Food waste composting – effects of heat, acids and size

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Abstract

The objective of this thesis was to increase our knowledge of issues relevant to process problems in large-scale composting. The investigations focused on acid-related process inhibition and the relationships between temperature, aeration, evaporation and the scale of the process.

Three manuscripts are summarised in the thesis proper. The first investigated composting at different scales; at full-scale, in a 2 m high reactor and in a one-litre vessel. The process in the reactor resembled the full-scale process, but the theoretical calculations showed that the heat losses from the reactor were large. About 0.45 m of glass wool would be necessary to produce similar thermal properties in the reactor as in the full scale plant.

Accumulation of acids was studied in the second investigation. Different amounts of active compost were used as a starting culture in rotating three-litre reactors, which were fed daily with fresh waste and water. In reactors with a large amount of starting culture, more than four times the daily feed, a well-functioning process with high temperature, high CO_2 production and high pH was established. In reactors with a starting culture less than twice the daily feed, the composting process failed. The temperature was below 42 °C and the CO_2 production was small. In these reactors the pH was low and organic acids accumulated. It was concluded that acid inhibition of fed-batch processes can be avoided if sufficient amounts of a good starting culture are used.

In the third investigation, the combined effects of temperature and pH on the degradation were studied. Small samples of compost from the initial acidic phase were treated with sodium hydroxide to raise the pH. This resulted in high respiratory activity in samples at all pH levels at 36 °C and in those with pH over 6.5 at 46 °C. However, at 46 °C the activity was very low in samples with pH below 6.0. This shows that a combination of high temperature and low pH can inhibit the composting process.

The influence of the composting temperature on the evaporation was also analysed. Simulations showed that the difference in evaporation at different temperatures was very small for the same degradation, although there were large variations in airflow. Finally, addition of water to compost is discussed. It is often necessary to add water when composting energy-rich substrates, since otherwise the process may be halted due to drying before the compost has stabilised.

Keywords: carbon dioxide, decomposition, energy, fatty acids, mesophilic, organic waste, temperature, thermophilic

Sammanfattning

Kompostering av matavfall – effekter av värme, syror och storlek

Syftet med arbetet var att öka kunskapen om frågor av relevans för processproblem i storskaliga komposteringsanläggningar. Arbetet har fokuserats på syra-relaterade processtörningar sambandet mellan temperatur, luftning, avdunstning och processkala. I en litteraturstudie rapporteras om pH-utvecklingen i en komposteringsprocess – bildningen av organiska syror och de problem som de kan orsaka i komposteringsprocessen. Vidare beskrivs värmeutvecklingen i och värmespridningen från processen. Den mesta värmen avgår normalt genom avdunstning, vilket kan leda till för tidig uttorkning av komposten. Vissa komposteringstekniker beskrivs också– återanvändning av kompost i processen, statisk kompostering och kontinuerlig kompostering.

Tre studier finns som bilagor och sammanfattas i rapporten. Den första behandlar kompostering i olika skalor, i full skala, i en 2 m hög reaktor och i ett enliterskärl. I reaktorn lyckades vi delvis efterlikna den storskaliga processen, även om teoretiska beräkningar visade att värmeavgången från reaktorn varit stor jämfört med den storskaliga processen. Betydligt mer isolering, 45 cm glasull, hade varit nödvändigt för att få termiska egenskaper motsvarande dem i fullskaleanläggningen.

I den andra studien undersöktes syrabildning vid kontinuerlig kompostering av restaurangavfall. Olika mängd aktiv kompost användes som startkultur i roterande trelitersreaktorer som dagligen tillfördes färskt avfall och vatten. I reaktorer med mycket startkultur, mer än fyra gånger den dagliga tillsatsen, utvecklades en väl fungerande aktiv process med hög temperatur, hög nedbrytningshastighet och högt pH. I reaktorer med lite startkultur, mindre än dubbelt så mycket som den dagliga tillsatsen, utvecklades ingen fungerande komposteringsprocess. Där var temperaturen låg (under 42°C) och nedbrytningen liten. I dessa reaktorer var pH lågt och organiska syror ansamlades. Slutsatsen av studien var att tillräcklig mängd av en bra startkultur kan förhindra att kompostprocessen hämmas av bildade syror.

I den tredje studien studerades den kombinerade effekten av pH och temperatur på nedbrytningen. Små prover av kompost från den inledande sura fasen behandlades med natriumhydroxid för att höja pH. Resultatet blev att hög nedbrytningsaktivitet uppmättes både vid 36 °C vid alla pH och vid 46 °C då pH var över 6.5. Vid 46 °C och pH under 6.0 var aktiviteten däremot mycket låg. Kombinationen av lågt pH och hög temperatur verkar alltså hämmande på nedbrytningsprocessen.

I rapporten diskuteras också komposteringstemperaturens betydelse för avdunstningen. Simuleringar visade att skillnaden i avdunstning vid olika komposteringstemperaturer är mycket liten, trots att luftmängden varierar mycket. Slutligen diskuteras behovet av vattentillsats vid kompostering. Vid kompostering av energirikt avfall är det ofta nödvändigt att tillföra vatten eftersom processen annars avstannar på grund av uttorkning innan komposten har stabiliserats.

Contents

Appendix

Paper I-III

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

I. Sundberg, C., Jönsson, H., 2003. Down-scaling a large composting plant to pilot-scale for systematic research. In: Pullammanappallil, P., McComb, A., Diaz, L., Bidlingmaier, W. (Eds.), Proceedings of the 4th International Conference of Orbit Association on Biological Processing of Organics. Perth, Australia. vol 1, pp. 388-397.

II. Sundberg, C., Jönsson, H., 2003. Process inhibition due to organic acids in fed-batch composting of food waste – influence of starting culture. Manuscript.

III. Sundberg, C., Jönsson, H., Smårs S. Low pH as an inhibiting factor in the transition from mesophilic to thermophilic phase in composting. Submitted to Bioresource Technology.

Paper I is reproduced with permission of the ORBIT Association.

Notes on the authorship of the papers:

In Paper I, Jönsson and Sundberg planned the investigation. Sundberg performed the experiments, the calculations and the writing, with revisions by Jönsson.

In Paper II, Jönsson and Sundberg planned the investigation. Sundberg performed the experiments, the analysis of the results and the writing, with revisions by Jönsson.

Paper III was planned by Smårs, Sundberg and Jönsson. The experiments were performed by Sundberg and Smårs. Sundberg performed the statistical analysis and the writing, with input from Jönsson.

Background

Organic waste is not only the result of human activity. Since the beginning of life on earth, living organisms have produced waste, and other organisms have used that waste by utilising the energy and nutrients it contains. Recycling of organic waste is thus an integrated function of any ecosystem. Composting is a process in which the naturally occurring ability of organisms to recycle organic waste is used for the benefit of humans in an accelerated degradation of organic waste. With increased understanding of how this process works, we can control it better and make it work more efficiently according to our requirements.

In this work, the effort to understand and control the composting process sets off from the present status of waste management in Sweden, and from the previous composting research at SLU. Swedish municipal solid waste management is in a process of transition whereby landfilling of organic waste is being reduced, and will be banned from 2005. Several other waste treatment process are increasing, especially incineration, composting and anaerobic digestion. Source separation of biodegradable waste has been introduced in several cities in Sweden and in many countries in Europe. In Scandinavia the growing season is short, so during a large part of the year there is very little garden waste available and the collected biodegradable waste consists of food waste.

Knowledge about the composting process is limited, and therefore an increased research effort has been put into composting in recent years. A composting reactor built at SLU has been used for research on gaseous emissions and process dynamics (Beck-Friis, 2001; Smårs, 2002). A major finding of that work was that the start-up in batch composting could be inhibited by low pH in combination with high temperatures (Smårs, 2002). Results from research in a lab-scale composting reactor are not directly transferable to large-scale processes, and that issue was the starting point for the work reported in this thesis.

Objectives

The overall objective was to increase the knowledge on issues relevant to process problems in large-scale composting and this was done through theoretical and experimental investigations. A specific objective was to improve the understanding of acid-related process inhibition and methods for abatement of such inhibition. This was done through investigations of acids in fed-batch composting (Paper II), and the combined effects of pH and temperature in the initial phase of batch composting (Paper III). Another specific objective was to investigate the relationships between temperature, evaporative water losses and aeration in composting, as well as the thermal effects of composting at different scales (Paper I).

Literature and theory

This literature review contains a description of the composting process, emphasizing the complex interaction between the biology and physics of the process. Furthermore, there is a review of certain aspects of relevance to the present work, regarding low pH and organic acids; heat, air and water; and composting technology.

Introducing composting

Composting is a process that fulfils several waste management purposes: stabilisation, volume reduction and sanitation by thermal inactivation of pathogens. The aim of the stabilisation is to produce a material that does not putrefy, self-heat, deplete oxygen, produce odours or attract vermin. The compost product can be beneficial, supplying nutrients for plant growth, organic matter for soil improvement and agents for plant disease suppression.

Composting is environmentally preferable to landfilling (Sundqvist *et al.*, 2002). In spite of this, there are several environmental issues to consider in composting. Ammonia emissions can be large, and ammonia contributes to acidification and eutrophication. The greenhouse gases methane and nitrous oxide are normally formed during composting, although in small amounts (Beck-Friis, 2001). Composting can also produce odours, which can cause severe problems.

Composting is commonly described as aerobic degradation of organic wastes where heat is released in the oxygen-consuming microbial metabolism, resulting in increased temperature. A composting system is dynamic, with very intense biological activity. This causes the system to change its own environmental conditions. Most notable is the increasing temperature. Equally important is the consumption of oxygen and production of carbon dioxide. In an active compost, the oxygen in the pore space is consumed within minutes, so a continuous supply of fresh air is crucial for the process to remain aerobic.

Composting is a microbial process, and the overall performance of the composting process is therefore the combined effect of the activity of individual microorganisms. It is thus important to understand and control the environmental factors that affect microbial life in composts. The most important parameters for the microorganisms are temperature, oxygen, moisture, pH and substrate composition (Miller, 1993).

All living organisms need water, so moisture is essential for the function of the composting process. For the microorganisms there is no upper limit for the water content as such, but excessive moisture reduces the airspace in the compost matrix and thus causes oxygen limitation (Miller, 1993).

Based on their use of oxygen, microorganisms can be classified into three groups:

- obligate aerobes, microorganisms that require oxygen for survival.
- obligate anaerobes, microorganisms that cannot function in the presence of oxygen.

- facultative anaerobes, microorganisms that have both aerobic and anaerobic metabolism. Since aerobic metabolism renders more energy for the microorganisms, they grow faster when oxygen is present.

Heat is produced in aerobic decomposition of waste, which is a highly exothermic process. The heat produced can either remain in the compost mass, resulting in an increased temperature, or leave it either by conduction or radiation from the surface, or with the air passing through it.

The elevated temperature during composting is not only caused by the microorganisms, it also determines their activity. Each microbial species can only grow within a certain temperature range, and most microorganisms are killed by too high temperatures. Mesophilic microorganisms are active up to 40-45 °C, while thermophilic organisms have optimum temperatures above that. The temperature for maximum degradation rate in composting is normally near 55 °C, and the degradation rate is much lower at 70 °C (Miller, 1993).

The pH value changes during composting, due to changes in the chemical composition. In general, the pH falls below neutral in the beginning due to the formation of organic acids and later rises above neutral because the acids are consumed and because ammonia is released (Beck-Friis *et al.*, 2003).

Substrate and amendment are two terms that are commonly used in composting. From a technical point of view, substrate normally refers to the wastes that are the primary objective of the operation, and an amendment is any compound that is added to improve the process, structurally, biologically or chemically. Most biological material can be composted. Depending on the composition of substrates and amendments, the composting process will be faster or slower, and composting will be easy or more problematic. Four characteristics of the substrate are of primary importance to the process: energy, nutrients, water and structure. Energy, nutrients and water are needed for microbial growth, and structure is essential for the aeration, which supplies oxygen and cools the compost.

Many composting systems have been used for treatment of different wastes under different conditions. Common systems are (i) naturally aerated windrow system - long rows with a triangular cross section, (ii) forced aeration static pile systems, (iii) tunnel systems – closed rotating cylinders, and (iv) smaller scale static or rotating composts. There are in principle two different ways to perform composting; as a batch system or a fed system. In batch systems, a batch of waste is prepared and composted separately from other batches to a final product. In fed systems, fresh substrate is intermittently added and mixed with the active compost. Fed systems are often called fed-batch or continuous, but there is no consistent terminology within this field.

In this text the batch process is classified into three phases, based on process dynamics and inspired by the works of Smårs (2002) and Hamelers (2001). The phases are (A) the initial phase, (B) the high-rate phase and (C) the curing phase (Figure 1). Apart from the particle size, temperature, and moisture, which affect the degradation rate in all phases, there are certain parameters that are more important in each phase. Microbial biomass growth is limiting in the initial phase, often in combination with low pH. The initial phase is characterised by rising temperature and increasing CO_2 production. The time of the initial phase can range from less than a day to a few weeks. The next phase is the high-rate phase, when neither microbial biomass, substrate availability nor low pH is rate-limiting. This phase is normally thermophilic, and one rate-limiting factor is oxygen diffusion into the solid-liquid compost particles. The time-span of the high-rate phase ranges from a few days to several months. In the later phase, the readily available substrate is depleted while the microbial biomass is still large, so the substrate availability is rate-limiting. The CO_2 production declines and the temperature may also decline.

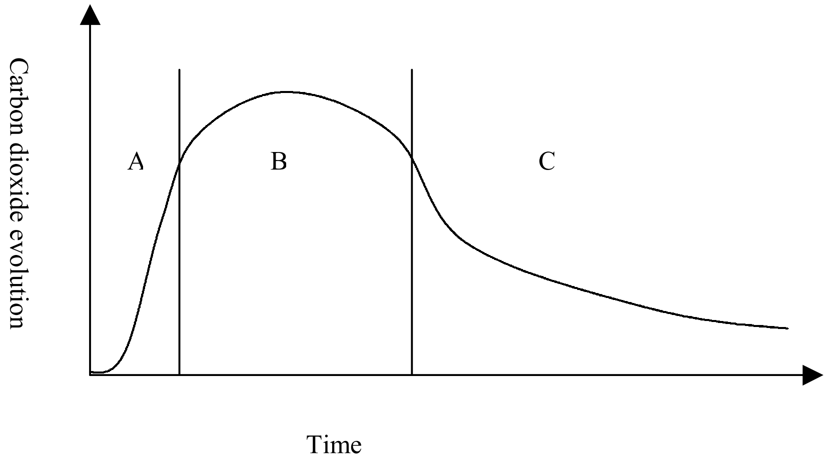

Figure 1. A schematic representation of the different phases of the composting process. A – initial phase, B – high-rate phase, C – curing phase. This is not a figure of a real process and the axes are not to scale.

Increased computational power has made it feasible to use mathematical models of the composting process, which can improve understanding and reduce the need for costly experimentation. Many mathematical models of the composting process have been presented (Finger, Hatch & Regan, 1976; Whang & Meenaghan, 1980; Moreno, 1982; Bach *et al.*, 1987; Nakasaki *et al.*, 1987; Haug, 1993; Keener *et al.*, 1993; van Lier *et al.*, 1994; Kaiser, 1996; Stombaugh & Nokes, 1996; VanderGheynst, Walker & Parlange, 1997; Mohee, White & Das, 1998; Bari, Koenig & Guihe, 2000; Hamelers, 2001; Higgins & Walker, 2001; Mysliwiec *et al.*, 2001; Seki, 2002). Mass and heat balances form the core of most models. These balances are combined with kinetic equations on degradation rates to predict changes in temperature, moisture and oxygen consumption. The mechanisms of energy and mass transfer are well known and similar in most models, but the mathematical description of the kinetics of degradation differs between models.

Facing low pH – the acidic phase

The pH in composts is influenced by three acid-base systems. One is the carbonic system, with carbon dioxide (CO_2) that is formed during decomposition and can escape as a gas or dissolve in the liquid, forming carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). This system has two dissociation constants (pK_a), 6.35 and 10.33 at 25 °C, and thus it tends to neutralise the pH of the compost, increasing low pH and reducing high pH. The second system is ammonium (NH_4^+) – ammonia (NH_3), which is formed when protein is decomposed. During the initial phase of composting most of the metabolised nitrogen is retained by growing microorganisms, but during the high-rate phase ammonia is released. The ammonia system has a pK_a of 9.24 at 25 °C and thus increases the pH towards this value. The third system is composed of several organic acids, of which acetic and lactic acid dominate. This system can reduce pH down to 4.14, which is the pK_a of lactic acid at 25 °C (Weast *et al.*, 1989-1990), and it is important in the beginning of composting as is described below. These three systems combine to form the typical pH curve for batch composting, with initially falling pH and a sharp rise during high-rate degradation (Figure 2).

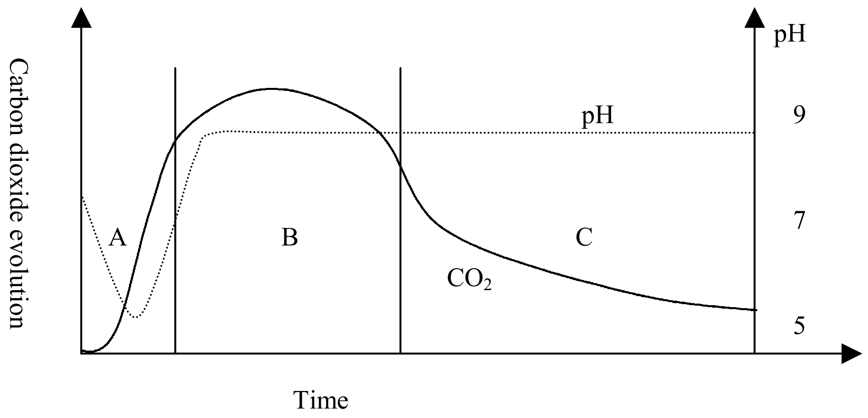

Figure 2. A representation of a typical pH curve in a batch composting process. The pH falls initially, and the start of the high-rate phase coincides with a rise in pH. A – initial phase, B – high-rate phase, C – curing phase.

Organic acids are formed during fermentation of organic matter. There are several metabolic pathways for acid production. One is fermentation by anaerobic microorganisms. Acetic acid is the main product of such processes, but longer-chained acids such as butyric or propionic acid are also formed. Another important organic acid found in composts is lactic acid, which is formed by lactic acid bacteria, a group of facultative anaerobes (Brock & T, 1988). Acetic acid is mainly produced anaerobically, but it can also be produced when oxygen is present, *e.g.* when *E. coli* is subject to high concentrations of glucose (Enfors & Häggström, 2000). The bacteria take up more glucose than they can oxidize aerobically and acetate is formed in what is called the overflow metabolic pathway.

Organic acids are not only formed in composts, they are also decomposed. Most microorganisms can utilise organic acids as a readily available substrate for aerobic oxidation. The acid concentration in composts is therefore influenced both by production and consumption of the acids.

Organic acids are suppressive to microbial activity and growth at low pH (Cherrington *et al.*, 1991). Different microorganisms have different sensitivity to organic acids. Generally, bacteria are more sensitive to acids than fungi (Atlas & Bartha, 1998). The acids interfere with cellular functions of the organisms. The acids can enter the cell when they are in their undissociated form, *i.e.* when the pH is low. The negative effect of organic acids on microbial activity is thus strongly dependent on the pH of the medium. The acids themselves reduce the pH, but in composts the pH is also influenced by the carbonic and ammonia systems. Acid concentration and pH are therefore connected and both influence the toxic effect of organic acids.

In municipal solid waste, acetic and lactic acids are produced during storage, and in source-separated organic waste, these acids can reduce the pH to 4-5 (Eklind *et al.*, 1997). During the initial phase of batch composting, reduced pH and high concentrations of organic acids can occur (Beck-Friis *et al.*, 2003). During successful composting, the acids are decomposed and pH increases. Compared to well-aerated composting, composting at low oxygen levels results in a larger acid production and a slower break-down of acids (Beck-Friis *et al.*, 2003). The initial period of low pH can be significantly reduced if the temperature in the compost stays below 40 °C until pH rises (Smårs *et al.*, 2002).

The heat machine

During aerobic decomposition of organic substances, the chemical energy in the material is either released as heat or used for the construction of new substances within the organisms consuming the organic material. A large proportion is released as heat, which can be quantified either calorimetrically or through indirect methods. Weppen (2001) calorimetrically measured a heat release of 15-19 kJ/g decomposed matter from composting organic waste amended with wood chips or straw. In experiments spiked with fat this value increased to 22-25 kJ/g, and the average from all experiments was 20.7±2.9 kJ/g, or 452±29 kJ/mol oxygen consumed. The energy release can be expressed in relation to the consumption of either substrate or oxygen and the latter shows less variation between different substrates (Haug, 1993). Indirect methods to estimate the heat released during aerobic decomposition use information on substrate composition or oxygen consumption. If the chemical composition of the substance is known, the heat release can be calculated from the proportions of carbohydrates, lipids and proteins. The heat release can also be calculated from the oxygen consumption. The heat of combustion per electron transferred to a methane-type bond is relatively constant, giving 110 kJ/mol e^- (Weppen, 2001). Formulae have also been suggested based on the content of C, O, H, N and S in the material (Haug, 1993).

The heat produced during decomposition can either remain in the compost mass, or leave it. Both mass and energy are conserved, so balances can be set up. These physical processes in a composting system are well known and several models have been presented. The major difference between them is that some models are lumped (Bach *et al.*, 1987; Haug, 1993) whereas others include spatial variations (Stombaugh & Nokes, 1996; Bari & Koenig, 2000; Seki, 2002).

The energy, Q_s, for heating of the composting mass, is calculated as:

$$Q_s = \Delta T\left(c_{pw} \cdot m_w + c_{ps} \cdot m_s\right) \tag{1}$$

where ΔT is the temperature change, m_w and m_s are the masses of water and solids, and c_{pw} and c_{ps} their respective specific heat capacities (Bach *et al.*, 1987). The heat capacity of water, $c_{pw} = 4.2\ \mathrm{J\ g^{-1}\ °C^{-1}}$, is well known whereas c_{ps} depends on the solids composition, but it is normally in the range 0.5-2.0 $\mathrm{J\ g^{-1}\ °C^{-1}}$. In all calculations in this report, a literature value of 1.2 $\mathrm{J\ g^{-1}\ °C^{-1}}$ is used (Bach *et al.*, 1987).

If all the energy released during decomposition were to remain in the compost, the temperature would rapidly rise above the maximum temperature of microbial survival. The 15-20 kJ that are released from the decomposition of 1 g of organic matter are enough to heat 35-50 g of water by 100°C. It is thus obvious that most of the heat produced during degradation must leave the compost mass in some way, either by conduction or radiation from the surface or with the air passing through it. The conductive surface losses, Q_l, are calculated as:

$$Q_l = U \cdot A \cdot (T - T_o) \cdot \Delta t \qquad (2)$$

where U is the heat transfer coefficient, A is the surface area, T is the system temperature and T_o is the outside temperature and t is time (Bach *et al.*, 1987). Surface cooling by conduction is important in small-scale composting (Weppen, 2001). In small composts, up to a few cubic metres, insulation is therefore often needed to obtain the elevated temperatures required for sanitation. Larger composts have a larger volume-to-surface ratio, so surface cooling is smaller. The effect of surface cooling is further limited by the low thermal conductivity of composts (Haug, 1993) which implies that large temperature differences can be maintained over short distances (Beck-Friis *et al.*, 2000). When surface cooling is limited, the major heat transfer process is by airflow. Both sensible heating of dry air and latent heat from water evaporation account for this heat transport. The water carrying capacity of air increases exponentially with temperature, and therefore the evaporative cooling capacity per volume of air is larger at higher temperatures. The heat removal by heating of dry air, Q_a, is calculated as:

$$Q_a = c_{pa} \cdot m_a \cdot (T_{out} - T_{in}) \qquad (3)$$

Where c_{pa} is the specific heat of dry air, m_a is the mass of the air, and T_{in} and T_{out} are the input and output air temperatures. Changes in mass and specific heat capacity of the dry air occur due to the consumption of oxygen and production of carbon dioxide. These small changes are neglected in Equation 3.

Evaporation of water removes heat, Q_w, from the compost according to:

$$Q_w = c_{pe} \cdot m_{e,in} \cdot (T_{out} - T_{in}) + \Delta H_{vap} \cdot (m_{e,out} - m_{e,in}) \qquad (4)$$

where c_{pe} is the specific heat of steam, $m_{e,in}$ and $m_{e,out}$ represent the mass of steam in the incoming and outgoing air, and ΔH_{vap} is the enthalpy of evaporation at T_{out}.

The thermal characteristics of compost reactors are normally quite different from those of large-scale facilities, which is explained by the difference in surface-to-volume ratio between laboratory and full-scale composts. Weppen (2001) and Bach *et al.* (1987) reported that 60% of the heat was conducted from their reactor surfaces even though they were well insulated, while it was found that in large-scale reactors, 4-11% of the heat dissipated through surface and walls, while the rest was transported with the air. In reactor studies, the surface losses can be minimised by keeping the reactors in a closed chamber where the conductive heat flow can be controlled (Hogan, Miller & Finstein, 1989).

The dilemma of air and water

Aerobic microorganisms require both oxygen and water. Since water is a liquid and oxygen is gaseous, there are obvious problems with achieving a balance between good moisture and oxygen conditions in compost. The relation between solids, liquids and gas in the composting matrix is important for this balance. A useful conceptual model of the compost matrix involves particles of solid and liquid that are surrounded by a connected gas-filled pore space (Figure 3). Since the oxygen is consumed and carbon dioxide is produced, the gas needs to be continuously replenished. In the gas-filled pores in composts the oxygen transport is dominated by mass-flow, whereas in the liquid films on the compost particles the oxygen is transported by diffusion. Diffusional transport is slow and it is the limiting process in the oxygen supply of well-aerated composts (Hamelers, 2001). Since microorganisms consume a lot of oxygen, only a thin outer layer of each compost particle will be aerobic during the active stages. At low concentrations of oxygen, a few per cent or less in the composting gas, the process rate is highly influenced by changes in the oxygen concentrations, but this influence is less pronounced at higher oxygen concentrations. For example, during the first two weeks of composting in a reactor there was a larger difference between the process rate at 1% and 2.5% O_2 than between 2.5% and 16 % O_2 (Beck-Friis *et al.*, 2003).

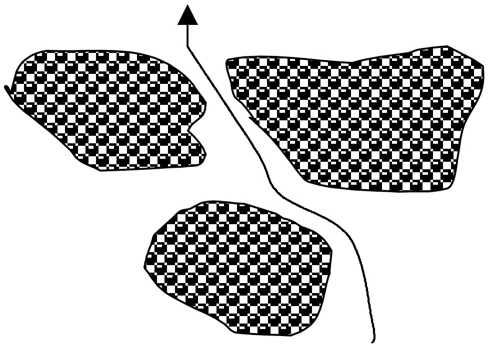

Figure 3. Schematic representation of compost particles. The gas is transported by mass flow (arrows). The solid components (substrate, microbial biomass and inert matter) form a matrix in which the pore-space is water-filled. The water in the outer part of the particles contains dissolved oxygen, whereas the inner part is anaerobic during active composting. Adapted from Hamelers, 2001.

The balance between water and oxygen is further complicated by the fact that the gas removes water from the compost, as water evaporates. Evaporation is the major means of cooling, and it is not possible to maintain the same moisture content over long periods of time. The relative humidity in an active compost is always near 100% due to the high water content and large surface area in the compost matrix. The relative humidity of the gas passing through compost increases as the gas is heated and water evaporates from the compost. In large composts evaporation is a major mechanism in compost cooling. The 20 kJ produced by 1 g of decomposed matter is equivalent to the heat of vaporisation of 10 g of water. Therefore the evaporation due to heat has the capacity to dry the compost significantly, even though about 0.5 g of water is produced when 1 g of organic matter is decomposed. The aeration needed for cooling the compost is usually larger than the aeration needed for oxygen supply.

Drying of the substrate is often a key objective of composting (Nakasaki *et al.*, 1987; Choi, Richard & Ahn, 2001). In household waste composting, the waste normally has a solids content of 30-60% and the concentration of readily available substrate is high. This makes the compost susceptible to high temperatures and excessive drying. In fact, water addition can often speed up the composting process (Walker *et al.*, 1999).

Searching for solutions

The previous sections have introduced important aspects that affect the turnover in composting processes. Acids can inhibit the process in the initial phase when there are high concentrations of easily available substrate, and when the temperature increases rapidly to thermophilic levels. Another cause of process inhibition is excess heat in large-scale processes, where aeration is the major means of cooling. This aeration dries the process; sometimes to the extent that microbial activity is limited by lack of moisture. In this section, certain key issues relevant to the alleviation of process inhibitions in composting are presented. They relate to specific composting configurations, substrate mixture and amendments.

Static pile composting

In forced aeration static pile systems, the waste is piled on top of an aeration system that forces air through the composting mass. The height of the piles are normally within the range of 1-3 m during high-rate decomposition. These composts can be out in the open, enclosed in buildings or under textile covers. In the case of closed systems, the off-gases can be collected and treated to reduce odours and other pollutants. Since the systems are aerated by fans, process control through variation of the aeration rate is possible.

Static-pile research reactors are often only scaled down in the directions perpendicular to airflow, in order to obtain the same gradients in temperature, oxygen and moisture that develop in the direction of airflow in the large-scale process. These dimensions are often scaled down to 30-60 cm (VanderGheynst, Gossett & Walker, 1997; Bari & Koenig, 2001; Cabanas-Vargas & Stentiford, 2001). Such static pile research reactors have normally been insulated with *e.g.* 50 mm expanded polystyrene (Cabanas-Vargas & Stentiford, 2001), 100 mm polyurethane (Bari & Koenig, 2001) or 12.7 mm foam insulation (VanderGheynst, Gossett & Walker, 1997). In one case, the heat loss from evaporation was estimated to be 53%, but the heat loss from conduction was not reported separately (Bari & Koenig, 2001). In other cases, heat losses have not been reported at all, and the results have not been compared with results from full-scale composts.

Effects of aeration have been investigated in reactors and full-scale systems with upflow and downflow, air recirculation (Bari & Koenig, 2001), alternating flows (Moreno, 1982; Sesay, Lasaridi & Stentiford, 1998), temperature feedback control

(Sesay, Lasaridi & Stentiford, 1998; Bari & Koenig, 2001) and carbon dioxide feedback control (Moreno, 1982). More uniform temperature conditions were achieved with air recirculation (Bari & Koenig, 2001) and alternating upflow-downflow aeration (Sesay, Lasaridi & Stentiford, 1998). Reduced decomposition due to drying of the material in the lower portion of the pile, at high upflow aeration rates, has been reported (Moreno, 1982; VanderGheynst, Gossett & Walker, 1997).

Fed-batch composting

Fed-batch composting has not been as extensively investigated as batch composting, although some work was documented more than 30 years ago (Schulze, 1962; Jeris & Regan, 1973). In recent years, interest in continuous composting has increased, especially in Asia (Nakasaki, Akakura & Atsumi, 1998; Hwang, Shin & Tay, 2002). This is connected to an increased use of decentralised composting machines, used mainly for food waste in households and restaurants, and the reported experiments have therefore been carried out on food waste, either real (Hwang, Shin & Tay, 2002) or artificial (dog food) (Nakasaki, Akakura & Atsumi, 1998). Feeding of the compost was in both those cases made on a daily basis. A peak in CO_2 evolution rate was noted daily shortly after waste addition, indicating a rapid degradation of the easily degradable matter in the waste. Conditions of low pH during heavily loaded fed-batch composting was noticed by Schulze (1962). Low pH during a period of low microbial activity and declining temperature was also observed by Hwang Shin & Tay. (2002). The daily feed rates in fed-batch composting research have been about 10 % of the starting culture (Nakasaki, Akakura & Atsumi, 1998; Hwang, Shin & Tay, 2002) or 8.4-18.3% (Schulze, 1962).

Substrate, amendments and recycle

Food wastes are increasingly being composted in Europe, as well as in other parts of the world. This waste is normally mixed with green waste from gardens and parks, which gives a good structure and a well-balanced concentration of rapidly degrading organic waste. In Scandinavia, however, the growing season is short, so during a large part of the year there is very little garden waste available and the collected waste consists of food waste. Compared to a biowaste with more green material, this waste has a higher concentration of easily degraded matter, and a poorer structure. This waste also has a lower pH, and during the winter months it is very cold. All these factors contribute to start-up problems during composting.

Compost recycle is available at any compost facility and can be used as an amendment. There are in principle two different reasons for using compost recycle as an amendment in batch composting. The first is to use it as a structural amendment, in order to dilute the fresh waste and increase the free airspace by moisture absorption and pore space increase. The second reason for using recycle is to add microbial biomass to improve the degradation process.

The use of microbial seeding has been debated. Seeding has sometimes had no effect on the degradation rate of compost (Golueke, Card & McGauhey, 1954; Schloss & Walker, 2000), and sometimes a large positive effect. In effective cases of seeding, the microbes added have not been abundant in the substrate, and they have been specialized to the compost environment in question. Examples are seeding with thermophilic bacteria and actinomycetes in thermophilic composting of household waste (Nakasaki & Akiyama, 1988), thermophilic acid-tolerant microorganisms in low-pH compost (Nakasaki *et al.*, 1996; Choi & Park, 1998), and feather-degrading bacteria in poultry waste compost (Ichida *et al.*, 2001).

Summary of papers

Down-scaling a large-scale composting plant to pilot-scale for systematic research (Paper I)

Materials and methods

This study was set up in order to develop an experimental system for the study of large-scale static composting. Therefore, composting in a full-scale facility was compared with composting of the same type of waste material in a static pile reactor and in laboratory-scale vessels. The investigation consisted of two composting experiments (A and B) performed in winter and in spring, complemented with experimental and theoretical studies of the thermal properties of the composting systems used.

The waste was composted at the Isätra composting plant in Sala, Sweden, in concrete boxes (6.5 m x 21 m). The material was kept in a 2 m high static pile for 3½ weeks under a roof made of a semi-permeable membrane. It was then mixed and composted in open boxes for three further weeks. Air was supplied from below with high-pressure radial fans, 1.6 kW in the covered boxes and 0.8 kW in the open boxes.

The static-pile pilot-scale reactors (Figure 4) were constructed from 2 m high steel cylinders with a diameter of 0.63 m. The outside of the reactors was insulated with glass wool, 0.05 m in Experiment A and 0.12 m in B. The reactors were filled with 450 litres of substrate, to a height of 1.45 m. The reactors were aerated by a fan attached to the outlet, drawing the air up through the compost. The temperature was monitored with thermocouples in four positions in the reactor. In Experiment A, samples were taken through holes in the cylinder at 0.3 and 1.0 m height on several occasions. In Experiment B, samples were only taken from the final compost, both from different layers and from a mixture of all compost.

Figure 4. A static pile composting reactor covered with glass wool.

One waste (B) was also composted in a one-litre Dewar vessel (Isotherm, Germany) covered with a polystyrene lid that was kept slightly open (about 5 mm) for aeration (Figure 5). The vessel was filled with 375 g of substrate, which had been sieved to remove large particles. The material was composted for 19 days. The thermal properties of the Dewar vessels were investigated by allowing water (80 °C) to cool in the vessels, one with the lid open and the other with the lid closed.

Figure 5. A one-litre Dewar vessel with a polystyrene lid.

In all experiments, the substrate consisted of 75% (by volume) source-separated household waste (mainly kitchen waste) collected in paper bags, and 25% park waste. Analyses of solids, ash, and pH were performed on the materials composted in reactors and the small vessel, but at the large-scale plant only the temperature was recorded.

Results

In the Dewar vessel the temperature rose quickly to above 50 °C after 15 hours (Figure 6). The temperature continued to rise to a maximum temperature of 72 °C on Day 5, and then it declined steadily. After two weeks of composting, the temperature stabilised at a few degrees above room temperature.

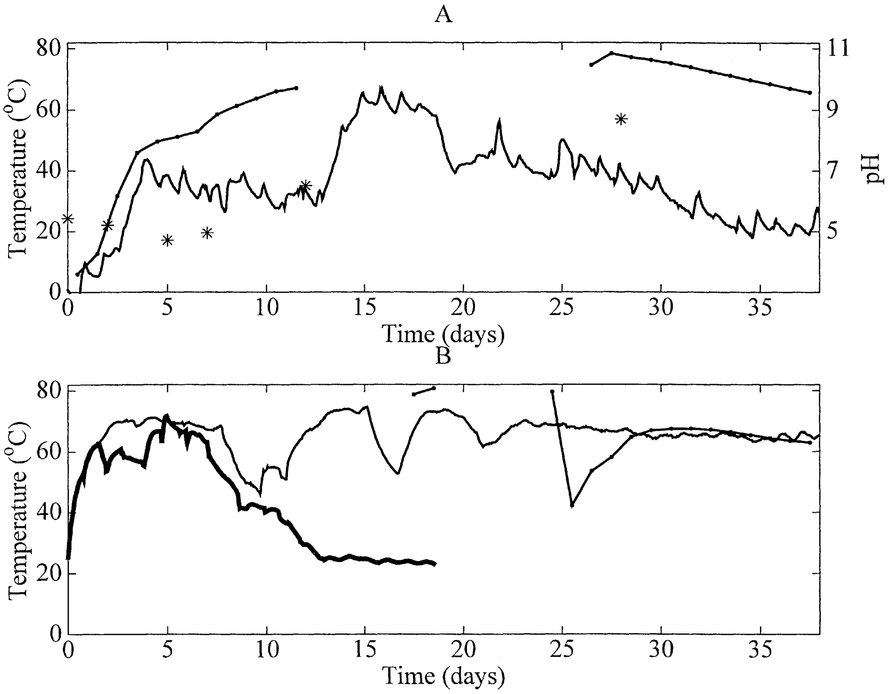

Figure 6. The temperature in the central position at the large-scale facility (dotted line), in the reactors (thin line) and the Dewar vessel (thick line). The pH (*) in reactor A is shown on the right-hand axis.

In both full-scale and pilot-scale systems, the temperature developed differently during different seasons (Figure 6). At the large-scale plant in winter (A), the temperature increased to 45 °C in the first four days, and then continued to increase more slowly to at least 65 °C. The temperature probes did not function all of the time. In the pilot-scale reactors, the temperature also increased to above 40 °C during the first four days, and then declined slowly. After 2 weeks the temperature increased rapidly, followed by a slow decline. The rise to thermophilic temperature occurred at the same time as the pH increased to above 6.

The temperature in Reactor B increased rapidly to 70 °C within three days and remained above 60 °C for more than a month, except for two periods when the aeration was inadvertently interrupted (Figure 6).

Analysis of the temperature in the reactors showed that both reactors were clearly influenced by the temperatures of the surroundings, and that this influence was larger in Reactor A. Maximum and average temperatures were higher in Reactor B, and the correlation between the temperature in the reactor and in the large-scale plant was also better for B. The distinct difference between day and night temperatures, which was more pronounced in Reactor A, indicates a large heat flow to the surroundings.

The thermal properties of the Dewar vessel and the static-pile reactors were estimated and compared. The heat losses from the Dewar vessel were estimated from experiments where 80 °C water was allowed to cool in the vessel. The surface losses from the reactors were calculated from materials data on the insulation, and the heat production was estimated from the degraded mass.

When comparing the conductive heat losses from the reactors and the Dewar vessel, the heat flux was found to be 0.1 kJ $h^{-1}°C^{-1}$ kg $waste^{-1}$ in the Dewar vessel and 0.01-0.04 kJ h^{-1} $°C^{-1}$ kg $waste^{-1}$ in the reactors. Although the estimated heat loss per time unit was larger in the Dewar vessel, the percentage of the total heat that was lost through the walls during composting may have been similar or smaller, since the degradation was 3-4 times faster.

For the reactors, the calculations of the heat loss showed that a large part of the heat produced during decomposition could be expected to leave the reactor through the walls. Depending on the compost and outdoor temperatures, the heat loss from walls would be 40-80% when 0.05 m of insulation was used, and 20-40% in the case of 0.12 m insulation. To reduce the heat loss to below 10% at the highest temperature difference, 0.45 m of insulation would be required.

Process inhibition due to organic acids in fed-batch composting of food waste – influence of starting culture (Paper II)

The effects of starting culture on fed-batch composting of food waste was examined in laboratory reactors. Six experiments of continuous composting were carried out in laboratory reactors (Figure 7). Food waste (50 g), sawdust (5 g) and water (10-50 g) were added daily to reactors with different amounts of starting culture (20-400 g). Three identical cylindrical rotating reactors, made of three-litre insulated Dewar vessels were used for the experiments.

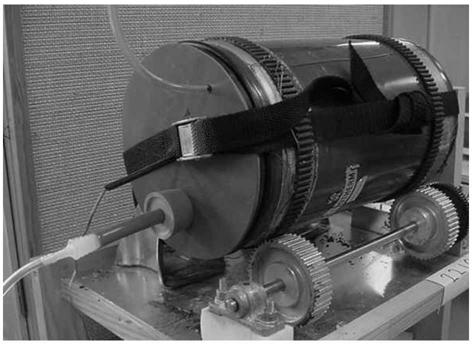

Figure 7. One of the 3-litre rotating reactors used for fed-batch composting.

The temperature in the reactors was monitored continuously with thermocouples. The reactors were aerated with 0.7 l min^{-1} with air pumps by negative aeration. The exhaust gas was bubbled through a sodium hydroxide solution to absorb the carbon dioxide produced. The carbon dioxide was later determined by titration with hydrochloric acid. Solid samples were extracted daily and the solids content, ash, pH and acidity were determined.

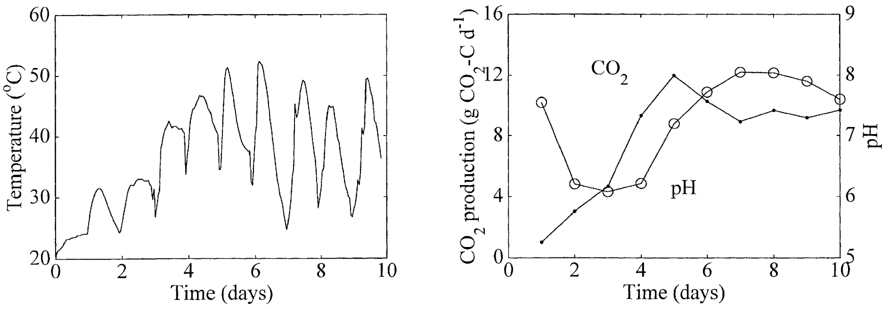

Figure 8. Temperature (left), CO_2 and pH (right) in a reactor with a successful process, with 200 g of starting culture.

The process performance in the reactors with 200 and 400 g of starting culture was distinctly different from those with 20 and 100 g. In the reactors with more starting culture, pH declined during the first few days and then increased above 7 (Figure 8). The CO_2 production increased and after three days the temperature increased to steady thermophilic levels (Figure 8). In the reactors with less starting culture, the temperature did not reach above 42 °C, the CO_2 production remained low and the pH remained below 6 (Figure 9).

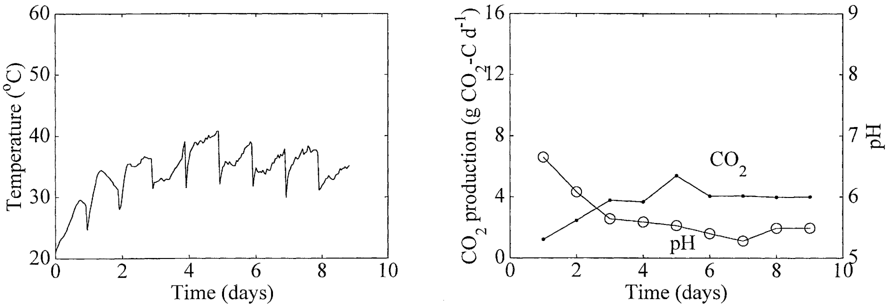

Figure 9. Temperature (left), CO_2 and pH (right) in a reactor with a failing process, with 100 g of starting culture.

Low pH as an inhibiting factor in the transition from mesophilic to thermophilic phase in composting (Paper III)

In this study, the effects of temperature (36-46 °C) and pH (4.7-9.2) on the respiration rate during the early phase of composting were investigated. Respiration experiments were carried out with source-separated organic household waste from two different sources. The wastes had been composted for 1-6 days, reached a temperature of 35-37 °C and a pH of 4.6-5.4. Before the respiration measurements, the samples were treated with sodium hydroxide (7 M) to adjust the pH to values ranging from 4.6 to 9.2. The compost samples (3.0 g) were placed in 118 ml airtight bottles. The bottles were placed in water baths that were held at 36±1 °C and 46±1 °C, respectively. The compost gas was analysed for CO_2 by absorption in 7 M sodium hydroxide.

At 36 °C, the CO_2 production of the compost samples was high irrespective of the pH (Figure 10). At 46 °C, however, the degradation rate at the naturally occurring pH of about 5 was very low. At this temperature the activity was substantially higher in the samples where the pH had been raised above 6.5 with sodium hydroxide.

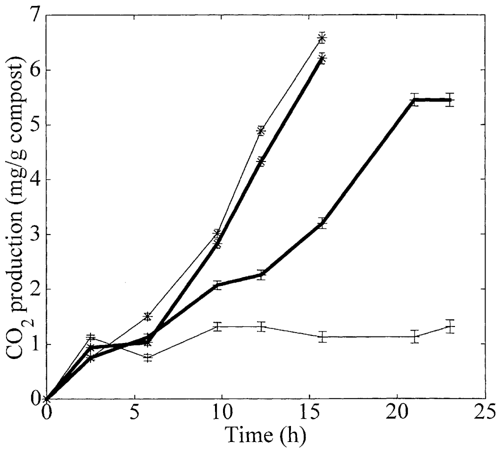

Figure 10. Time series showing the cumulative carbon dioxide production in compost samples kept at 36 °C (*) and 46 °C (+). The thick lines indicate samples that had been treated with NaOH to raise the pH value.

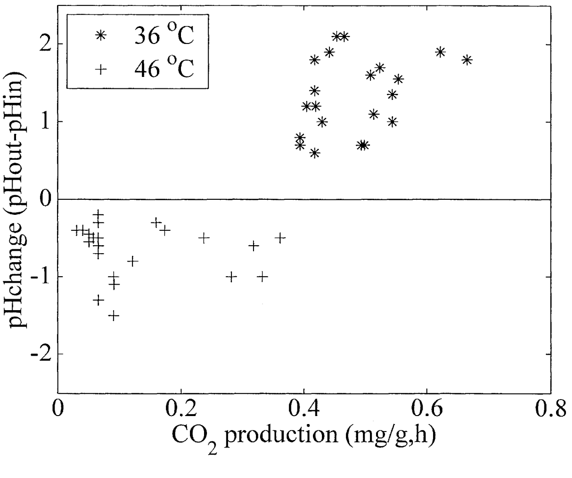

Fig. 11. The change in pH versus the total respiration during the experiment for all samples from with an initial pH below 6.5.

The pH was recorded before and after the respiration experiments. In compost samples treated at 36 °C the pH increased during the experiment, whereas the pH decreased in all compost samples at 46 °C (Figure 11).

Discussion

The objective of this work was to improve the understanding of the composting process, focusing on food waste in large-scale processes and on early phases, especially regarding low pH conditions. This was done through experimental and theoretical studies, which were summarised in the previous section. In this section some general aspects of the work will be discussed.

Energy

The energy balance is crucial to the process development in composting since it (i) determines the temperature and (ii) affects the evaporation. The temperature is a very important parameter determining microbial activity and thus the degradation rate. The evaporation reduces the moisture content, and moisture is important for the degradation rate both directly, as it affects microbial activity, and indirectly, as it affects the structure and therefore the oxygen supply. In order to study the relationships between heat and moisture, a theoretical investigation was set up.

Aeration and water losses at different temperatures

The objective was to compare the evaporative water losses when large-scale composting was controlled at different temperatures. The alternative outcomes were that either the compost would dry faster with more aeration, or that the reduced temperature caused by the increased aeration would make evaporation smaller.

Method

Calculations were made with a static model based on energy and mass balances (eq. 1-4). The substrate was 1 ton of waste with a water content of 65% and an ash content of 24% (of solids). The input temperature of the material was set at 0 or 20 °C, and these temperatures were also used for the outside temperature and input air, which had a relative humidity of 50%. The temperature of the material increased to the output air temperature, which was 37, 55 or 70 °C. The output air was assumed to be saturated. The surface heat loss was quantified as 1.06 J g^{-1} $°C^{-1}$ which is equivalent to 5% of the heat produced during 20 days of composting at 55 °C with a 30% reduction of VS, at an input air temperature of 10 °C. Two different scenarios were used for the decomposition rate and the composting time:

- Initial phase. The degradation of the organic matter was 10%. At 37 °C this was accomplished in 5 days. At 55 °C and 70 °C, twice that time was required. These are crude assumptions based on Smårs *et al.* (2002).

- High-rate phase. The degradation of the organic matter was 10% in 5 days at 55 °C, and twice that time was required at 37 and 70 °C (Nakasaki *et al.*, 1987).

The output variables were the aeration needed for cooling and the water losses from the composting mass.

Results and Discussion

The need for aeration varied considerably between the three temperatures. It was 6-10 times larger at 37 °C than at 70 °C (Tables 1 & 2). The water losses, however, varied less than 25% between composting temperatures.

Table 1. Aeration need and water loss during degradation of 10% of the organic matter in initial stage composting of 1 ton of waste

Composting temperature (°C)	Outdoor temperature (°C)	Aeration need (m^3)	Water Loss (l)
37	0	2500	110
55	0	790	100
70	0	290	90
37	20	4200	150
55	20	1200	140
70	20	430	120

During the initial phase the water losses were highest at 37 °C and 55 °C and during the high-rate phase the water losses were highest at 55 °C and 70 °C. Evaporation was the major means of heat transfer at all temperatures, and it made little difference for the total evaporation whether the heat was transported with much air with little steam or less air with more steam.

Table 2. Aeration requirement and water loss during high-rate degradation of 20% of the organic matter in 1 ton of waste

Composting temperature (°C)	Outdoor temperature (°C)	Aeration need (m^3)	Water Loss (l)
37	0	5600	250
55	0	2200	290
70	0	890	290
37	20	8800	330
55	20	2800	330
70	20	1100	330

It was assumed that the outlet air was saturated. This assumption can be expected to be valid when the moisture level in the compost is higher than 50%.

These calculations confirm that composting at low temperatures requires much more air, but they also show that drying is not proportional to aeration. If the increased aeration leads to lower composting temperature, aerating the compost more does not increase the evaporation. This is because the saturation vapour pressure of water increases exponentially with temperature, leading to increasing evaporation at higher temperature. In the initial stage, a little more water is lost at 37 °C, but this may be acceptable considering that the reduction in start-up time may be larger than the 50% assumed here. However, the large increase in aeration requirement is a major technical challenge when setting the strategy of cooling the compost to 37-40 °C during the initial stage into practice in large-scale composting.

Water ratio

Composting is a process with very high drying potential, since evaporation is the major means of cooling a large process. The self-heating process can be used for intentional drying of wet substrates such as sewage sludge or manure (Nakasaki *et al.*, 1987; Choi, Richard & Ahn, 2001). When the substrates are wet, there is a risk that there is too little energy available to heat and dry the substrate during the process. As a rule of thumb the water ratio, W, defined as:

$$W = \frac{\text{weight of water}}{\text{weight of degradable matter}}$$

should not exceed 8-10 (Haug, 1993). The ratio of water to degradable matter, W, is also of importance for composting of dry substrates. Substrates with large amounts of easily degradable energy in relation to the water content can dry up before the compost is stabilised. With the same model as used in Paper I and the calculations above, the critical moisture contents were estimated. The calculations showed that to achieve 50% degradation of the organic matter and a product with 30% water content, a waste with 76% volatile solids (of dry matter) would need to have an initial water content of 69-73%, depending on the composting and outdoor temperatures. This is equivalent to a water ratio of 3.2-4.0. It is therefore recommendable that water addition is considered for composting of waste with water ratios lower than 3-4. The wastes used in the experiments reported in this thesis had water ratios of 0.9 (Paper II) and 1.6-2.6 (Paper I). It can be difficult to add water to large static operations, but it is easier in fed-batch operations, which are designed for mixing and intermittent addition of substrate.

Scales

The energy balance is largely affected by the scale of the operation. In larger masses, the surfaces losses are relatively small, so either the temperature becomes higher than in an equivalent smaller operation, or more aeration is needed to cool the compost. If the aeration is increased, the evaporation will also increase. This means that if we want to scale down large processes for research purposes without altering the temperature and moisture conditions, we must minimise the surface losses. The theoretical and experimental work showed that this requires very thick insulation (Paper I). Another possible way to achieve the same insulating effect would be to use active insulation, either by placing the reactors in a temperature-controlled chamber (Hogan, Miller & Finstein, 1989) or by temperature control with electric heating of the reactor surface.

The composting experiments were performed at different scales (Table 3). There are several advantages with this kind of approach, in terms of time, costs, applicability and flexibility. Large-scale experiments are costly and difficult in terms of control, sampling and measurements. The conditions in a large composting mass are normally spatially variable, with gradients of moisture and temperature. Lab-scale reactors are easier to control and monitor, and the process conditions can be kept more uniform (Smårs *et al.*, 2001), or they can be designed to have similar gradients to the large-scale process (Paper I). On the other hand, reactors are thermally different from the large-scale, and this has implications for temperature development and drying. Unless special measures are taken, the surface cooling of laboratory-scale reactors is much larger than an equivalent large-scale process. Compared to full-scale process, the reactor will have lower temperatures or less drying, or both. The porosity is also different, due to the different particle sizes and pressure, and this affects aeration and heat transfer, and thus the degradation (Veeken *et al.*, 2003, Paper 1). Reactor or large-scale experiments can be combined with detailed composting of parallel samples from the larger process in small scale. Such experiments can provide detailed insight on special issues, and allow certain parameters to be investigated in detail, as was the case with pH and temperature in Paper III. However, small detailed composting experiments cannot represent the process development over larger time scales, since the conditions are too special.

Table 3. Overview of experimental scales

Process type	Full-scale	Scaled down	Detail
1. Batch composting of food waste (Paper I)	Isätra composting plant	Static pile reactor	Dewar vessel
2. Fed-batch composting of food waste	Commercial composting machine	Laboratory reactors (Paper II)	-
3. Batch composting of food waste	-	Laboratory reactor Smårs *et al.*, 2001	Respiration, pH, temperature (Paper III)

Acid inhibition

Organic acids that are formed microbially during decomposition of organic matter can severely inhibit the composting process. Investigations of low-pH conditions have been performed with food waste composting both in fed-batch processes (Paper II) and in the early phase of batch processes (Paper III). In batch processes, it was found that by keeping the temperature down, below 40 °C, the acids disappeared and the pH increased faster than when the temperature was allowed to rise to thermophilic levels (Paper III). At thermophilic temperatures, the activity increased when the pH was raised artificially above 6.5. Although the acid concentration was the same, the acids were not inhibitory to the microorganisms. This is because it is the undissociated form of the organic acids, which are present at low pH, that can pass through the cell walls of microorganisms and cause damage (Cherrington *et al.*, 1991).

The inhibition of the process when low pH and high temperature is combined is a likely explanation to the lag in the transition from mesophilic and thermophilic temperatures (Figure 12) that was seen in Paper I (experiment A) and that has been noticed by many others when composting food waste or other acidic wastes (Haug, 1993; Day *et al.*, 1998; Schloss & Walker, 2000; Beck-Friis *et al.*, 2001; Weppen, 2001; Reinhardt, 2002). This transitional phase has normally been attributed to slow growth of thermophiles, but the synchronous rise in pH and temperature that has been noted in Paper II, by Beck-Friis *et al.* (2001), and Reinhardt (2002) is not likely to be a coincidence. The transitional phase occurs because the mesophiles are inactivated by the high temperature, and the thermophiles are suppressed by the low pH and organic acids. When the pH rises, the thermophilic activity increases and the temperature rises further. This connection between the often observed lag and the low pH was noted by Reinhardt (2002) and is further supported by the experimental results in Papers I and III.

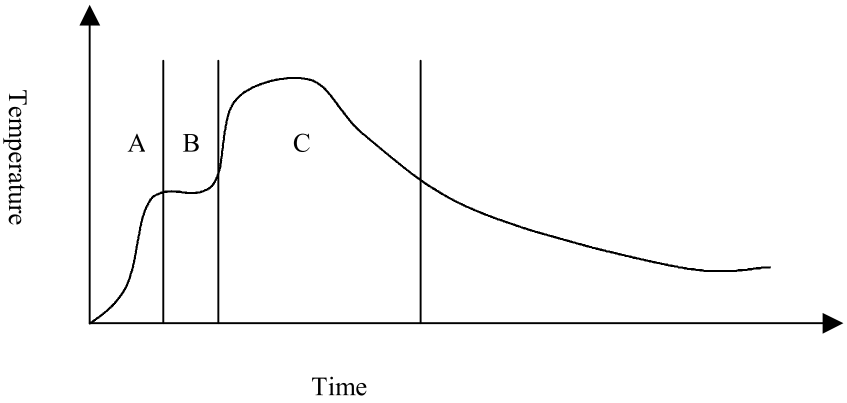

Figure 12. A schematic representation of the temperature development in a self-heating batch composting process. There is a lag (B) in the transition from mesophilic (A) to thermophilic (C) temperature.

Adding lime or other alkaline substances to raise the pH is one method to alleviate the inhibition caused by acids in compost and it functions well (Paper I, Nakasaki *et al.*, 1993). However, it is not a perfect solution to acids in compost. First, liming involves extra costs, both for purchase and for the work of adding it to the substrate. Second, lime addition can be technically demanding, especially from a work environment perspective (Toren *et al.*, 1996). Third, it increases the ammonia emissions, thus increasing the environmental effects of ammonia release and reducing the nutrient status of the product (Nakasaki *et al.*, 1993). As a consequence of the economic, technical and environmental drawbacks of liming, there is reason to search for other ways of overcoming low pH and acid inhibition. One such way is cooling to keep the temperature below 40 °C (Paper III, Smårs *et al.*, 2002). However, the large increase in aeration required may be a major technical obstacle when setting the strategy of cooling the compost to 37-40 °C during the initial stage into practice in large-scale composting.

In the fed-batch process (Paper II) it was found that addition of a starting culture of active compost caused a quicker start of the aerobic degradation and prevented continued conditions of low pH and high organic acid conditions. A starting culture has several stabilising effects on the composting process. First, it provides a structure that supports the oxygen supply to the process. Second, it dilutes the fresh waste. This reduces the risk of local oxygen depletion caused by rapid degradation of easily degradable matter. Oxygen supply is important since the concentration of organic acids in composts becomes higher at low oxygen concentrations (Beck-Friis *et al.*, 2003), probably because of acid formation in anaerobic microenvironments. Third, a starting culture supplies microorganisms, which can decompose the acids that are formed. Fourth, the starting culture may provide a chemical pH-buffer, which may reduce the inhibitory effect of the organic acids by reducing the depression of the pH. It is difficult to distinguish between these different effects, and no such attempt was made in our experiments. However, results from experiments with microbially active as well as sterilised structural amendments show that the microorganisms in the starting culture can accelerate the start-up of the composting process when there is not an adequate microbial community present in the substrate (Nakasaki & Akiyama, 1988; Nakasaki *et al.*, 1992).

Because organic acids are weak acids and because there are several acid-base systems present in compost, pH alone is not a direct measure of acid concentration. Acidity determined by titration can be used to determine the acid concentration. However, there is no standard method for measuring acidity in compost, and preliminary investigations in the project presented in Paper II did not give consistent results.

Future work

There are several possible future directions of this work. Some of them are explored below.

Understanding acids in continuous composting

Accumulation of acids is a serious problem that can lead to process failure in continuous composting of food waste. The factors that regulate production and consumption of acids are not yet fully understood. In the study presented in Paper II, the effects of starting culture on the process performance were investigated. It would be interesting to extend this work to study the effects of other factors. The experimental set-up that was used in Paper II worked well and could be used for investigating the effects of moisture, rotation interval, feeding interval and oxygen supply. All of these are likely to influence the production and decomposition of acids, and the experiments should be designed to answer questions such as:

- Are acids better controlled if the compost is drier?
- Are rotating systems more susceptible to acid problems than static systems?
- Are frequent small feedings better or worse than larger, less frequent feed additions?
- How much does the oxygen supply affect the dynamics of acids?

There are also other issues of interest, especially temperature-related acid inhibition, but the available experimental set-up is not suitable for that, since it does not have temperature control.

Modelling the kinetics of an acidic initial phase

With the available knowledge on acids in composting, and general knowledge about compost modelling, it is worth considering the development of a model that includes acids and pH in composting. Modelling could be useful in the understanding, prediction and prevention of problems with acids, especially for design or process control.

Kinetics is the study of process rates and in composting the rate of interest is the aerobic degradation of matter. The degradation rate depends on the activity of microorganisms, and thus on the combined effect of all factors that determine the microbial activity: temperature, oxygen, moisture, pH and substrate composition.

The kinetics of composting have not been well described. Many attempts are based on empirical relationships, which have limited relevance for substrates or process conditions other than those used in compost development. Several models use a function for the degradation rate (r) with multiplicative influence of several factors such as temperature (T), oxygen (O_2) and moisture (w) (Equation 5).

$$r = f_1(T) \cdot f_2(O_2) \cdot f_3(w) \cdot r_{max} \tag{5}$$

where $0 < f_i < 1$ and r_{max} is the maximum degradation rate.

Hamelers (1993; 2001) introduced a biofilm-type model to account for oxygen transport within compost particles and to include the coexistence of aerobic and anaerobic microenvironments in compost. This model is mechanistic, and it includes spatial gradients on the particle level. A limitation is that it only considers processes with constant temperature.

A major risk with more complex models is that they become a jungle of parameters that cannot be calibrated or verified. Methods to overcome this have been considered by Hamelers (2001) and these include dimensional analysis and identifiability analysis.

There are several complexities involved in the start-up phase of composting, and several modelling attempts have not been successful. The temperature changes quickly during start-up, so an accurate description of the influence of temperature is important. Furthermore, the microbial community structure changes rapidly, causing the dynamics of the system to vary. Finally, the production and degradation of organic acids, and the microbial inhibition that they cause, add extra complexity to the system. There does not seem to be any composting model that includes organic acids. Relevant modelling approaches can, however, be found in related fields where other microbial biodegradation processes have been modelled, such as microbiology, anaerobic digestion and silage research.

Rosso *et al.* (1994) presented a model for combined pH and temperature dependence of microbial growth, based on minimum, optimum and maximum growth temperature and pH. The temperature and pH dependencies were assumed to be independent in pure cultures as well as in composts, an assumption that is questionable (Cherrington *et al.*, 1991; Smårs *et al.*, 2002).

Anaerobic digestion modelling is a relevant source for modelling strategies of acetic acid metabolism, since acetate production from monomers in an important step in anaerobic digestion. Kinetic modelling of the anaerobic digestion process involves growth rate of acidogens, which is modelled by Monod kinetics including inhibition by acids and by low pH (Kalyuzhnyi, 1997; Mösche & Jördening, 1999).

Aerobic deterioration of silage is a process of great economic importance, and it can in fact be described as composting of an acidic substrate. A model including microbial growth dependent on substrate, temperature, acids and pH has been presented and shown to be just as accurate as more complex models involving several substrates and microbial groups (Ruxton & Gibson, 1993).

Aerobic acetate production through overflow metabolism in *E. coli* grown in a defined mineral medium has been described by a dynamic model based on Monod kinetics (Xu, Jahic & Enfors, 1999). The model is complex with many parameters, and includes biomass growth, degradation of glucose into carbon dioxide and acetate, and degradation of acetate.

A mechanistic model of the start-up phase, including acids, would need to include microbial growth, production and degradation of acids, and pH. It could preferably be integrated with a model including particle-level transport of oxygen and soluble substrate.

Process control during start-up phase in large-scale

There are several reasons to improve the process control in composting plants: odour control, fulfilment of standards for sanitation and product quality, and efficient turnover. To improve the degradation rate and thus the turnover, the three most important objectives of process control are (i) providing enough oxygen, (ii) keeping an optimal temperature and (iii) keeping a correct moisture balance.

Many of the factors that affect the composting process performance are determined by process design and substrate preparation, but some can be influenced by external control during the process. Parameters that affect the degradation rate in composting and may be available for online feedback control are temperature, oxygen, moisture and pH. The only means available for direct process control of static batch processes is the airflow rate. The airflow has a direct influence on the oxygen levels, temperature and moisture of the compost, since it provides oxygen, cools the mass and dries it. The relation between airflow and pH is more complex.

Since heat production and oxygen consumption are proportional in aerobic decomposition, oxygen and temperature control are intertwined. In an active large compost, the aeration demand is considerably larger for heat removal than for oxygen provision (Haug, 1993). This implies that if the temperature is controlled at a constant level, the oxygen supply will be sufficient on the macro-level. Since the oxygen is not depleted in the exhaust gas, it can be recirculated the air. This has advantages for odour and emission control, since the exhaust gas volume is smaller. Another implication of the connection between oxygen and temperature is that either temperature or oxygen can be used as a control parameter and that they cannot be independently controlled, unless the compost gas is cooled and recirculated as in the laboratory scale reactor presented by Smårs *et al.* (2001).

The most widespread process control strategy in composting is temperature control. After the start-up phase, a constant temperature in the range 55-60 °C is generally considered optimal for degradation (Miller, 1993). Controlling the process at a set-point temperature can be achieved with standard equipment, and this is commonly done in large-scale composting. However, when the optimal set-point temperature is not known, and perhaps not constant, other tools are needed. This is the case during an acidic initial phase, when the optimal temperature is considerably lower than 55 °C (Smårs *et al.*, 2002).

The inhibition of the composting process at high temperature and low pH is not only of scientific interest, since it is a problem in several large-scale plants in Scandinavia. It would therefore be very interesting to test different strategies for alleviating this problem in a large-scale process. One important strategy is to keep the temperature down, to 35-40 °C. This requires a lot of aeration, which will keep the oxygen levels high, and that also reduces the acid accumulation. Another interesting strategy is to use compost recycle in order to boost the microbial activity and perhaps shorten the acidic phase.

Environmental assessment of the composting process

The ORWARE (ORganic WAste REsearch) model is a tool for evaluation of the environmental impacts of different waste management practices that has been developed at Swedish universities and research institutes since 1996. ORWARE is a substance and energy flow model based on Life Cycle Assessment methodology. Environmental assessments of waste management with the ORWARE model have favoured incineration and anaerobic digestion before composting. However, the results from environmental assessment models are not more reliable than the submodels of the different processes, and the composting part of the ORWARE model can be queried on two issues:

- the composting process - resource use and emissions
- the end-use of the compost

In the ORWARE model, the compost is used in agriculture, and its nutritional value (nitrogen, phosphorous and potassium) is the only benefit from the product. In Sweden today, however, most compost produced from household waste is used as a soil conditioner. In that case the compost is used instead of peat, which is classified as a fossil resource in Europe, so the compost reduces the global warming potential.

Recent process research can be used to improve the composting submodel in ORWARE and thus provide more accurate composting data for future waste management assessments.

Conclusions

- Low degradation in the initial stage of composting can occur during a prolonged acidic phase, both in batch and fed-batch composting of food waste.
- The inhibition of thermophiles at low pH is an important key to explaining the lag in the transition from mesophilic to thermophilic conditions in the initial phase of batch composting.
- The acidic phase can be shortened by:
    - keeping the temperature low, near 35 °C
    - mixing the fresh substrate with compost
    - adding alkaline substances
- Experimentation at different scales is an efficient experimental strategy, but requires that thermal issues be properly addressed.
- To properly simulate the thermal properties of large-scale composts, static pile reactors need to be very well insulated.
- The composting temperature has an insignificant influence on the water loss per unit of matter degraded.
- If the ratio of water to degradable matter in the substrate is lower than 3-4, water addition may be necessary in order to avoid premature drying of the compost.

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