Biological Waste Treatment

Unit 3

The aerobic process (composting)

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A manuscript for students

Weimar 2016

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3.1 What does composting mean?

Golueke demonstrates the most circumstantial description of the tasks of composting in one sentence [8].

“Composting is a procedure of waste management where parts of the waste stream are biologically decomposed under controlled conditions by being handled, stored and/or applied on the soil without a disadvantageous effect on the environment.”

Despite of its shortness this description contains the essential components and requirements of the process:

- Integration into waste management
- Treatment of partial waste streams
- Biological decomposition under controlled conditions
- No impacts on the environment

From a rather subordinate method compared to landfilling and incineration composting has developed itself to one of the most important methods of waste management, especially in Germany.

In *Chapter 3.2 Biology/Biochemistry of composting*, the biological, chemical and physical basics of this waste utilisation process are shown (compare also *Chapter 1.1 Introduction*).

3.2 Biology/Biochemistry of composting

3.2.1 Principle of the aerobic decomposition

The process of composting (aerobic process) is very similar to the degradation of organic components in nature. Complex organic molecules are split in smallest units by microbial activity and are used by higher developed plants. These elements are (partly) selectively absorbed by the plant roots and are included into the plant biomass, whereby the natural loop is closed (see *Chapter 1.1 Introduction*).

The energy that is necessary for the plant growth comes from photosynthesis with which carbohydrates are constituted

- under influence of sunlight,
- under fixation of carbon dioxide,
- fission of water and
- release of oxygen.

After the death of the plants or their parts mineralisation starts. Principally mineralisation is the opposite process to photosynthesis, consisting of

- degradation of carbohydrates,
- consumption of oxygen under formation of carbon dioxide and water and
- the release of stored energy.

3.2.2 Role of microorganisms in the degradation process

The microorganisms are responsible for the degradation and conversion. The term microorganisms describes a very heterogeneous group of living organisms, the characteristic of which is that they are formed of one or a few cells (see *Chapter 1.1 Introduction*).

Microorganisms can be classified into two groups:

- **Prokaryotes** with a relatively simple cell construction
- **Eukaryotes** with a more complex cell construction.

Bacteria, including actinomycetes and cyanobacteria ("cyanophycea") belong to the group of prokaryotes, whereas **fungi**, including yeast, mould fungi, protozoans and algae can be classified as eukaryotes.

An important classification is the categorisation of the bacteria according to tolerated temperature stages which are described in *Table 3.1*.

Tab. 3.1: Tolerated temperature ranges of microorganisms [10]

	Unit	Minimum	Optimum	Maximum
psychrophile	°C	0-10	15-20	25-30
mesophile	°C	10-15	25-35	35-45
thermophile	°C	25-45	50-55	75-80

During composting the number of microorganisms increases, especially that of bacteria, which accomplish the main degradation job in composting. They are able to do this in a very short time (generation time between 0.3 - 1 h for bacteria and 2 - 10 h for yeasts) and they are also able to mobilise habitats quickly. In principle it is not necessary to add microorganisms for the composting of household waste or biowastes in order to start or accelerate the process. Waste contains sufficient microorganisms, the population density is usually 10^{10} bacteria per gram dry matter. They can be enumerated very quickly in a composting plant by an optimal process control.

The conditions are not the same with special organic wastes such as mono charges from food production (compare *Chapter 6.2.1 Substrates from Agriculture*), aseptic materials or sewage sludges. Often **inoculation** is here the only means to get the process of composting started.

Table 3.2 shows the most important functions and living conditions of microorganisms which are taking part in decomposition.

Tab. 3.2: Environment conditions and microorganisms [21]

	Bacteria	Actinomycetes	Fungi
Substrate		suitable for difficult degradable substrates	suitable for difficult degradable substrates
Humidity		prefers dry areas	prefers dry areas
Oxygen	lowest requirement of oxygen content	prefers well aerated areas	prefers well aerated areas
pH value optimum	neutral to weak alkaline	neutral to weak alkaline	weak acid
pH value range	6...7.5		5.5...8
Mechanical conversion	no influence	unfavourable	unfavourable
Portion of decomposition	80-90 % of the decomposition ability		
Temperature	up to 75 °C, but decrease of the decomposition ability at higher temperatures	limit assumed at 65 °C	limit assumed at 60 °C

3.2.3 Degree of decomposition

The decomposition degree of composts informs about the stage of conversion of the biologically more easily decomposable organic matter. It characterises the actual stage of the decomposition and represents a generally valid scale of characteristics which comparably show the progress of decomposition.

The decreasing transferable mass which increases during the time of decomposition is indicated by biochemical parameters like self-heating and respiratory activity. The decomposition degree of a compost material is indicated by the achieved maximal temperature during the self-heating test. With an increasing maximum of the temperature curves and the area under the temperature curve (after 72 hours) this can be brought in relation.

The totally used oxygen in the sapromat after 4 days or the maximum respiratory intensity can be used for the definition of the decomposition degree.

The less the decomposition is advanced at the time of compost application and the more organic matter that can be converted is still available, the more vivid the conversions of the organic matter are in the soil and the effects in a biological, chemical and physical point of view. This has to be considered when composts are used.

Tab. 3.3: Classification of the decomposition degrees in dependence on the maximum temperatures in the self-heating test [22]

Decomposition degree	T_{max} [°C]	Product name
I	> 60	Compost raw material
II	50-60	Fresh compost
III	40-50	Fresh compost
IV	30-40	Mature compost
V	< 30	Mature compost

3.2.4 Proportion of the microbial biomass at the total organic matter

Despite the high number of microorganisms of 10^7 to 10^{10} CFU (colony forming units) per gram material the weight portion of the microbial **biomass** at the organic matter is often overestimated. The following example will explain this:

The portion of **nitrogen** from the microbial biomass at the total nitrogen is only about 0.1 % of the total nitrogen [30]. The C/N ratio of microorganisms is usually at 4 to 7, i.e. at an average of 5.5. Normal composts from biowastes (30% humidity) contain a mean of 1.2 % total nitrogen in the dry matter.

Thus follows:

- 1 kg compost contains 700 g dry matter,
- thereof 1.2%, i.e. 8.4 g are total nitrogen,
- from the total nitrogen 0.1% are microbial biomass nitrogen, i.e. 0.0084 g,
- a carbon content of 0.0462 g can be calculated from the C/N ratio of 5.5,
- the unitary ratio of carbon on organic substance is 1.742 (mean C-content of the organic substance 57%) and
- resultant follows a quantity of 0.081g of microbial dry matter.

At an assumed water content of 70% in the bacteria cell this would correspond to 0.27 g microbial mass per kg compost fresh matter, roughly about 0.3 per thousand.

3.2.5 Biochemical degradation processes during composting

The biochemical processes at the **degradation** of organic matter in composting can be summarised as follows [15]:

- Release of the extracellular enzymes by microorganisms and transport to the substrate
- Hydrolysis of the substrate
- Diffusion of the dissolved substrates to the cell
- Diffusion of the dissolved substrates into the cell
- Transport of the oxygen through the pores
- Cross-over of the oxygen from the gas into the liquid phase

- Diffusion of the oxygen through the liquid phase
- Diffusion of the oxygen in the cell
- Aerobic degradation of the substrate in the cell

The microbial decomposition in an unregulated windrow composting runs in 4 phases (compare *Chapter 1.4.1 Growth phases*).

The curve in *Figure 3.1* shows in principal the growth curve of a bacteria culture, during composting it is dependent on different factors:

1. In the starting phase the microorganisms adjust themselves to the new external conditions.
2. The greatest additional growth of microorganisms is realized in the exponential phase. The essential precondition is that all environmental conditions like pH value, temperature, aeration and the quality of the substrate are optimal.
3. A further growth in the stationary phase is not possible. Reasons are mostly a shortage of substrates, of the oxygen or mostly toxic metabolic products.
4. The dying phase characterises a higher dying rate than regeneration phase.

The degradation of the organic matter usually runs according to the following sample [32]:

Formula 3.1: $Organic\ matter + O_2 \rightarrow CO_2 + H_2O + (N + S + P) + energy$

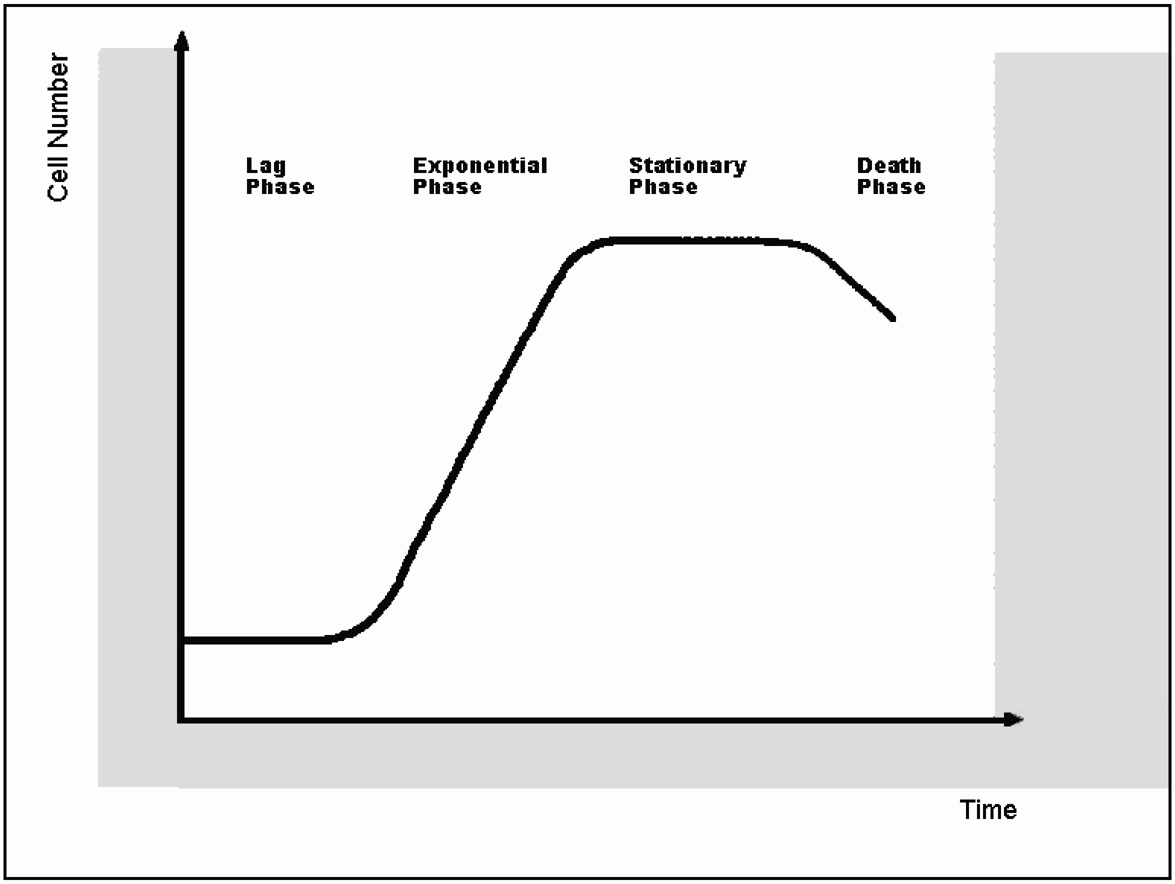

Fig. 3.1: **Developing phases of microorganisms during composting [30]**

The materials prepared for composting contain a great number of microorganisms, their metabolic reactions are responsible for the warming of the process. As a rule of thumb it can be assumed that in an unregulated process a temperature rise of one degree per hour is achieved.

Figure 3.2 shows the ideal temperature march during the composting process.

1 The composting process starts during the first phase of temperature rise, which is destined by the mesophile microorganisms. This phase lasts about 12 to 24 hours.

2 Little by little the thermophile microorganisms take over with increasing warming-up and the mesophile organisms are dying or turn sporiferous. The main degradation phase is destined by the thermophile microorganisms, their temperature optimum lies between 50 to 55 °C degrees.

3 Do the temperatures increase further on, the number of microorganisms and also the wealth of species decrease. At a temperature above 75 °C microorganisms, which join the composting process, have no possibility to survive.

This has advantages but also disadvantages. The advantages are to be seen in **hygienisation** of the material at these temperatures. A temperature that is higher than 60 °C over a longer period leads to the death of pathogenic microorganisms and weed seeds. This, however, is a desired effect.

On the other hand the decreasing number and wealth of species of the organisms which are involved in the decomposition process has a considerable influence on the velocity of degradation. A population that turned sporiferous on account of hygienisation or has totally perished needs more time in order to fulfil the total degradation efficiency.

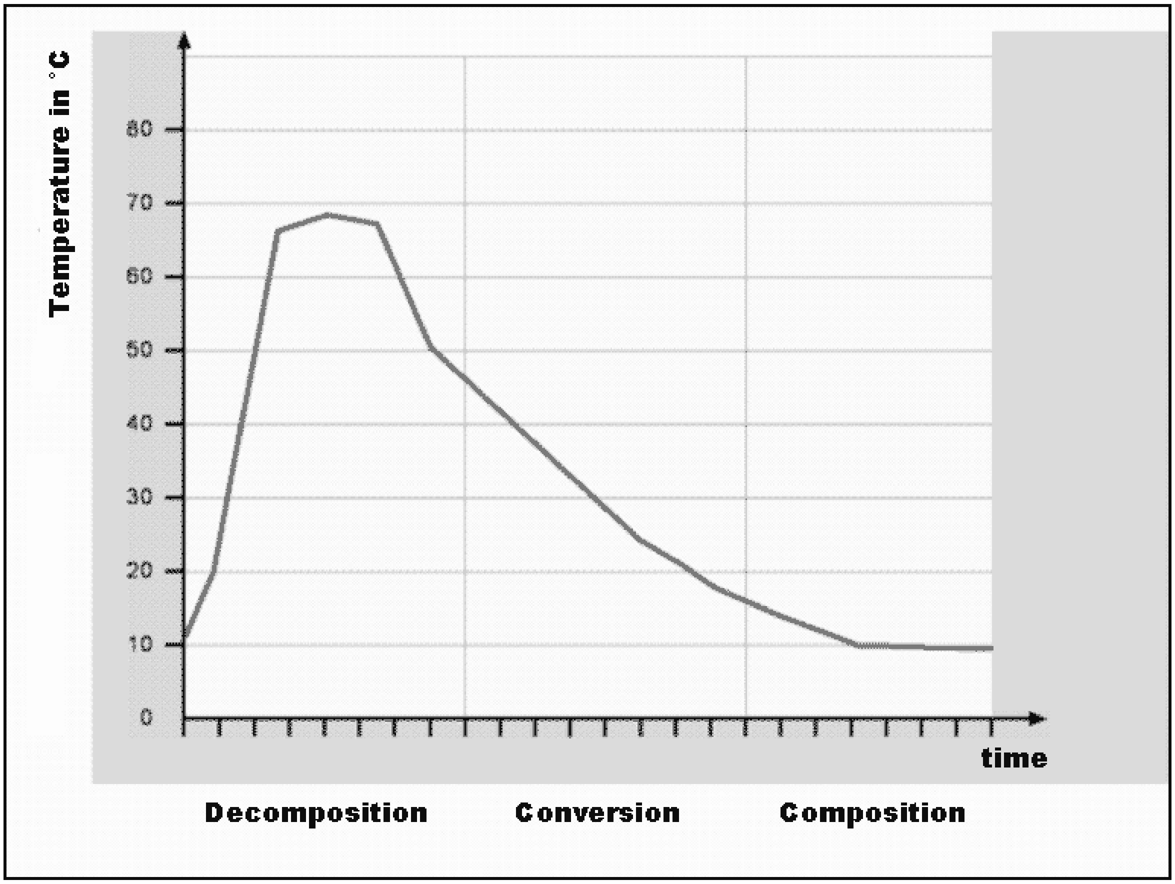

Fig. 3.2: Temperature march during composting [32]

Of course, metabolic products arise during the decomposition which must be discharged. These are:

- Water,
- heat energy,
- carbon dioxide and
- odorous material.

This is mainly done by aeration (see *Chapter 3.3 Aeration*),

- at windrow processes by re-stacking,
- at technical processes by forced aeration.

Hereby considerable amounts of material and energy are operated, which in the frame of a composting process must be handled by the used plant technology (see *Chapter 3.2.7 Mass balance of the organic degradation*).

3.2.6 Nitrogen dynamic during decomposition

The dynamic of the nitrogen is of great importance during the decomposition process. Many, if not most of the input materials contain nitrogen, usually bound in organic forms. The proteins are the main source of organic nitrogen.

One of the characteristics for degradability of biowastes is the C/N ratio, the ratio of organic matter with the total nitrogen. A favourable starting value for an optimally running decomposition lies between 20 and 40.

Proteins are decomposed by definite enzymes, the proteases, in

- polypeptides,
- oligopeptides and then in
- amino acids.

Amino acids are degraded by

- transamination and decarboxylation or by
- desamination.

Under aerobic degradational conditions NH_3 is separated from the amino acids during desamination. At pH values below 7 the ammoniac dissolves directly in the ammonium. The conversion processes of organic bound nitrogen in the decomposition material are primarily running in the direction of ammonification besides the accumulation of a microbial biomass. Contrary to nitrification this also proceeds at temperatures usually found in main decomposition, i.e. 45-65 °C. A high rate of ammonification therefore also characterises a high organic degradation. Well aerated main decomposition systems convert (at decomposition degree II) about 10 % of the original nitrogen into NH_4-N (ammonium nitrogen), composts with decomposition degree III may have a result of 3 % [30].

The next stage of nitrogen conversion is the way from ammonium to nitrate nitrogen, a process which is named **nitrification**. The nitrification proceeds under aerobic conditions. Bacteria of the species nitrosomonas and nitrobacter (obligatory aerobe!) are involved. With this step NH_4^+ is converted to NO_3. Favourable conditions are the presence of oxygen, a neutral to weak acidly pH value, a mean water content and temperatures between 20 °C and 25 °C. The protons released during the reaction lower the pH value.

Together with water, ammoniac establishes an equilibrium dependent on temperature and pH value, i.e. as NH_4^+ it is kept in solution by low temperature and/or low pH value. An increase of temperature and/or increase of the pH value, both factors which are characteristic for the decomposition process of aerobic composting, leads to a release of ammoniac that, to some extent, can strongly influence the odour freight. The higher the pH value the higher the potential for NH_3 losses.

A further possible nitrogen loss can be realised by denitrification. Anoxic conditions may reduce nitrate (utilisation of nitrate as hydrogen acceptor by some aerobic bacteria), whereby as a result nitrogen will be released as N_2 via NO_2, NO and N_2O.

Thus the progress of decomposition is also characterised by the ratio of nitrate nitrogen with ammonium nitrogen. An accumulation of nitrate and a decline of the ammonium values are consulted e.g. in the Low Countries (Netherlands, Belgium, Luxembourg) as an indicator for compost quality.

3.2.7 Mass balance of the organic degradation

Haug gives an exemplary compound of organic matter as a sum formula [14]:

Formula 3.2: $C_{99}H_{148}O_{59}N$

During the aerobic decomposition of these molecules the following chemical reaction formula arises:

Formula 3.3: $4(C_{99}H_{148}O_{59}N) + 423O_2 \rightarrow 396CO_2 + 290H_2O + 4NH_3$

The following mass flows, related to one kilogram of water and an ash-free organic matter can be derived from this (*Table 3.4*).

Tab. 3.4: Mass flows in composting processes, example of an intensive decomposition

Input	1 kg	Organic matter (free of water and ash)
	1.475 kg	Oxygen
Composting process		
Output	1.899 kg	Carbon dioxide
	0.569 kg	Regenerated process water
	0.007 kg	NH3
	Approx. 20,000 kJ	Energy (acc. to Haug 13,659 kJ/kg oxygen consumption [11])

Usually the microbially produced heat is rapidly released into the environment.

However, if the heat release into the environment is hampered, like e.g. in composting processes, the result is a self-heating of the system; self-heating is the macroscopically most ostentatious phenomenon of composting. An exact calculation of heat formation in a compost heap is scarcely possible [17].

The heat released at composting is always lower than the heat which is released at thermal utilisation. Only approx. 60% of the energy are released as heat [20]. The residual 40% are used by the microorganisms for their own existence. That means, approximately 12.000 kJ of heat energy remain, able to evaporate water. If we determine the evaporation enthalpy of the water with 2400 kJ per kg of evaporated water, 1 kg of decomposed organic matter is able to evaporate approximately 5 litres of water.

The mass flows for a biowaste model in an **intensive decomposition** process (2week decomposition) are shown in *Table 3.5*:

The following conclusions can be drawn from the example:

- The decomposition of an organic matter in this example of an intensive decomposition lies at 30 %, this being an acceptable value considering the possible total decomposition of 50-60 % within the total decomposition period of 12 - 14 weeks.
- For a proper operation, decomposition without a drying-out that hampers the life processes, a ratio of organic matter with water of 1:2 (weight/weight) should be granted in the input material. Thus 30% of the decomposed organic matter correspond to 78 kg.
- These 78 kg deliver the energy to evaporate 392 kg of water. Therefore in the output material a water content of only 35 % exists. This corresponds to a ratio of organic matter with water of just 1:1.
- Therefore 164 litres of water must be added for the following subsequent decomposition in order to have optimal conditions again for this part of the decomposition process.

Tab. 3.5: Mass flows for the composting of 1 Mg biowaste (waste model)

Parameter	Unit	Input	Output
Water	% of FM	54.8	35.0
Organic matter	% of DM	57.8	48.9
Ash	% of DM	42.2	51.1
Water	kg	548	156
Water – new formation	kg		45
Organic matter	kg	261	183
Ash	kg	191	191
Sum	kg	1,000	575

3.3 Aeration

The aeration necessary for decomposition can be transferred into the material in different ways,

- by re-stacking (see Chapter 3.3.1 Aeration by re-stacking),
- by suction or pressure aeration (see Chapter 3.3.2 Forced aeration),
- by rotation in drums etc.

3.3.1 Aeration by re-stacking

An aeration which is exclusively made by re-stacking is only partially able to assure a sufficient air supply of the decomposition material. Based on the statements of various authors (e.g. [1]), after few hours the oxygen content in many areas of a windrow already decreases onto zero percent. Convection and diffusion can guarantee only a small air exchange with the windrow centre. Factors like structure and water content of the material are of major importance.

On account of natural conditions the lowest aeration rates are found in the centre and at the bottom of the windrow. Therefore a definite windrow height must not be surpassed when forced aeration is not used. This maximal height is usually below two meters.

3.3.2 Forced aeration

To remove an unsatisfactory aeration in the windrows, an active aeration can be installed (**forced aeration** = **active aeration**). The mostly used procedures are:

- suction aeration and
- pressure aeration or
- combined (alternating) procedures.

Both procedures are used in practical operations, yet the pressure aeration has certain advantages. These result from a lower fan performance and thus lower operational costs. No condensation is possible in the fans and their feed cable, thus lower consequential damages by corrosion have to be suffered.

The suction aeration is often used, when no exhaust air collection is possible like in the aerated windrow systems in closed halls.

The most optimal, but very costly method of aeration is the control-regulated aeration rate which is adjusted according to the requirements of the system. Temperature, oxygen demand or CO_2 production can be the control parameters. The possibilities of a control are increased by a decomposition procedure in an enclosed system. (see *Chapter 3.3.3 Control possibilities in an enclosed system*).

3.3.3 Control possibilities in an enclosed system

Control possibilities

Besides the collection of exhaust air in an enclosed decomposition system (tunnel, box, container etc.) further possibilities of a process control and regulation are given. As an example it is possible to

- lead back a part of the process air into the system and to
- optimise the air circulation guidance.

This procedure allows a reduction of the necessary additional air and minimises the emitted exhaust air. Thus, necessary filters can be kept compact.

The necessary oxygen demand for one Mg of biowaste, as shown in the examples of *Table 3.6*, lies at 115 kg oxygen only for the decomposition of the organic matter (1.47 kgO_2 per kg decomposed organic matter).

As air under normal conditions has a specific weight of 1.2 kg/m^3 and the oxygen has a portion of 23.2 % w/w of it, a stoichiometric air demand of 413 m^3 results for one Mg of the exemplary biowaste.

The quantity of water which is evaporated in the described example and thus should be discharged, lies at 392 litres.

Assuming from the precondition that

- the entry temperature of the additional air is 20 °C and
- its water saturation is 60 %,
- the exhaust air is 55 °C warm with
- a water saturation of 90 %,

Tab. 3.6: Air quantity calculation

Parameter	Unit	Input	Output
Organic matter	kg	261	183
Oxygen	kg	115	
Air (20 °C, 1bar)1)	m^3	Approx. 413	
Carbon dioxide	kg		148
Process water	kg		45
NH_3	kg		0.6
1) Conversion factor according to Haug [14]			

approx. 3,600 m^3 are necessary in order to discharge the corresponding quantity of water. That is 9 times more air than is necessary for the biological process. This higher quantity of air that is necessary for the discharge of the water and for cooling of the process is called Excess Aeration Rate (EAR) in the American-speaking part of the world. It can be 10 to 30 times higher than the stoichiometric air demand.

3.4 Literature

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