, the German Technical Instructions for Municipal Waste from 1993 [8] demanded for an ignition loss of less than 5% for municipal waste to be deposited. In the case of MBP, the ignition loss drops from a range of 50% to 60% to an end value between 25% and 35%, dependent on the composition of the waste. Thus, MBP formerly has only been accepted on pilot plant scale or as an interim solution, if incineration capacities were lacking.
But ignition loss has several disadvantages as a criteria of waste stabilisation, which may lead to wrong conclusions from the test's results:

- A part of the waste, which is biologically inert, cannot be degraded by microbial attacks, especially normal plastics, but also other heavily degradable material, as wood. This part will mostly not contribute to the landfill reactions.
- Positive effects of the remaining or biologically converted organics, as the high binding capacity of humus-like substances, are not considered.
- The ignition loss also comprises volatile non-organic substances.

Thus, the ignition loss is not well suited as an indicator for the stabilisation in the case of biological waste treatment, nor for its effects in the landfill body, where mainly anaerobic biological processes occur. For MBP, as a better suited indicator of the stabilisation, the landfill gas production was defined, which correlates directly with the residual biological activity of the pre-treated waste in the landfill body [9] (Fig. 6).
As a characteristic indicator for the landfill gas production, the gas formation within 21 days is set out as the so-called GB_{21}. A good correlation of this parameter with the respiration rate (AT_4) as well as with the total organic content in the eluate (TOC_{Eluate}) was experimentally proven in many cases. The respiration parameter AT_4 is defined as the amount of oxygen consumed by microbial processes in a defined apparatus (e.g. the Sapromat) in 96 hours per gram of dry mass [3, 10]. Amongst these 3 parameters, the AT_4 is most easily determined, and the time for an analysis is short enough for technical purposes, as landfill management. Thus, this value is the preferred parameter, also in the new German Ordinance on the deposition of municipal waste [1].
Typical values of the AT_4 are in the range of 30 to 50 mg O_2/g dry matter for untreated material. A sufficient biological treatment results in an $AT_4 < 5$ mg O_2/g dry matter and in a $GB_{21} < 20$ l/g dry matter (Fig. 5). These numbers are the actual state of the art in MBP-technology. These values do not only represent a technological limit, but also a level of environmental impacts, which is acceptable under the ecological point of view, for it was proven, that the degree of stabilisation of MBP output is similar to that of humified organic matter in top soils (Tab. 2).

Tab. 2: AT_4 values of natural soils and residual waste (after [11])

Substrate	**AT_4** [mg O_2 / g DM]
Alder litter (L-horizon)	8.6 – 48
Organic layer (O-horizon)	1.7 – 6.9
Podsoil (A-horizon)	0.03 – 0.5
Residual waste	
• before treatment	20 – 60
• after MBP	1.1 – 7.4

Emissions from Pre-Treatment Processes and Gas Cleaning Efficiency

The emissions from the biological pre-treatment process belong to five groups of substances which are typical for bioprocesses:

- Carbon dioxide and methane are produced by aerobic resp. anaerobic biological activities,
- Organic compounds are metabolised or generated by biological reactions,
- Volatile substances are stripped out from the original waste,
- Heavy metals and heavily volatile substances remain in the residues; they are not substantially emitted with the waste gas stream,
- Germs, as bacteria and moulds, are emitted from the system as a result of the microbiological character of the process.

The total of organic compounds emitted from the biological treatment step amounts to about 600 g per ton of original material, measured as non-methane volatile organic compounds (NMVOC). Methane is also produced under typical conditions, for insufficiently aerated zones occur generally in all kinds of waste agglomeration. It may sum up to approximately 100 g per ton of original waste. In the case of difficulties in the process, the amount increases considerably. Thus, methane can be used as a control parameter for the aerobic process. With respect to the nitrogen compounds, ammonia is of special importance. It amounts to about 500 g per ton of original waste. In the bio-filter it can be transformed into N_2O, which is of high importance as a climate relevant gas. The process balance of a bio-filter is given in Fig. 7.

The highest rate of pollutant emitted into the environment occurs during the self-heating phase in the very first days of the bio-process. This phase is largely completed within two weeks. In the case of BTEX (benzene, toluene, ethylbenzene, and xylene), 86% are emitted in the first week, another 6% in the second week, so that only 8% are emitted in the residual processing time or remain in the material.

To avoid health and climate risks by the emission, the waste gas has to be collected and cleaned during this period. As cleaning techniques, scrubbers and bio-filters are used. Their efficiency depends on the general bio-degradability of the substances. In the mean, a reduction by 50% is achieved, so that about 300 g TOC per ton of waste remain. Some typical substances in MBP emissions and their degradation rate by a combination of bio-filter and scrubber are given in Tab. 3.

Tab. 3: Some components of waste gas emissions of MBP and their degradability in bio-filters/scrubbers [12]

Substance-(group)	Bio-filter efficiency
Aldehydes	75%
Alkanes	75%
Alcohols	90%
AOX	40%
Aromatic hydrocarbons (benzene)	40%
Aromatic hydrocarbons (toluene, xylene)	80%
NMVOC	83%
PAK, PCB, PCDD/F	40%
Odour	95 – 99%
Ammonia	90%

In the case of non degradable components, such as chlorinated hydrocarbons, further detoxification is necessary, which is only partly possible by optimising the bio-filters with respect to the filter material, the technology and the intensity of the process. An extra thermal processing of the waste gas is definitely needed. After practical trials, the thermal regenerative waste gas treatment results in a total emission of less than 40 g carbon per ton of original material [13].

Consequences on landfill behaviour

The decisive result of the MBP is determined by the behaviour of the pre-treated waste in the landfill, given by the landfill gas production, leachate amount and quality, as well as the hydraulic conductivity and landfill settlements.
Results of the behaviour of MBP-treated wastes in real landfills do not yet exist; experiments in landfill simulation reactors (lysimeters) indicate, that the level of contaminants in both leachates and gas emissions of the treated residual waste is reduced by more than 98% compared with untreated waste. One kilogram of treated waste potentially releases a total load of 1–3 g COD, 0.5–1.5 g TOC, and 0.1–0.2 g NH_4-N into the leachates. The real numbers clearly depend on the intensity resp. the duration of the pre-treatment. Tab. 4 illustrates the influence of the process duration in the case of a windrow system.

Tab. 4: Range of organic carbon, nitrogen and chlorine transfer by gas and leachate; minimum values represent the stabilisation degree reached by state of the art MBP [9]

Emission Potential		Unit	Untreated MSW	Mechanical-biological pretreated MSW
…by gas:	carbon	[l/kg DM]	134 – 233	12 – 50
		[g $C_{org.}$/kg DM]	71.7 – 124.7	6.4 – 26.8
…by leachate:	TOC	[g/kg DM]	8 – 16	0.3 – 3.3
	N	[g/kg DM]	4 – 6	0.6 – 2.4
	Cl^-	[g/kg DM]	4 – 5	4 – 6

After the removal of all high calorific components, as well as 3–4 months of biological treatment, the waste can be compacted in the landfill to a density of 1.5 ton/m^3 (wet). This is accompanied with a more efficient use of landfill capacities. The hydraulic conductivity of the compacted landfill waste is approximately 10^{-8} m/s or even lower. Water flow through the landfill is therefore limited, and leachate production by biological and physical activities decreases considerably.

These positive effects on the landfill behaviour can only be realised, if the landfill construction is adopted to the conditions given by the waste. A special aspect is the remaining very low gas production, especially for methane, which at maximum is estimated to about 1 l CH_4/m^2*h in a typical landfill. In this case, no active landfill gas collection is possible. To prevent gas emissions into the atmosphere, a passive method of oxidation of the residual gas is necessary. As a suitable approach, the use of a bio-active oxidising landfill cover is proposed, consisting of biologically active material like compost. It oxidises the methane gas during its passage through the layer. As a survey of several experimental results indicate, the oxidising capacity of soils and landfill layers are in the range of 0,01 to 16,8 l CH_4/m^2*h [9]. Most values are between 0,l to 5 l CH_4/m^2*h, so that a mean value of 3 l CH_4/m^2*h seems realistic. Even considering a strong influence of temperature, water content, as well as the varying gas qualities, it seems probable, that such a layer is able to oxidise practically all methane from the landfill gas. First trials indicated that a gas oxidation layer of about 120 cm combined with a gas distribution layer of 50 cm is suitable [16].

Conclusion

Mechanical-biological pre-treatment technology (MBP) is an established complex technology for the pre-treatment of residual municipal solid waste prior to deposition in landfills, which includes several bio-processes. In Europe, actually two million tons of waste are processed this way, further development in the EU and other regions is to be envisaged. This makes it useful to continue investigations into the whole process by biotechnological means to improve its performance and to minimize the remaining environmental impacts.

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Figures

Fig. 1: Waste composition of 5 German cities [12]

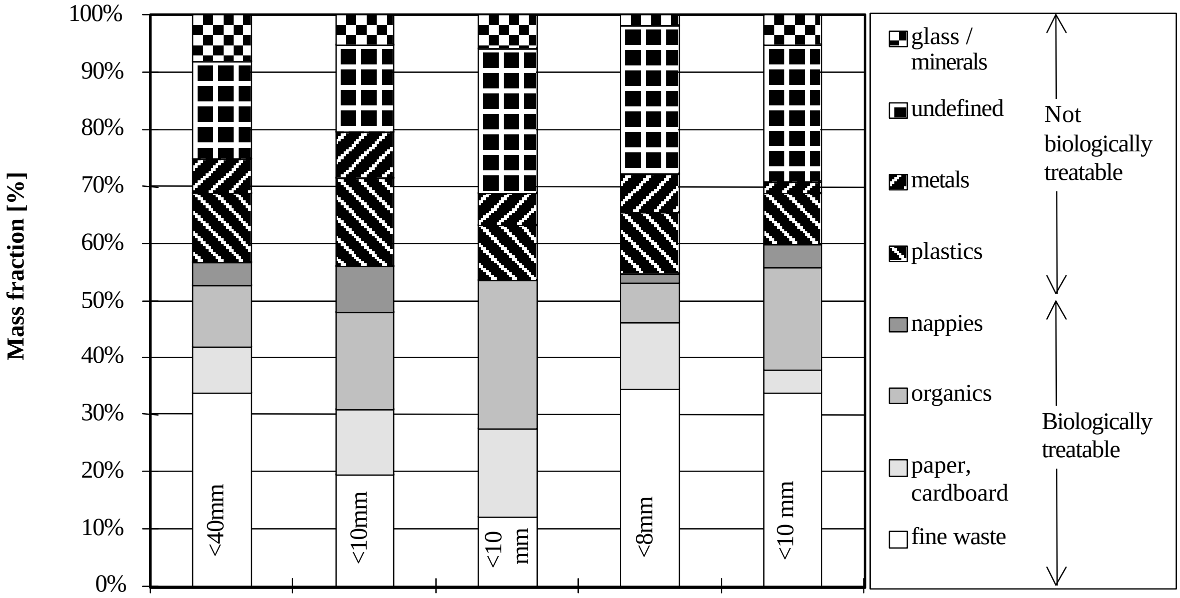

Fig. 2: Degradation of different organic components of waste as a function of process time [11]

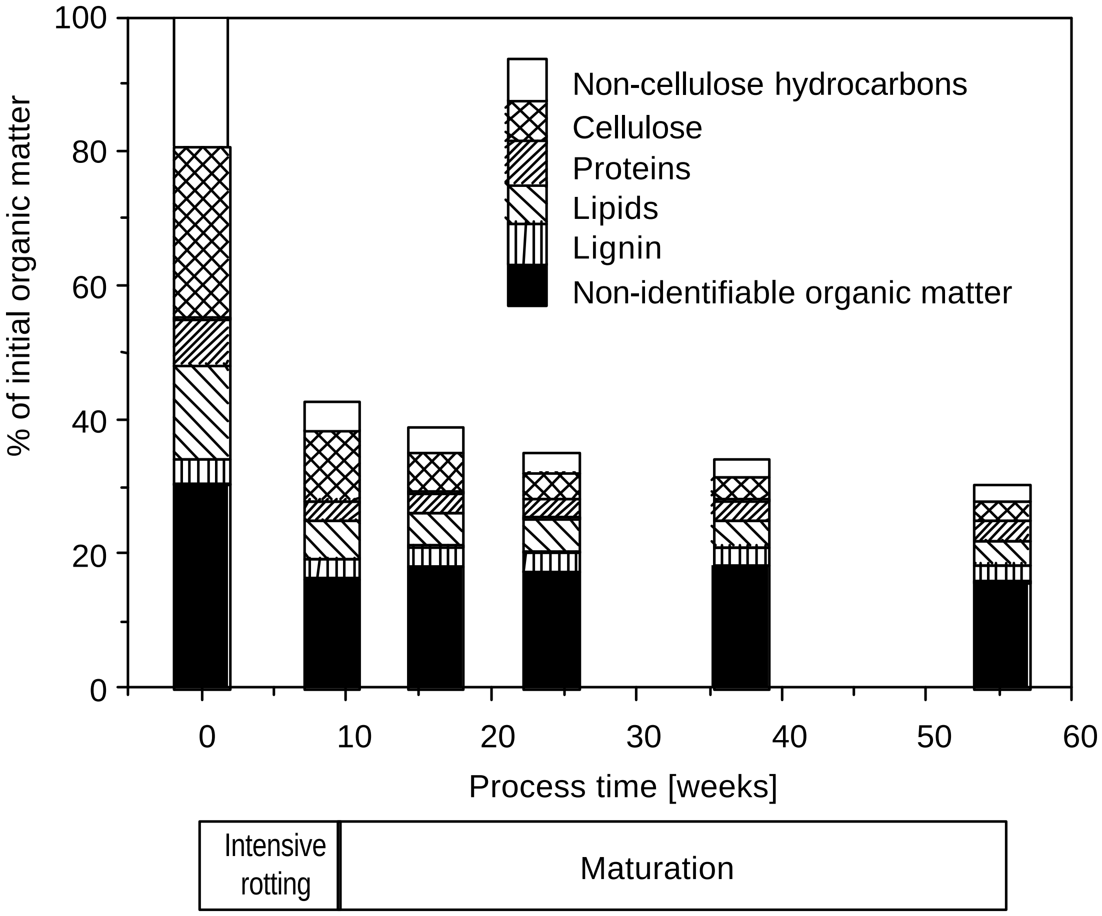

Fig. 3: Anaerobic degradation of waste components in a 4-stage alternating anaerobic/aerobic process [7]

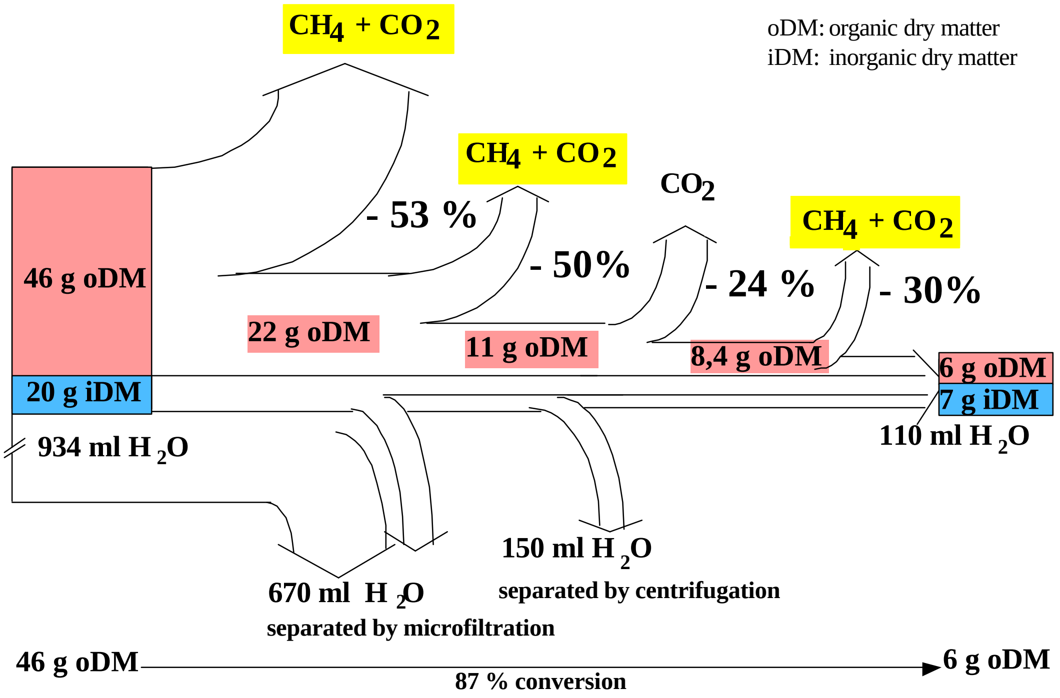

Fig. 4: Organic matter degradation by different anaerobic and aerobic processes [2]

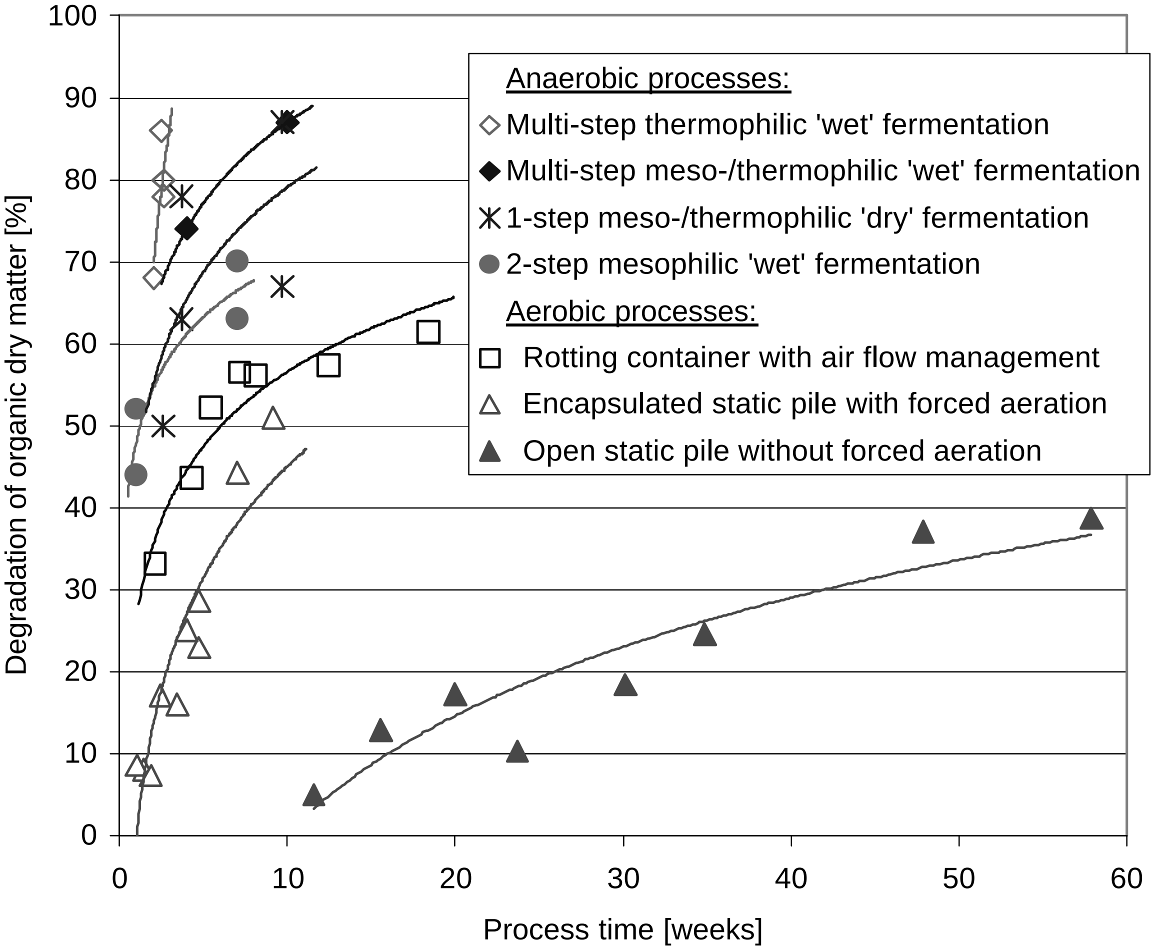

Fig. 5: Stability parameter AT_4 as a function of the treatment duration [2, S. 208]

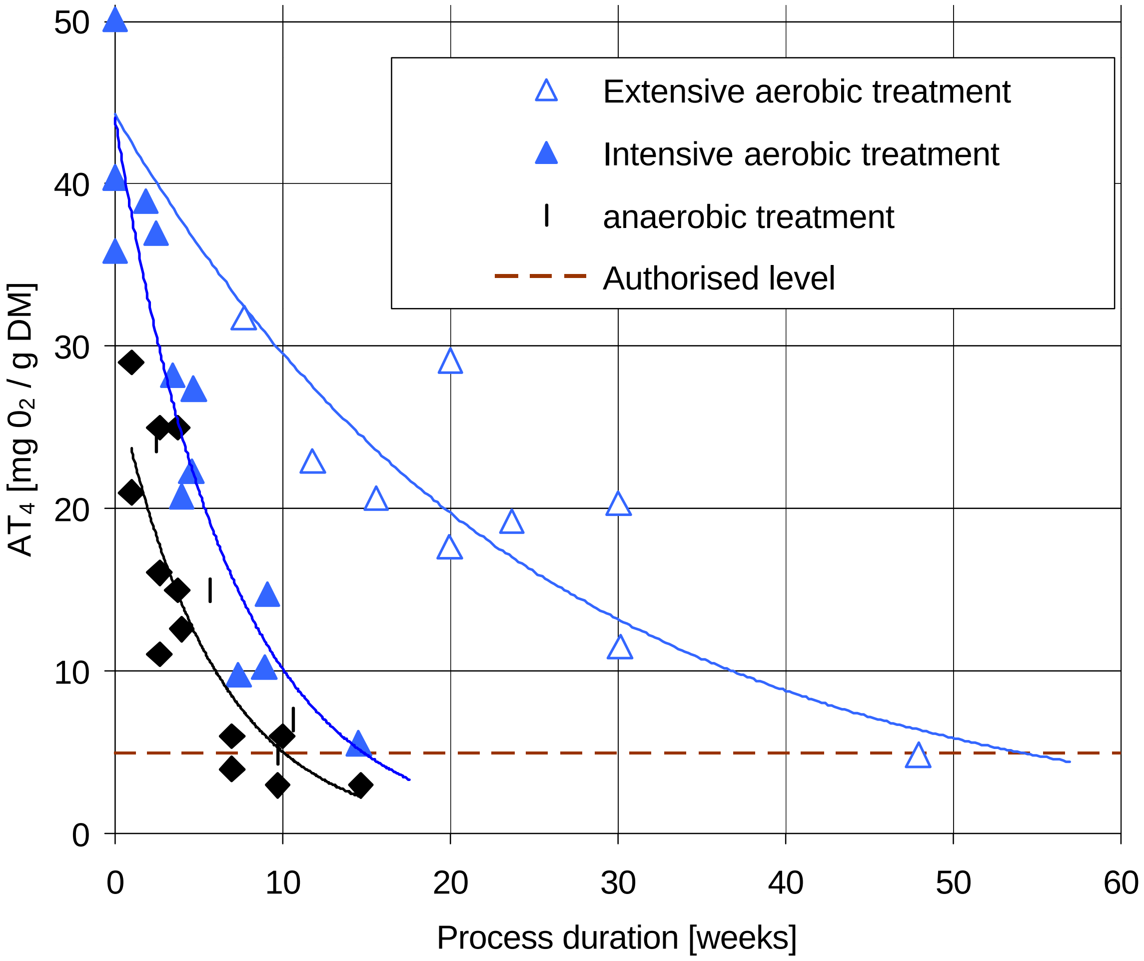

Fig. 6: Landfill gas production as a function of the stability parameter AT_4 [17]

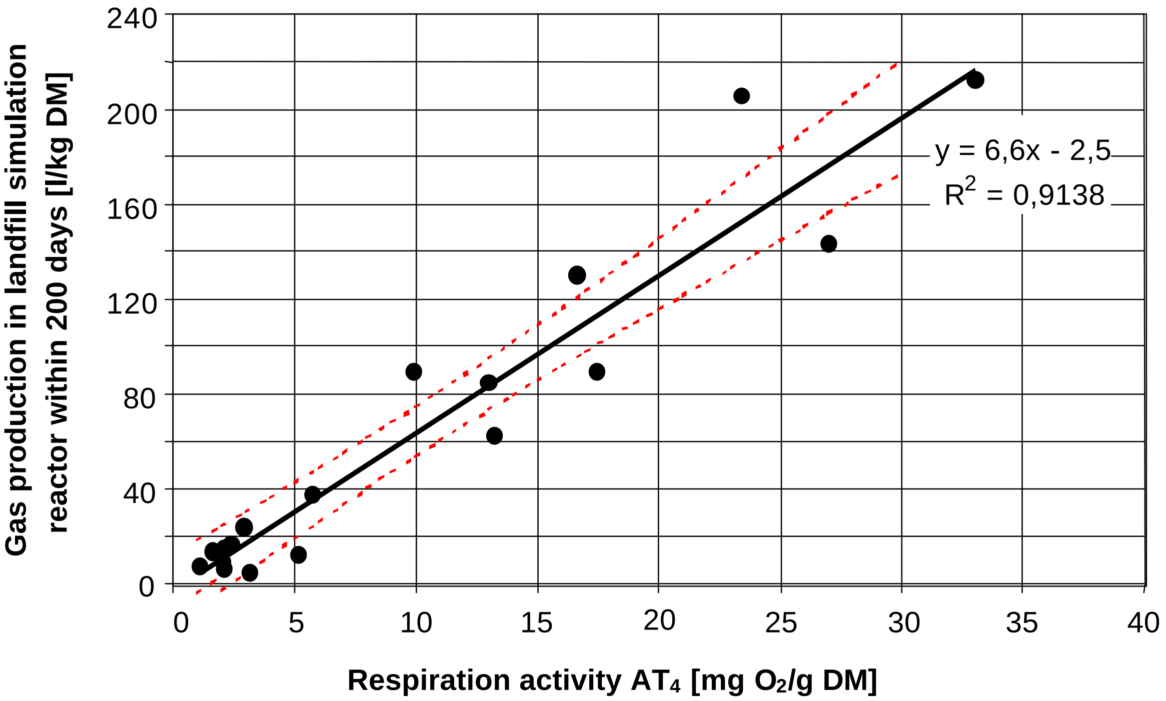

Fig. 7: N-balance of a one step biofilter at the MBP plant in Bassum, Germany [15]