Influence of Different Temperature and Aeration Regulation Strategies on Respiration in Composting of Organic Household Waste

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Abstract

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A laboratory scale composting reactor was constructed for systematic studies of the effects of oxygen levels and temperature on carbon and nitrogen turnover in household waste compost. The reactor was equipped for independent control of oxygen level and temperature. The results presented showed that the performance of the reactor concerning uniform regulation of temperature and O_2 level in the compost matrix, gas and over time was good.

The effect of three temperature regimes performed at the constant level of 16% O_2 in the compost gas was studied in eight experimental runs in the compost reactor. The effect of reduced O_2 levels of 2.5 and 1% in the compost gas was studied in two experimental runs for one of the above temperature regimes. It was found that the highest rate of degradation was achieved when the temperature was actively regulated to below 40°C during a low pH phase. The lowest degradation was obtained when the temperature was already regulated to 55°C from the start. It was further found that reduced O_2 levels of 2.5 and 1% in the compost gas reduced the degradation rate and enhanced methane emission.

Keywords: household waste, oxygen, temperature, control, compost, reactor, nitrogen, carbon, carbon dioxide, greenhouse gas, pH, fatty acids.

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Appendix

This thesis is based on the following papers, which will be referred to by their Roman numerals.

I. Smårs, S., Jönsson, H., Beck-Friis, B. and Kirchmann, H., 2001. An advanced experimental composting reactor for systematic simulation studies. Journal of Agricultural Engineering Research 78 (4), 415-422.

II. Beck-Friis, B., Smårs, S., Jönsson, H. and Kirchmann, H., 2001. Gaseous emissions of carbon dioxide, ammonia and nitrous oxide from organic household waste in a compost reactor under different temperature regimes. Journal of Agricultural Engineering Research 78 (4), 423-430.

III. Beck-Friis, B., Smårs, S., Jönsson, H., Eklind, Y. and Kirchmann, H. 2002. Composting of source-separated organic household waste at different oxygen levels: Gaining an understanding of the emission dynamics. Accepted by Compost Science & Utilization.

IV. Smårs, S., Gustafsson, L., Beck-Friis, B. and Jönsson, H. Improvement of the composting time for household waste during an initial low pH phase by mesophilic temperature control. Accepted by Bioresource Technology.

The papers are published with permission of the journals concerned.

Introduction

The production of organic household waste in many countries including Sweden is increasing. Therefore there is a need for an increased capacity to take care of these wastes. The main available methods for treating the organic waste are recycling of material, biological treatment, incineration and landfilling. There is increasing awareness in society that the sustainability of the use of fossil resources for production of mineral fertilisers and food may be questionable. This awareness has in many countries resulted in a political endeavour to direct the stream of waste towards biological treatment in order to close the loop of plant nutrients from urban to rural areas. In Sweden, this endeavour has resulted in a law which prohibits landfilling of organic waste by the year 2005. This law may lead to an increase in the use of biological treatment in the form of composting and/or biogas fermentation.

Composting is regarded as being a cheap and robust process. Composting has the capacity to kill pathogens, stabilise organic matter and reduce the volume of the waste material. However, composting can lead to emissions of greenhouse gases and odorous compounds. These emissions depend on microbial activity and are probably linked to temperature, oxygen and pH levels, but this dependency is sparsely recorded and not well understood. In order to optimise the performance of composting and minimise emissions, there is a need to improve our knowledge in this field by making systematic studies of composting using different oxygen and temperature control regimes.

Background

Chemically bound energy is released as heat during the microbial degradation of waste. If this heat is not removed by ventilation, radiation or conduction, it results in an increase in temperature in the material. During composting, a higher temperature results in an acceleration of the degradation rate due to increased microbial growth rate, increased production of enzymes and increased reaction rates of the enzymes produced (Richard and Walker, 1998). Higher degradation rates result in an increase in the release of heat in a positive feedback loop until the temperature becomes so high that it is no longer favourable for microbial growth. Many authors have contributed models, relevant data or studies related to the performance of composting in relation to temperature.

Snell (1957) composted ground garbage in a batch composter at temperatures ranging from 40 to 70°C in steps of 5°C. The highest rate of respiration in these experiments was obtained at 45°C. However, at the higher temperatures the samples became dry, indicating that the rate of respiration was probably limited by low moisture. Schultze (1962) made a number of observations of temperature and respiration in a continuously fed laboratory scale reactor system and in small scale laboratory units. The observed respiration rates were plotted against the temperature and it was found that the observations of the respiration were grouped not too far from an exponential relationship to temperature in the range 35-68°C.

Jeris and Regan (1973) composted different mixtures of newsprint, refuse and composted refuse with high contents of cellulose at well-defined temperatures and with adequate aeration. They obtained optimal respiration at different temperatures depending on the mixture of material. Haug (1993) compared results previously obtained by other authors of respiration rates in relation to temperature. On the basis of these data and theoretical considerations, he formulated a mathematical expression of the respiration which, with his choice of parameters, has a seemingly exponential shape up to 65°C, peaks at 70°C and thereafter steeply declines to zero at 80°C.

Composting is considered to be an aerobic process and this process is highly dependent on the availability of oxygen. The oxygenation of compost includes transport via incoming air through ventilation or convection and diffusion into the liquid around and in the compost particles. Active microbial transport of oxygen, for instance by fungi, may further complicate the picture of oxygen transport in composting. Several authors have contributed more or less detailed models of the oxygenation of composting as a function of the oxygen level in the compost gas: Hamelers (1993) formulated a sophisticated model on how oxygen diffuses into a thin liquid layer around a compost particle, where an outside part of the core is aerobic and an inner part of the core may be anaerobic. This model is further discussed in the Results and Discussion sections below. Haug (1993), Stombaugh and Nokes (1996) and Richard et al. (1999) all used a Monod type of equation to describe how reduced O_2 content in the compost gas inhibited the respiration, although by use of different parameters. The parameters to the Monod function suggested by Haug (1993) give a halved degradation rate at approximately 2% O_2, whereas the parameters suggested by Stombaugh and Nokes (1996) give a halved degradation rate at approximately 5% O_2 in the compost gas. In the Monod type equation the parameter, i.e. the half-saturation constant, is identical to the value in % O_2 where it predicts the respiration to be halved. In the study performed by Richard et al. (1999), the parameters resulting from a best fit under the temperature conditions 35, 45, 55 and 65°C; the O_2 conditions 1, 4, 21% O_2; and moisture conditions in the range 36-60% water content; predicted half-saturation constants in the range –0.67 to 1.74. Negative values of the half-saturation constant imply that low O_2 levels would actually increase the microbial activity. However, the negative values obtained in the half-saturation constants were probably the result of artefacts due to some error in the measurement procedure (Richard, 2000)

In our first study in Paper I, we observed that the composting process may be inhibited by pH and/or the occurrence of organic short chain fatty acids during an initial phase. A number of authors have observed low pH in connection with an initial phase during composting of organic waste material: Schultze (1962) observed that the composting process normally goes through a mesophilic phase which includes fermentation and acid formation and that mesophilic organisms such as yeast and bacteria are predominant during this phase. That this was not an isolated phenomenon is confirmed by others (Poincelot, 1974; Andersson, 2001). Kirchmann and Widen (1994) observed that the low pH phase could last for several weeks. Nakasaki et al. (1993) tested liming and found that the degradation rate of organic matter in the pH-controlled experiment was faster than that in the experiment without pH control. Nakasaki et al. (1996) found that inoculation with

Bacillus licheniformis clearly enhanced the carbon turnover by shortening the low pH phase when composting in a laboratory scale composting reactor at 60°C. Choi and Park (1998) detected an early growth and decay of yeast which seemed to coincide with the length of the low pH phase. In addition, they found that inoculation with an especially thermo-tolerant strain of yeast had a positive effect in an experiment where the microorganisms failed to grow normally when composting at 50°C. Reinhardt (2001) found a correlation between acetic acid and inhibition at about 40°C. Robertsson (2001) studied the effects of turning off the aeration in small laboratory scale compost reactors at different stages. He found that the anaerobic conditions enhanced the net production of short chain fatty acids and low pH.

Overall objectives

The aims of this work were to systematically study the influence of temperature and aeration strategies (i.e. temperature and oxygen levels in the matrix) on the degradation rate and to study the emissions of CO_2, NH_3, N_2O and CH_4 during composting of source separated household waste. The intention was also to obtain a deeper understanding of the dynamics of carbon and nitrogen turnover and, if possible, to improve the process.

The scope of the work

The work for this doctoral thesis was performed within a group and with several persons and other associated projects involved. The reader should therefore bear in mind when reading this thesis that the main interest and scientific responsibility of the author has been directed more towards degradation rate and carbon turnover. The main interest and scientific responsibility of the co-worker and co-author in Papers I-III, Barbro Beck-Friis, has been directed more towards the dynamics of nitrogen turnover and related emissions. The findings, however, are a result of a close cooperative work and the ownership is shared.

The scope of the work and the main responsibilities of the author are summarised in paragraphs 1 - 5 below. The author was responsible for:

1. The construction, development, implementation and testing of the reactor system and its measurement and regulation system. This work is presented in Paper I and was completed during approximately two years.
2. The performance and maintenance of the technical system and the design of the routines of the experiments described in Papers I-IV.
3. The collection, handling and analyses of data, involving the devising and use of computer programmes concerning measurements and computations of flow or turnovers of gas, liquid and solid volumes.
4. The ideas behind the study and the design of the study as described in Paper IV.

5. A large part of the daily work in taking samples of gas, liquid and solids from the reactor and maintenance of the reactor system during the execution of the experiments.

The main author of each article is evident from the order of the author names.

Materials

The compost material

The same proportions of mixed source-separated organic household waste, wheat-straw and water were used in all the experiments in this thesis. In the wintertime, early 1995, Eklind et al. (1997) collected and chemically characterised twelve tons of source-separated organic household waste from Uppsala and cleaned it of contaminants. Plastic bags and iron objects were removed by rotary sieving and magnetic separation. The material was then mixed and visible contaminants were manually picked from the waste. The material was milled in a cutting mincer (Palmia, 200 mm 18 kW, Sweden) equipped with a holeplate with 13 mm holes. The material was thereafter divided to approximately 24 kg portions and packed in polyethene plastic bags and cartons and stored at -24°C for future use. The material consisted of 65.8 % water, 25.6 % organic matter and 8.6 % ash. The chemical composition of the organic matter in the waste material is summarised in Table 1.

Table 1. Chemical composition of the organic matter in the household waste material used in the experiments (source Eklind et al., 1997)

Component	% of organic matter
Sugar	1.6
Starch	13.2
Crude fat	15.0
Cellulose	15.6
Hemicellulose	3.2
Lignin	9.9
Crude protein	6.4
Lactic acid	1.5
Acetic acid	0.6
Ethanol	0.5
Unidentified	32.5

Before composting, the material was thawed slowly for 3-4 days and then mixed with wheat-straw and water in a free fall mixer (Universal 180-litre, ATIKA, Germany). The relative proportions of household waste, straw and water were adjusted to give an initial water content of 65% w/w and a C/N ratio of 22. The compost material was then homogenised using the above mincer with a hole diameter of 28 mm. Finally, the compost material was placed in a 200-litre airtight reactor.

The composting reactor

An advanced experimental compost reactor was constructed between 1996-1998 for systematic studies of the effects of oxygen levels and temperature on carbon and nitrogen turnover in the compost process (Fig. 1).

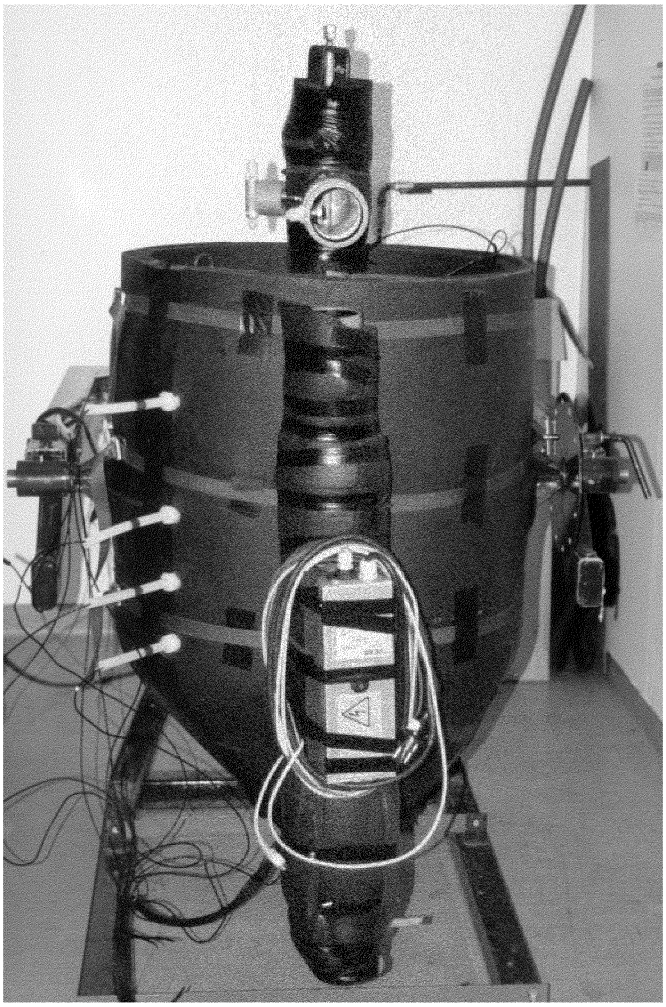

Figure 1. The compost reactor.

The reactor is thermally insulated and equipped with a fan to mix the compost gases in order to eliminate gradients in temperature and gas composition. It is also equipped for independent control of oxygen level and temperature in the compost matrix. The volume of the reactor is approximately 200 litres, to allow for extraction of samples for different biological and chemical analyses during prolonged experiments. The system is equipped for continuous monitoring of gas flow and emissions of CO_2, NH_3, and N_2O from the reactor. The water content in the compost matrix is controlled by adding water once a day to compensate for moisture losses due to drying as an effect of heat production and aeration. The evaporated water is trapped as condensate in a cooler which serves as part of the regulation system.

Daily turning of the reactor (a few revolutions) serves the purposes of mixing the material to even out moisture gradients, exposing new surfaces, breaking established channels for preferential airflow and preserving the structure of the material to simplify aeration. The compost reactor is described more in detail in Paper I.

Methods

Measurements of the compost gas composition

Paper I gives a detailed description of the system for analysing the compost gas composition in the compost reactor. Three gas analysers, Servomex 1131 (UK) for O_2, Binos 4b.2 (Germany) for CO_2 and Innova Type 1312 (Denmark) for CO_2, NH_3 and N_2O concentrations were used in all experiments. The Servomex 1131 uses paramagnetic susceptibility, the Binos 4b.2 infrared radiation absorption and the Innova Type 1312 uses a photoacoustic absorption of light of different visible wavelengths as a principle for measuring the respective gas concentration in the sample gas. The data from the gas analysers were logged every fifth minute and stored in two computers. The photoacoustic determinations proved to be questionable regarding NH_3 measurements during the first 5 days of composting in the experiments performed in Paper II, probably because of interference from other gases. Another method used for measuring NH_3 was passive diffusion samplers (Ferm, 1991). These measured only trace levels of NH_3 during the first 5 days (Paper II) which corresponded with the low pH in the material during this period. To improve the precision in measuring NH_3 another method, in which a measured amount of off-gas was pumped through a battery of two H_2SO_4-traps, was introduced into the experiments with reduced O_2-levels performed in Paper III. In these experiments, supplementary samples for CH_4 and N_2O measurements were collected on a more or less daily basis in glass vials for analysis by gas chromatography.

Analysis of solid and liquid matter

In all reactor experiments described in this thesis, material and liquid samples for different analyses were taken on a daily basis until the degradation rate in the compost process had culminated and decreased to a lower level. Thereafter the sampling was done less frequently.

The compost material was analysed for dry matter, pH, organic short chain fatty acids, total-N, NH_4^+-N and NO_3^--N. The dry matter determination was done by drying the samples at 105°C overnight. A pH meter was used to determine the pH in the material samples which were mixed with deionised water in a weight ratio of 1:5. Organic short chain fatty acids were determined by use of high performance liquid chromatography on extracted sample, weight ratio 1:4, sample to ultra pure water. Inorganic N was extracted with 2M KCl with a weight ratio of sample to KCl of 1:5 prior to analysing NH_4^+-N and NO_3^--N on an autoanalyser (Technicon TrAAcs 800, Germany).

Total C and N were determined in the raw and final compost materials. The C-content was analysed with a dry combustion method (LECO CN-2000, USA) and the N-content with the regular Kjeldahl method.

Experimental design

We started out with the intention of having as clear and well defined environmental conditions as possible during our composting experiments. Our first attempt was therefore to regulate temperature and oxygen levels at fixed levels from the beginning to the end of the experiments. We intended to start with a series of four experiments in which we composted at four different oxygen levels and held other parameters as constant as possible. We outlined that the oxygen levels should be exponentially distributed at the levels 16, 5, 2.5 and 1% and that our first experiment should be conducted at the highest level to ensure good aerobic conditions. Concerning temperature, we had found in the literature (Schultze 1962; Jeris and Reagan, 1973; Strom, 1985; Haug, 1993) that the optimal level for composting was probably in the interval 40-65°C. Our ambition was to investigate this later but we decided to start at 55°C in order not be too far from the optimum and not to take the risk of trying to compost at a too high temperature. In our first experiment (Paper II, regime A, referred to as A also in the following) we therefore wanted to regulate the temperature, the oxygen level and the moisture content at the constant levels of 55°C, 16 vol. % and 65% wet weight from the start to the end of the experiment. To quickly reach 55°C from the start, this regime required that heat be artificially added to the process.

However, this regime was not very successful in terms of degradation of the material. After one week the respiration activity was close to zero and there were no signs of improvements. The experiment was repeated twice with the same result. Since we suspected that the artificial heating was the cause of the low activity, we designed a similar regulation regime (Paper II, regime B referred to as B also in the following), but here, we waited with the regulation of temperature until the temperature had reached 55°C as a result of the heat produced by the biological process. This regime for regulation of temperature proved to give satisfactory results for the time being and we decided to continue with it as we composted at reduced oxygen levels (Paper III). We chose 2.5% as the set-point for the regulation of O_2 in the next experiment and this seemed to hamper the activity but it was not even halved. We therefore decided to omit the 5% level and proceed at 1% O_2 in the subsequent experiment.

During all the experiments so far, except those according to regime A, we had observed an oscillating behaviour of the respiration activity around 40°C during the initial low pH phase lasting approximately 1-2 weeks. A possible interpretation of the behaviour in all experiments was that the respiration activity was hampered by a combination of temperatures above approximately 40°C and low pH or the occurrence of short chain fatty acids. If this interpretation was true, it would be expected that a temperature regulation regime in which the temperature was regulated slightly below 40°C during the low pH phase would lead to an increased respiration rate and a shortened low pH phase due to a faster microbial consumption of short chain fatty acids. Such a regime C (Paper IV, regime II) was tested and compared with the previous regime. The number of composting experiments at the different control regimes are summarised in Table 2.

Table 2. Number of composting experiments at the different control regimes

Temperature regime	**O_2 regulated at: 16%**	**2.5%**	**1%**
A	2	-	-
B	3	1	1
C	3	-	-

Results and discussion

The performance of the compost reactor (Paper I)

The control of oxygen content in the compost gas was such that 95% of the readings of the oxygen level were in the interval 16.01±0.26% during an initial experiment. In the same experiment, 95% of the temperature readings were in the interval 54.6±0.5°C. The volume of the reactor was approximately 200 *l* to allow for taking samples for analysis during prolonged experiments. The system was equipped for continuous monitoring of gas flow and emissions of the gases CO_2, NH_3 and N_2O from the reactor. The water content in the compost matrix was controlled by adding water and mixing the material once a day to compensate for moisture losses due to drying as an effect of heat production and aeration. The regulation of water content was less precise than regulation of temperature and oxygen content and the average water content in the reactor varied within the interval 57.5 - 70.5%. It was concluded that the performance of the reactor was satisfactory for future systematic experiments.

Respiration and gaseous emissions during composting under different temperature regimes (Paper II)

The result of the first experiment performed according to temperature control regime A at 16% was that the activity during composting was inhibited and a very low and decreasing flow of CO_2 emission was detected after a week. The objective of having a high degradation under these presumably nearly optimal conditions was not at all fulfilled.

The compost process in the experiments performed according to regime B at 16% O_2 followed a pattern of swinging temperature and respiration activity for almost one week before the activity abruptly increased and peaked during a few days and thereafter slowly declined. The maximum rate of carbon turnover was less than 4% per day in the experiments performed according to regime A at 16% O_2, whereas it amounted to more than 15% per day according to B. After an experimental period of 7 days, the cumulative CO_2-C according to A averaged less than 20% of that in two of the experiments according to B.

The abrupt rise in the respiration activity after about six days (Fig. 2) occurred simultaneously with either a fast decrease in short chain fatty acids and/or a fast pH shift from below 6 to about 8 or higher in the compost material (Fig. 3). A reasonable interpretation of the pH pattern is that the pH increase is a result of a combination of NH_4^+-N mineralisation and of short chain fatty acids being consumed by microbes (Figs. 2-4). The early increase in fatty acid content from Day 1 to Day 3 before it started to decrease (Fig. 3) may be interpreted as a sign of partly anaerobic conditions in the compost material. This is in accordance with the model presented by Hamelers (1993) which shows that most likely both aerobic and anaerobic conditions coexist during composting.

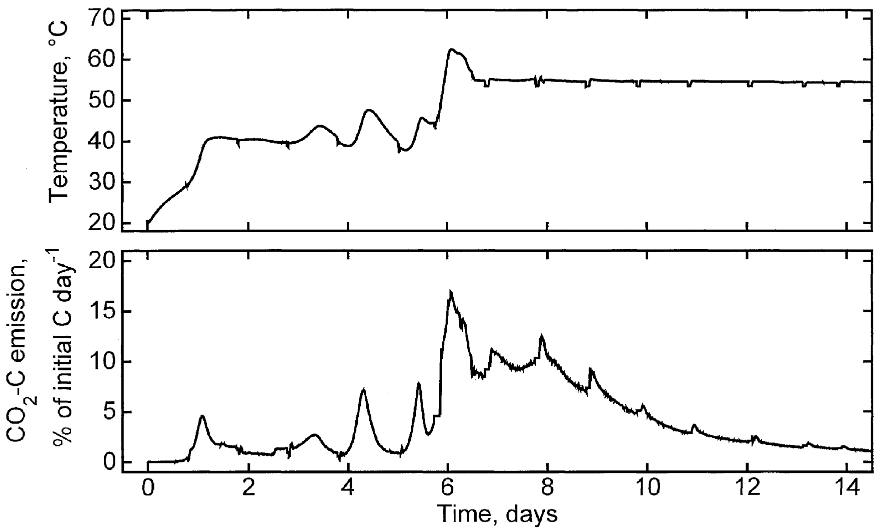

Figure 2. Temperature and CO_2-C emission as % per day of the initial C according to regime B, replicate no. 2 Paper II.

The pattern of NH_4^+-N in the compost material (Fig. 4) showed an increase from Day 2 to Day 6 followed by a strong decrease from Day 6 to Day 8. This may be interpreted as net mineralisation followed by an immobilisation of NH_4^+-N in combination with the volatilisation of NH_3, which coincided with the abrupt increase in the microbial activity shown at Day 6 as change in CO_2-C turnover rate

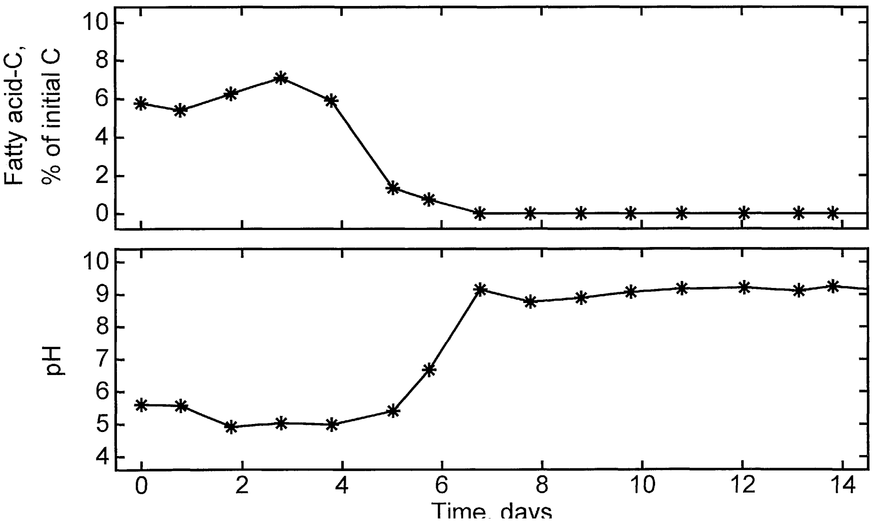

Figure 3. Content of fatty acid C as % of the initial C and pH in the compost material according to regime B, replicate no. 2 Paper II.

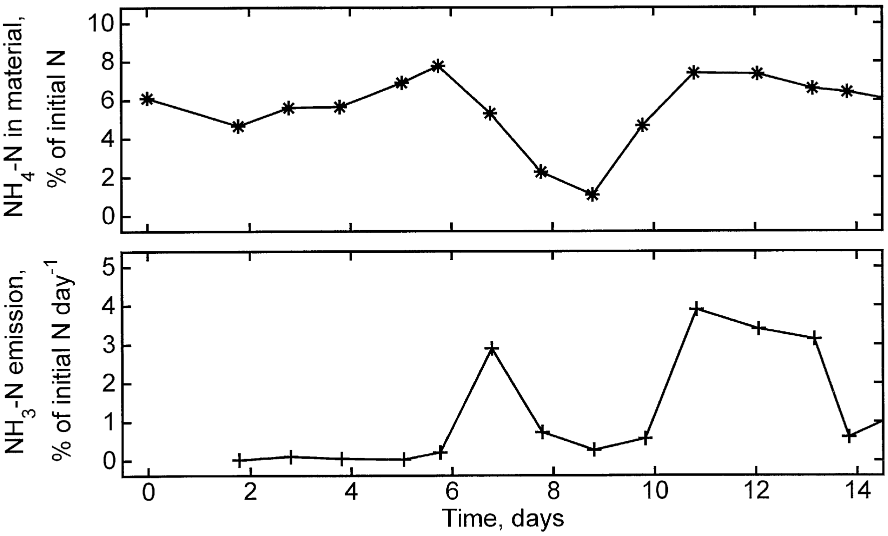

Figure 4. NH_4^+-N in the material as % of initial N and NH3-N emission from the compost in the experiment according to regime B, replicate no. 2 Paper II.

in Fig. 2 and pH shift in Fig. 3. The strong increase in NH_4^+-N in the material from Days 9-11 coincided with a declining microbial activity and may be interpreted as a remineralisation of microbial nitrogen in addition to the net mineralisation of N from the material.

The emission of ammonia (Fig. 4) started abruptly with a peak at the time of the pH shift at Day 6. After this peak followed three days with low NH_3-N emissions at the time of immobilisation. At Day 11, there was a new peak in the ammonia emission which coincided with a new high level of NH_4^+-N after remineralisation. After this peak, the emission of NH_3-N showed a mostly declining pattern. More than 85% of the NH_3 was recovered in the condensate from the cooled compost gas and the remainder in the gas.

Composting under low oxygen conditions (Paper III)

In Paper III, composting experiments were performed in which the oxygen level was regulated to 16, 2.5 and 1% in the re-circulated compost gas. The intention with the experiments was to study the effect of low oxygen conditions on the compost process. More specifically, we wanted to study the effect of low oxygen content in the compost gas on the degradation rate, the occurrence of organic short chain fatty acids, and emission of the gases NH_3, N_2O and CH_4. We also wanted to know if it was possible to reach thermophilic conditions when composting at an oxygen level of only 1% and at which oxygen levels we would get a shift towards mainly anaerobic digestion as indicated by CH_4 emission. Furthermore, we wanted to learn more about the role of organic short chain fatty acids during composting and how their occurrence would be influenced by low oxygen conditions.

Influence of reduced oxygen levels on occurrence of short chain fatty acids

In our experiments performed at reduced oxygen levels, we found that these conditions enhanced the early increase in fatty acids before they started to decrease. Fatty acids are regarded as being a product of microbial anaerobic metabolism (discussed in Paper III). In accordance with this, the results from our experiments indicated that the early net production of organic short chain fatty acids was enhanced, and that the time for their net consumption was prolonged, by low oxygen conditions during composting of household waste (Fig. 1 in Paper III). This is also in accordance with findings from Robertson (2001). Our results also indicated that the occurrence of short chain fatty acids was the key factor which determined the length of both the low pH phase and the mesophilic phase. The pH in compost is probably, like that in slurries, regulated by the three groups: organic short chain fatty acids; NH_4^+/NH_3; and $CO_2/HCO_3^-/CO_3^{2-}$ (Georgacakis et al., 1982; Paul and Beauchamp 1989; Sommer and Husted 1995a,b). This is more thoroughly discussed in Paper III .

Influence of reduced oxygen levels on carbon turnover rate

When the low pH phase was over, the biological activity at all three O_2 levels was high enough to reach thermophilic conditions. The rate of carbon turnover was, however, hampered by the low oxygen conditions as could be expected. Several authors (Haug, 1993; Hamelers, 1993; Stombaugh and Nokes, 1996) have mathematically modelled compost degradation as a function of oxygen level by the use of a Monod function. The parameters of the Monod function chosen by Haug (1993) give a halved degradation rate at approximately 2% O_2 whereas the parameters chosen by Stombaugh and Nokes (1996) give a halved degradation rate at approximately 5% O_2 in the compost gas. The model by Hamelers (1993) is much more sophisticated and models how oxygen diffuses into a thin liquid layer around a compost particle where an outside part of the core is aerobic and an inner part of the core may be anaerobic. The model by Hamelers predicts that three composting phases can be discerned during the composting process. In phase I, the number of microbes is the main rate limiting factor and is characterised by an increasing respiration. After this follows a phase II, in which the oxygen is the main rate limiting factor for a short period during which the degradation culminates. Then follows phase III, during which the hydrolysation of nutrients from the surface of the particles into their liquid surrounding layer becomes the main rate limiting factor. Phase III is characterised by a declining degradation.

In our experiments we also could discern three phases, but not exactly as described by Hamelers (1993). In the first phase characterised by mesophilic temperatures, the microbial growth was probably limited by low pH and/or the occurrence of fatty acids (Fig. 2., se also Fig. 5 and Fig. 6 in the Overall results and discussion). The second thermophilic phase was characterised by a high microbial activity after the pH shift and the disappearance of the organic short chain fatty acids at the end of the first phase. During this second phase, the carbon turnover rate was about halved in the experiment performed at 1% compared to the experiment at 16% O_2 in the compost gas during the first three days of the thermophilic phase. This result is in the range of Richard et al. (1999) but a little bit above what was predicted by parameters according to Haug (1993), Stombaugh and Nokes (1996). In all three experiments the turnover rate peaked just after the pH shift at the end of the mesophilic phase. After this second phase followed a third phase of declining activity where the limiting factor may have been the hydrolysation of nutrients as suggested by the model formulated by Hamelers (1993). The declining activity has an exponential-like shape and in Paper II a curve fit of an exponential function was performed and the results are presented in Table 2 of Paper II. The results from this curve fit should be regarded just as a test of how well an exponential function could be fitted within the time interval for the third phase in each experiment. When these functions were plotted, it was quite clear that they levelled out too fast and could not be used for any extrapolations, not even for the experiments to which they were fitted. Much more sophisticated and probably better models for this phase have been proposed by others, for instance by Kaiser (1996).

Influence of reduced oxygen levels on methane emission

Emission of CH_4 was detected during the thermophilic phase just after the maximum CO_2 peak in the experiments performed at reduced oxygen levels. The maximum rate of CH_4 emission in the experiment performed at 1% O_2 was almost three times the maximum CH_4 emission rate in the experiment performed at 2.5% O_2. Unfortunately the CH_4 emission was not analysed during the thermophilic phase in the experiment performed at 16% O_2. The emission of CH_4 during the thermophilic phase here may be interpreted as a strong indicator that anaerobic conditions existed, at least at some microsite level. According to the model by Hamelers (1993), there is an O_2 gradient over the liquid film surrounding the compost particles as soon as there is O_2 consumption and this often leads to anaerobic conditions in the inner parts of this liquid film. Furthermore, according to this model the worst anaerobic conditions should be expected when the microbial activity is at its maximum. According to Kroeker et al. (1979) the methane producing bacteria are hampered by organic short chain fatty acids and cannot be expected to be active before the short chain fatty acids are consumed. This is probably why we did not detect any CH_4 during the mesophilic phase. Our results confirm that aerobic and anaerobic conditions can coexist, leading to both high temperature, high aerobic activity and emission of CH_4, even when strong measures are taken to ensure uniform conditions in the compost matrix.

Influence of reduced oxygen levels on emission of ammonia

The emission of NH_3 followed more or less a similar pattern as in the experiments performed according to regime B at 16% O_2 in Paper II. Similarly, the volatilisation started after the pH shift at the end of the mesophilic phase at all three O_2 levels. One difference, however, was that the pattern of decrease in NH_3 volatilisation observed during Days 8-10 and attributed to immobilisation in Paper II was not observed in the experiments with the reduced oxygen levels. A possible explanation for this would be that since the biological activity measured as turnover of CO_2-C was lower, perhaps the immobilisation of NH_4^+-N to microbial N was not strong enough to give a decrease in the volatilisation of NH_3.

Emission of nitrous oxide

Similar amounts of N_2O as in the experiments performed at 16% O_2 were detected in the experiments performed at decreased O_2 levels.

Further improvements of the composting activity by mesophilic temperature control (Paper IV)

A compost reactor experiment on household waste was designed to test whether the degradation time could be further reduced by actively preventing the temperature from rising above a presumed inhibitory temperature just above 40°C until the pH had reached a certain value. A second aim was to determine whether the pH in the material could be monitored by pH in the condensed liquid as a suitable marker for ending the mesophilic temperature control. A third aim, on basis of the outcome, was to gain further understanding of the mechanisms behind the previously observed oscillating activity and mesophilic temperature. The experiment was performed by monitoring pH in the condensate from the cooled compost gas and a change to the thermophilic temperature 55°C was allowed when the pH increased above 5. The results from 3+3 runs with and without mesophilic temperature control below 40°C strongly confirmed our hypothesis and a reduction in the composting time of about 3 days was achieved. The abrupt rise in pH (either to above 5 in the condensate or to above 7 in the material) when the fatty acids are consumed seems to be a good marker of the point when temperature control can be discontinued and the temperature allowed to reach a thermophilic level without hampering the activity.

A probable explanation of the results is that the microbes active in the low pH phase were strongly hampered by temperatures above approximately 40°C depending on pH or occurrence of short chain fatty acids. At least two plausible scenarios for how this functioned can be discerned. Either (i) the thermophilic group of microbes in the compost material was sensitive to low pH (the mesophilic group is presumed to be sensitive to high temperatures by definition), or (ii) the main group of microbes that contributed to the measurable respiration was sensitive to the double or triple stress of low pH, high concentration of short chain fatty acids and high temperature.

The first alternative (i) is supported by Choi and Park (1998). They suggested a model where yeast is the main group of active microorganisms during the low pH phase. The yeast is able to consume the short chain fatty acids and thereby give way to growth of thermophilic bacteria. They composted household waste mixed with sawdust regulated at a temperature of 50°C in a laboratory scale compost reactor. They tested the effects of inoculation with their strain of yeast *Kluyveromyces marxianus* Y60, selected for its ability to grow at high temperatures. In a couple of experiments they detected an early growth and decay of yeast which seemed to coincide with the length of the low pH phase. In another experiment, where the microorganisms failed to grow normally during the low pH phase, after 8 days they inoculated with their strain of yeast selected for its ability to grow at high temperatures. This seemed to have led to an immediate reduction in the acidity expressed as equivalent weight % of lactic acid in the material. This in turn resulted in an increase in pH and the numbers of thermophilic bacteria. They also supported their model by experiments showing that yeast, or at least their specially selected strain of yeast, grew well at pH 4.7 and 48°C and reduced the acidity in a medium. On the other hand, a simultaneously inoculated strain of the thermophilic bacteria *Bacillus* sp. B77 lost its viability under the low pH conditions until the acidity was reduced to 0. The viability was then regained.

Others have done similar experiments. Nakasaki et al. (1996) showed that inoculation of the lactic acid tolerant and thermophilic *Bacillus licheniformis* in a laboratory scale compost reactor regulated at 60°C could shorten the low pH phase (this is also discussed in Paper IV).

Theoretically, however, in a compost system without the removal of heat, the heat generated from the activity of the microorganisms will cause the temperature to rise until it becomes rate limiting. Hence, the inoculation of a high temperature and low pH resistant microorganism per se will not eliminate the need for temperature regulation as such, but may affect the level at which it is adequate to regulate the temperature. This depends on whether the inoculated microorganisms are sufficiently competitive.

Overall results and discussion (Papers I to IV)

The results in the studies in Papers I to IV have several implications for full scale composting process management. Low pH conditions are quite common in household wastes (Poincelot, 1974; Kirchmann and Widen, 1994; Andersson, 2001). The regime A in Paper II in which the compost material was artificially warmed up to 55°C showed that if compost material is warmed up too quickly during the low pH phase, there may be severe problems in starting the degradation process. This may also apply in large scale composting and may endure for a long time. Since compost material in itself is a rather good insulation material, once the temperature has come up in a large compost heap, the only practical way to get it down again is probably by appropriate ventilation. If naturally ventilated, this in turn requires proper structure of the material and proper size and shape of the windrows. If ventilated by forced air, appropriate regulation and distribution of the air into the biomass is necessary. Another possibility, at least in theory, would be to have cooling coils densely placed in the material. This implies that in large scale composting of household waste, the temperature may increase rapidly until the process is hampered to a degree where the material gets more or less preserved for a long time instead of being degraded. This will occur if the material has a tendency to have a low pH at the start of composting and is being composted without proper temperature control or ventilation.

In Paper IV, it was shown that a mesophilic temperature control below 40°C during the initial thermophilic and low pH phase clearly enhanced and shortened the establishment of a very high degradation rate early in the process and shortened the low pH phase. This strategy of using temperature control should often be an attractive alternative to other methods of pH control in large scale composting. Other alternatives may include pH measurements and amendment with extra material for pH adjustment. Measurements of pH are more expensive and difficult to handle than temperature measurements. Amendment using pH adjusting material means extra handling and costs. It may, however, not be easy to implement such a fast process in large scale composting. Similarly to the case in our laboratory scale reactor, substantial drying of the material will be the result of the necessary ventilation and heat generation. Therefore some kind of moisture control, i.e. the ability to add back water to the material, will be needed. An alternative solution, if the compost off-gas is cooled, is to have some kind of system to recirculate condensate from the cooler into the compost material.

Cooling the off-gas will generate other possible advantages. It is probably the most practical way to recover the energy from the compost. A lot of energy is generated during composting which could be utilised for various heating purposes. Cooling the off-gas will also have the result that the ammonia is to a large extent captured in the condensate. More than 85% of the ammonia was captured in the condensate during our experiments (Paper II). How to utilise this ammonia may be a topic for future research. Probably some of the N_2O and possibly some of the odorous emissions will also be caught in the condensate. The condensate generated in a cooler also offers the possibility of measuring its pH to determine when the low pH phase is over and when to start a thermophilic regulation of a compost process such as the one described in Paper IV, regime II.

A somewhat different perspective on the experiments performed in this thesis is obtained if the results are regarded from a scale of degraded material rather than a time scale. In Figs. 5 and 6, the data are plotted versus degree of degradation. Three phases of the compost process can be discerned here, independent of the strategies chosen for regulation of temperature and O_2 levels. These phases seem to occur at about the same levels of degradation. The first mesophilic or low pH phase occurs in the interval 0-10% degraded carbon. A phase characterised by a high and peak-forming activity occurs in the interval 10-30% degraded carbon. A last phase characterised by a declining activity occurs after about 30% of the initial carbon is degraded.

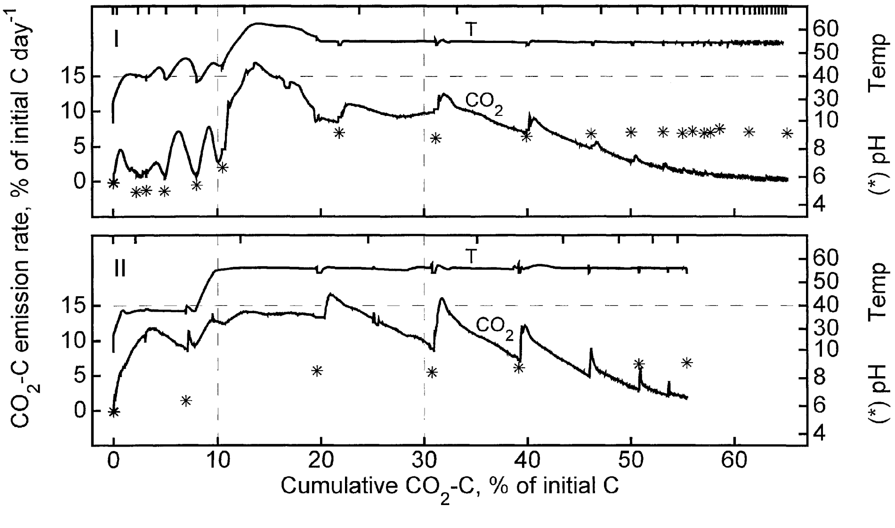

Figure 5. Examples of, from top to bottom, temperature, rate of turnover and pH (*) plotted versus degree of turnover for strategies I (the above stripe plot) and II (the lower stripe plot) in Paper IV. The turnover rate, as emitted CO_2-C in % of initial C day^{-1}, is indicated on the left vertical axis. pH 4-10 and temperature 30-60°C are indicated on the right vertical axis. The degree of turnover as cumulative C in % of initial C is indicated on the bottom horizontal axis. The time evolution is indicated as tick marks representing the start of each new day 1-30 and 1-9 at the top edge of the regime I and regime II stripe plot respectively.

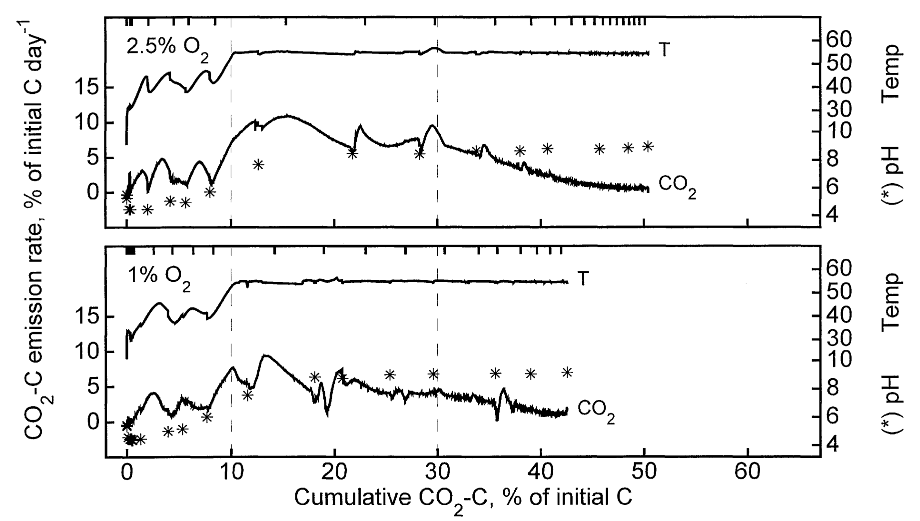

Figure 6. Examples of, from top to bottom, temperature, rate of turnover and pH (*) plotted versus degree of turnover for the experiments conducted at the reduced oxygen levels 2.5 (the above stripe plot) and 1% (the lower stripe plot), Paper III. The turnover rate, as emitted CO_2-C in % of initial C day^{-1}, is indicated on the left vertical axis. pH 4-10 and temperature 30-60°C are indicated on the right vertical axis. The degree of turnover as cumulative C in % of initial C is indicated on the bottom horizontal axis. The time evolution is indicated as tick marks representing the start of each new day 1-25 and 1-24 at the top edge of the 2.5% and the 1% O_2 stripe plot respectively.

The calculated mean degradation rates in the interval 10-30% degraded carbon for the regimes B and C in this thesis are given in Table 3.

Table 3. Mean degradation rates as % CO_2-C day^{-1} during the time interval when 10-30% of the initial carbon was degraded to CO_2 and their underlying number of replicates, n

Temp. regime	**O_2 regulated at:** **16%**		**2.5%**		**1%**	
	Rate	n	Rate	n	Rate	n
B	10.2	2*	7.5	1	4.4	1
C	11.7	3	-	-	-	-

*One of the three experiments was excluded due to technical problems during the experiment.

These results show that there is probably not much to gain from aeration rates resulting in higher O_2 contents higher than about 5% of the compost gas under the condition that the ventilation throughout the compost material is well distributed.

It should be mentioned here that in this thesis we only tested the concept of temperature control during the initial phase of low pH and the effect of low oxygen conditions during at most one month of composting. No attempts were made to find the optimal conditions of e.g. temperature and pH levels. Others have shown that similar results during the low pH phase can be obtained by liming

(Nakasaki et al., 1993) or by the use of special microbial inoculants (Nakasaki et al., 1996) in combination with temperature control. There may also be other methods to increase the pH value in the material. For instance, the pH can be increased by reuse of composted material at high pH together with other fresh raw ingredients of the compost material. However, this was beyond the scope of this thesis.

Areas for future studies include optimisation of temperature after the mesophilic or low pH phase concerning degradation rate; further studies on the emissions of greenhouse gases; and the effects of particle size and moisture.

Summary of Papers I to IV

In Paper I the reactor, its equipment and the routines for regulation and measurements of various parameters are described. The results presented show that the performance of the reactor concerning uniform regulation of temperature and O_2 level in the compost matrix, gas and over time was good. The performance concerning moisture control did not meet the same high standard as the control of temperature and O_2 level but was considered to be acceptable. In Paper II, experiments were performed which showed that the composting of household waste was inhibited if the temperature was raised too quickly. The results obtained from a second temperature control regime showed a much higher degradation if the compost material was allowed to generate its own heat and go through a mesophilic phase. The results further indicated that the length of the mesophilic low pH phase was determined by the presence of organic short chain fatty acids, which in their turn were correlated to the pH level. An oscillating behaviour of temperature and respiration was observed during the mesophilic phase. This could possibly be explained by inhibition of the microbial activity by temperatures above about 40°C in combination with low pH and/or occurrence of organic short chain fatty acids. If this was true, an increased microbial activity would be expected if the temperature was prevented from increasing above a critical point. This was tested in Paper IV and a drastically increased activity, which shortened the low pH phase, confirmed the hypothesis. In Paper III, composting experiments on household waste under low oxygen conditions were performed. The results showed that thermophilic composting could be carried out at a not much less than halved degradation rate under as low O_2 levels as 1% in the compost gas. Reduced oxygen levels enhanced the early production of organic short chain fatty acids during the mesophilic phase, a later production of methane during the thermophilic phase and prolonged the mesophilic phase.

Conclusions

The major conclusions of this work are:

- High temperatures above approximately 40°C may result in a strong inhibition of the degradation in composting during an initial phase if low pH and/or organic short chain fatty acids are present in the material.
- A regulation of the composting temperature to <40°C during an initial low pH phase can increase the degradation rate and decrease the time for composting.
- The presence of organic short chain fatty acids may be a key factor which keeps the pH down during the initial phase in composting of organic household waste.
- An early increase in fatty acids in the material during an initial phase of household waste composting may be enhanced by low oxygen conditions, resulting in a prolonged low pH phase.
- The cooling of the compost gas may be a method to regain energy and reduce emissions of NH_3 in particular, but perhaps also of N_2O and odorous compounds. The condensate from the cooler can be utilised for measurment of pH in order to decide when to change from mesophilic to thermophilic temperature control.

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