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Higher pH and faster decomposition in biowaste composting by increased aeration

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Abstract

Composting of source separated municipal biowaste has at several plants in Scandinavia been hampered by low pH. In this study the hypothesis that increased aeration would improve the process was tested in full-scale experiments at two large composting plants. The O_2 concentrations were high (>15%) even at the low aeration rates, so the prevailing low pH was not due to an anaerobic process environment. In spite of this, increased aeration rates at the start of the process resulted in higher microbial activity, increased pH and a more stable compost product. At one plant the decomposition rate varied in proportion to the aeration rate, to the extent that the temperatures and O_2 concentrations were similar during the early processes even though aeration rates varied between 10 and 50 $m^3/(h, m^3$ compost). However, increased aeration caused severe drying of the compost, but at one plant the addition of water was adequate to prevent drying. In conclusion, by increasing the aeration rates and adding water to compensate for drying, it was possible to shorten the time needed to produce a stable compost product and thus to increase the efficiency of the composting plants.

1. Introduction

Composting of biowaste (source-separated biodegradable municipal waste) is an important part of the European Union waste management strategy for reducing waste going to landfill, and many composting plants have been built in recent years. However, biowaste composting in Scandinavia has been troubled by low pH during the process, partly due to the low pH of the incoming waste, which often has a pH in the range 4.5–5.1 (Eklind et al., 1997; Norgaard and Sorheim, 2004). The low pH during the process results in corrosion, odour, slow decomposition and thus inefficient use of the facilities, low compost quality and difficulties in attaining temperatures high enough for proper sanitization.

Composting is an oxygen-consuming heat-generating microbial process, and a highly active dynamic microbial system that changes its own environmental conditions. Most notable is the increasing temperature. Mesophilic microorganisms are active up to 40–45 °C, while thermophilic organisms have optimum temperatures above that. Moisture is essential for the function of the composting process, but excessive moisture reduces the airspace in the compost matrix and thus causes oxygen limitation. In active composts, the oxygen present in the pore space is consumed within minutes, so a continuous supply of fresh air is crucial for the process to remain aerobic.

The low pH in biowaste is caused by short-chain organic acids, mainly lactic acid and acetic acid (Eklind et al., 1997). The microbial formation and decomposition of organic acids depends on the oxygen level and temperature. Higher oxygen concentration gives lower maximum concentrations of organic acids in the compost and a faster decomposition of the acids, and thus a faster rise in pH (Beck-Friis et al., 2003). In composting reactor experiments, it has been shown that the time until the pH increases and high-rate decomposition starts can be shortened if the composting temperature is kept in the mesophilic range (below 40 °C) until the pH in condensate

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formed from exhaust gas is above 5 (Smårs et al., 2002). Increased aeration increases cooling and may thus give both higher oxygen concentration and decreased temperature, two process conditions that have been shown to result in a faster increase in pH during composting. The main objective of this work was to test at full scale the hypothesis that increased aeration would make pH rise faster, reach a higher level during the composting process, and result in an increased decomposition rate. A further objective was to investigate the extent of drying caused by the increased aeration, and thus the water addition requirement.

2. Materials and methods

2.1. The composting plants

The Hogstad composting facility, managed by the municipal company IVAR in the Stavanger region of Norway, treats 25,000 ton of biowaste (source-separated household food and garden waste) per year. The waste mixture is composted in a hall, in an agitated bed system, where the substrate is entered at one end and removed at the other end (Fig. 1). The process is performed in reinforced concrete bays 5 m wide, 42 m long and 2.5 m deep, although only filled to a 2 m depth. The material is turned every 2–4 days by mechanised agitators, which move it 4.7 m forward each time. After nine turns, 20–30 days of composting, the compost has come to the other end and is removed from the hall. The aeration of each bay is divided into four zones with separate fans, each 7–15 m long. The bays are aerated by negative aeration (drawing the gases out through perforated floors underneath the bays) except for the first zone (first 5 m) in one bay, which is aerated by positive aeration.

The Støleheia composting facility, managed by the municipal company Renovasjonsselskapet for the Kristiansand Region (RKR) in Kristiansand, Norway, also treats source separated household biowaste (11,000 ton in 2004) in an agitated bed system in a hall with reinforced concrete bays, 2.8 m wide, 2.2 m deep and 64 m long, into which air is blown from below. The bays are aerated in five separate zones and turned by mechanised agitators at intervals of 2–3 days, each time moving the material 4.2 m towards the end of the hall. The residence time in each zone is 5–7 days. After 30–40 days the compost has reached the far end and is removed from the hall.

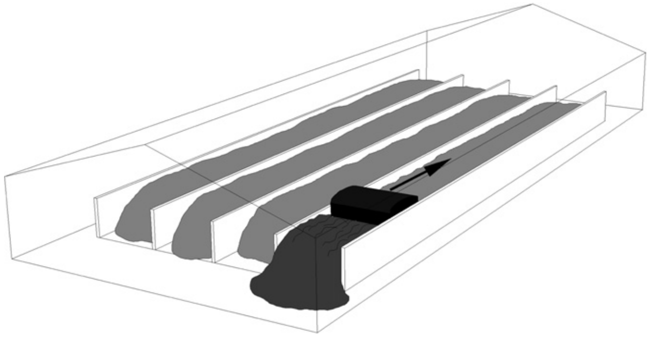

Fig. 1. Schematic drawing of the composting plants. Substrate is entered at the rear end of the building and compost is removed at the front end. The turning machine moves along the bay (arrow) and the compost is moved in the opposite direction. The bays are aerated from below by positive (RKR) or negative (IVAR) aeration. Aeration is supplied in 4 (RKR) or 5 (IVAR) zones separated along the length of the bays.

2.2. Experimental set-up

At IVAR, two composting bays (I1 and I2) were monitored in September–November 2004. Three consecutive batches, of which the first two (A and B) are reported here, were monitored in I1, and two consecutive batches in I2. At RKR, two consecutive batches (A and B) in three composting bays (R1, R2 and R3) were monitored in June–July 2004. At IVAR, the whole process was monitored, whereas the investigation at RKR focused on the first 8 days. Each bay had a different aeration schedule, with the lowest rate in I1 and R1. Other factors, such as turning frequency, were kept as similar as possible between the batches and bays at each plant.

The input air was taken from the hall (20–30 °C) at both plants. At IVAR, the aeration was continuous in all bays, while fan sizes and valve settings differed between bays, resulting in varying aeration rates (Fig. 2). At RKR, the varying aeration between the bays was due to differences in fan sizes and on/off intervals.

At both plants, the aeration rates were much higher in the first zone than in the later zones. The difference in aeration rate between the bays was large in the beginning and smaller later on (Fig. 2). At IVAR the aeration rate in the first zone was about three times higher in I2 than in I1. Also in the second zone, bay I2 received more air than I1. There were no distinct differences in aeration rates between the two bays in the other zones, i.e., from day 10 onwards.

At RKR, the aeration in the first zone in R2 and R3 was continuous, but in R1 the aeration was intermittent (2 min on, 10 min off), and the average aeration rate is presented in Fig. 2. In the second zone the aeration in R1 and R2 was set at 1 min on, 10 min off, and in R3 5 min on, 10 min off. At IVAR water was added and mixed in during turning of the compost, and at RKR water was added by spraying on top of the bays for 5–20 min/h at night (Table 1). At RKR, the sprinkler system for water addition did not cover the first 12 m of the bays, so no water was added during the first week of the process. The water addition was set to give more water to the bay that received more aeration, so 4.1, 8.2 and 11.5 m^3 of water was added to each batch in R1, R2 and R3, respectively.

At both plants, the main substrate was biodegradable waste from households, mainly kitchen waste. This waste was collected in bags made of paper or biodegradable plastics and was shredded on arrival to open the bags. At IVAR, a mixture of waste (73% on wet weight basis), crushed wood (variable size, <80 mm, 13%) and structural

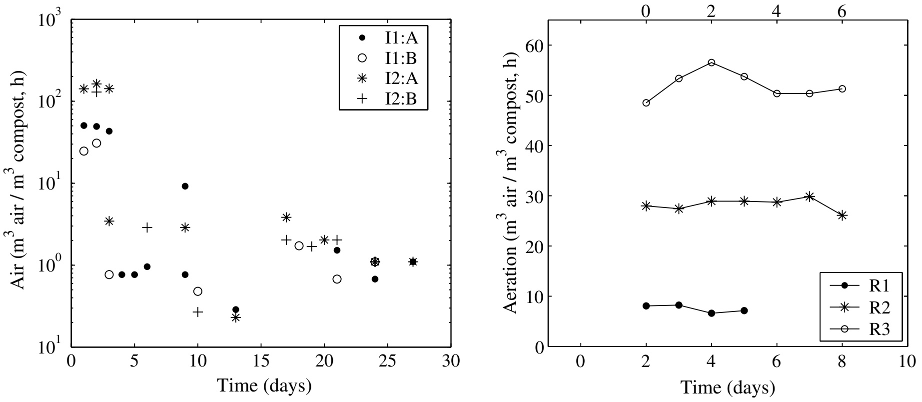

Fig. 2. Left: Airflow at IVAR. Right: Airflow in the first aeration zone at RKR; time for batches A and B below and above figure, respectively. Aeration started on day 1 in both batches at RKR, but no data were available on day 1 for batch A. The scale is logarithmic in the left figure and linear in the right figure.

Table 1
Water addition at IVAR

Batch	Water (m^3/ton wet weight in)	Water (m^3/ton dry weight in)
I1:A	0.09	0.21
I1:B	0.22	0.46
I2:A	0.65	1.5
I2:B	0.78	1.7

material recycled from final compost screening (>20 mm, 14%) and was used. At RKR, the waste (73%) was mixed with recycled structural material and compost (>10 mm, 11%), crushed garden and park waste (8%), and wood chips (coarse 5% and fine 3%). The mixtures were sieved in drum sieves to remove plastic bags before being moved to the composting bays.

The substrate at RKR was drier, had a higher volatile solids fraction and a lower pH than that at IVAR (Table 2). The nitrogen concentration and the SOUR were similar at both plants. At IVAR there was no significant difference between the batches, but at RKR the pH was significantly (at 99% confidence level) higher in the second batch.

2.3. Sampling

At IVAR, five 5-l grab samples of the substrate were taken during loading. Samples from the composting process were taken as three 5-l grab samples from each batch. At RKR, ten 1-l grab samples of the substrate mixture were taken from the pile during loading of the first batch (A). From the second batch (B), a 10-l bucket was filled with substrate samples from various places in the pile. These samples were mixed thoroughly by hand, and 1-l samples were extracted. Samples from the composting process were taken as 1-l grab samples from the surface, within 2 h after turning.

From the first aeration zone in I2, off-gas was collected using a circular chamber (0.5 m high, diameter 0.7 m) placed on top of the compost mass, with a hole (diameter 0.07 m) for the gas to flow through. In the other bays and zones at IVAR, the gas concentrations were measured in the off-gas pipes. At RKR, in all zones, off-gas samples were collected using 0.4 m high chambers covering 0.95 × 1.15 m^2, with a hole (diameter 0.14 m) for the gas to flow through. Gas samples were taken from within the chambers. Condensate samples (10–100 ml) were collected with a sponge from the inside of the chambers.

2.4. Physical and chemical analyses

At both plants, temperature was measured manually daily with digital thermometers with thermocouple temper-

Table 2
Substrate characteristics at IVAR and RKR in the first (A) and second (B) batches

Batch	DM (g/g fresh weight)	VS (g/g DM)	Nitrogen (% of DM)	pH	SOUR (g O_2/kg VS, h)
IVAR A	0.39[a]	0.71[a]	1.9 ± 0.2[b]	5.2 ± 0.1[c]	10.6[a]
IVAR B	0.40[a]	0.63[a]	1.9 ± 0.1[c]	5.3 ± 0.2[c]	16.3[a]
RKR A	0.48 ± 0.01[d]	n.d.[e]	2.1 ± 0.3[d]	4.5 ± 0.1[d]	n.d.[e]
RKR B	0.48 ± 0.01[d]	0.84 ± 0.05[f]	1.6 ± 0.3[f]	4.8 ± 0.1[d]	12.2 ± 1.4[f]

[a] Single sample.
[b] Average of 4 samples.
[c] Average of 5 samples.
[d] Average of 10 samples.
[e] Not determined.
[f] Average of 3 samples.

ature probes (Fluke, USA) placed in the compost mass. At IVAR, the temperature in the off-gas channels was also recorded manually daily with the same instrument.

At IVAR, airflow was measured with a hot-wire anemometer (SwemaAir 300, Swema, Sweden) in the outlet air channels. At RKR, airflow was measured with a vane anemometer (Testo 435, Testo, Germany) in the inlet air channels. Oxygen (O_2) and carbon dioxide (CO_2) concentrations were measured with a multi-gas analyser, GA 2000 (Geotechnical Instruments, UK). This instrument measures O_2 concentration with a galvanic cell sensor and CO_2 by infra-red (IR) absorption at 4.29 μm.

Measurements of pH were made with a glass electrode and a pH 211 Microprocessor pH-meter (Hanna Instruments, Norway) on samples (12 g) mixed with deionized water (60 ml), shaken for a few seconds and measured after 1 h. The pH was also measured on the condensate, either pure or, for small samples, diluted with deionized water. Dry matter (DM) concentration was determined on 1 kg samples dried at 105 °C for 72 h (IVAR) and 30–90 g samples dried at 105 °C for 24 h (RKR). Volatile solids (VS) concentration was determined as ignition loss in dry sieved (10 mm) samples kept at 550 °C for 3 h. The specific oxygen uptake rate (SOUR) was measured on sieved (10 mm) samples mixed with water, according to the method described by Lasaridi and Stentiford (1996), although without any nutrient amendment. Nitrogen was analysed by a standard Kjeldahl method (Bioforsk Laboratory, Oslo, Norway).

2.5. Statistical and mathematical analysis

The uncertainty presented in the figures and tables is the standard error of the mean. The statistical significance was determined by the two-sample *t*-test and tested at 90%, 95% and 99% confidence levels (Johnson, 1994).

The CO_2 emissions were calculated from airflow and the CO_2 concentration in the exhaust gas. The heat removal by heating of dry air, Q_a, was calculated as:

$$Q_a = c_{pa} \cdot m_a \cdot (T_{out} - T_{in}) \tag{1}$$

where c_{pa} is the specific heat of dry air (1.0 kJ kg^{-1} °C^{-1}), 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 Eq. (1).

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

$$Q_w = c_{pe} \cdot m_{e,in} \cdot (T_{out} - T_{in}) + \Delta H_{vap} \cdot (m_{e,out} - m_{e,in}) \tag{2}$$

where c_{pe} is the specific heat of steam (1.8 kJ kg^{-1} °C^{-1}), $m_{e,\,in}$ 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 relative humidity was assumed to be 100% for both inflow and outflow. The correlation between heat and carbon dioxide values at RKR was analysed by linear regression with the function *polyfit* in MATLAB 6.5 (The MathWorks, USA).

The degree of decomposition was estimated from the VS of the input and output (VS_i and VS_o) given as % of DM (Haug, 1993):

$$k = \frac{(VS_i - VS_o) \cdot 100}{VS_i \cdot (100 - VS_o)}$$

3. Results

3.1. pH

In I2 at IVAR there was a significant rise in pH from the start, which continued for 2–3 weeks (Fig. 3). After only 3 days, the pH had already increased by more than one pH-unit. In I1, on the other hand, the pH did not change markedly but remained below 7 during the whole process. At RKR the pH also increased faster in the bay that received most air and slower in the other bays (Fig. 4).

3.2. Carbon dioxide and oxygen

At both IVAR and RKR, the O_2 and CO_2 concentrations added up to 20–21% throughout the process, i.e., the respiration quotient RQ (the ratio of CO_2 emission to O_2 consumption) was close to 1 (Fig. 5, Table 3), indicating that the processes were aerobic. At IVAR, the CO_2 concentrations were high, often more than 5%, except in the first zone, where the aeration was high in both bays and the maximum CO_2 concentration was 2%. At RKR the CO_2 concentrations in the exhaust gas were 0.7–1.8% during the first week of composting (Table 3). The aeration rates in the first zone were in the ratio 1:3:5 in R1:R2:R3 and the CO_2 concentrations in the ratio 1.8:1.1:1.0, and thus the decomposition rates, measured as CO_2 emission, were about 1:1.8:2.8, clearly higher at higher aeration rates.

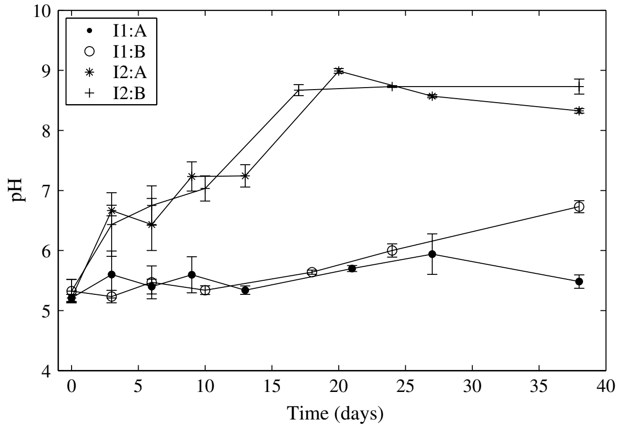

Fig. 3. The pH development in the different batches during the composting process at IVAR.

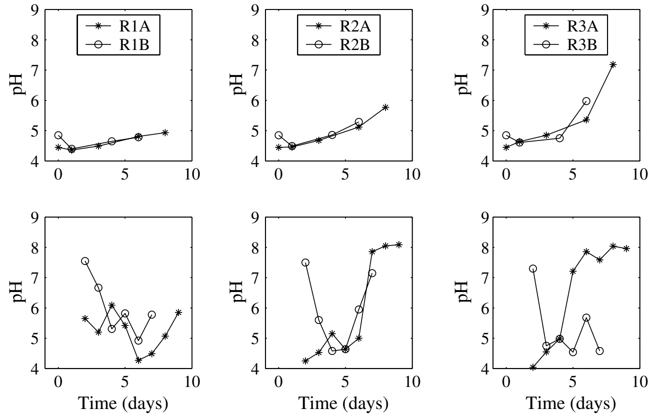

Fig. 4. The pH development at RKR. Top: pH in material samples, average of two samples, one taken near the edge and one near the centre. Below: pH in condensate.

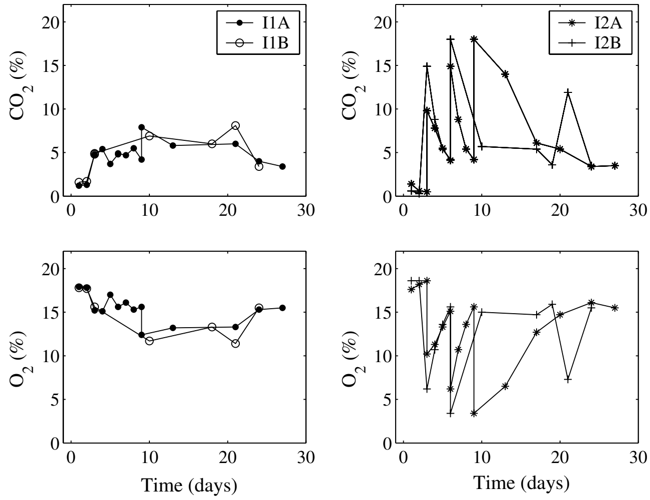

Fig. 5. Carbon dioxide (top) and oxygen (below) concentrations in the exhaust gas from the compost in I1 (left) and I2 (right). The results are given as volume percentage of dry air.

Table 3
Oxygen and carbon dioxide concentration in exhaust from R1, R2 and R3 (RKR) during the first 1–8 days

Bay	O_2 (all)	O_2 (pH < 7)	CO_2 (all)	CO_2 (pH < 7)
R1	18.1 ± 0.2	18.1 ± 0.2	1.8 ± 0.2	1.8 ± 0.3
R2	18.6 ± 0.2	18.7 ± 0.2	1.1 ± 0.1	1.1 ± 0.1
R3	18.9 ± 0.1	19.1 ± 0.2	1.0 ± 0.1	0.7 ± 0.1

Average of all data and of data from days when pH in the condensate was below 7, respectively. Data as % of volume content in exhaust.

3.3. Temperature

At IVAR, the temperature in I1 did not reach above 60 °C (Fig. 6). In I2 the temperature was below 50 °C for the first 3 days when the aeration rate was about 150 m^3/h/m^3 of compost, and increased to 60–72 °C after turning and moving to a zone with about 5 m^3/h/m^3 of compost.

At RKR, after 1–2 days the temperatures measured in the central upper part were in the range 48–56 °C while pH was low, even though the aeration rates differed largely between the bays (Fig. 7, Table 4).

3.4. Decomposition

The microbial activity at RKR was calculated by two methods – heat transport and CO_2 emission. They were correlated in R2 and R3 by a factor of 9.2 kJ/g CO_2, or 404 kJ/mol CO_2, but in R1 there was no significant correlation (Fig. 8). This may be due to the intermittent aeration in R1, which introduced errors into the measurement of CO_2, airflow and off-gas temperature.

3.5. Moisture

In the bay at RKR with most aeration (R3), the drying was severe already after a few days, and the dry matter concentration increased rapidly also in R2 (Table 5). The compost dried faster near the edges of the bays, and slower at the centre. The dry matter concentration in the end product was similar to the values measured after 8–9 days of composting, so most of the drying occurred during the initial phase. During the later stages the aeration rates and thus the drying rates were lower, and drying was balanced by the water added.

At IVAR, the dry matter concentration increased in I1, which received less aeration, but not in I2. This was because much more water was added to I2, and this prevented drying (Table 1). In I1, large amounts of water were added at unloading, resulting in output compost with only slightly higher dry matter concentration compared to I2.

3.6. Stability

During the composting process the specific oxygen uptake rate (SOUR) decreased by less than 30% in I1 and by 80–90% in I2 (Tables 2 and 6). The product from I2 was thus much more stable than the product from I1. By the volatile solids loss method it was estimated that the organic matter reduction was 11–16% in I1 and 40–45% in I2.

At RKR, the compost from R2 tended to have higher stability and higher pH than that from R1, but neither product was stable (Table 6). The SOUR decreased by 20–50% during the process in the bay with least aeration (R1) and by more than 60% in R2. However, the final values (4.7–9.8 g O_2/kg VS, h) still indicate a rather unstable compost (Lasaridi and Stentiford, 1996). The high pH in the bay with the highest aeration rate (R3) indicates that this compost was more stable than the other two, but unfortunately, SOUR was not determined for this bay.

4. Discussion

More aeration gave a faster rise in pH at both RKR and IVAR. At low aeration rates the pH did not increase, and

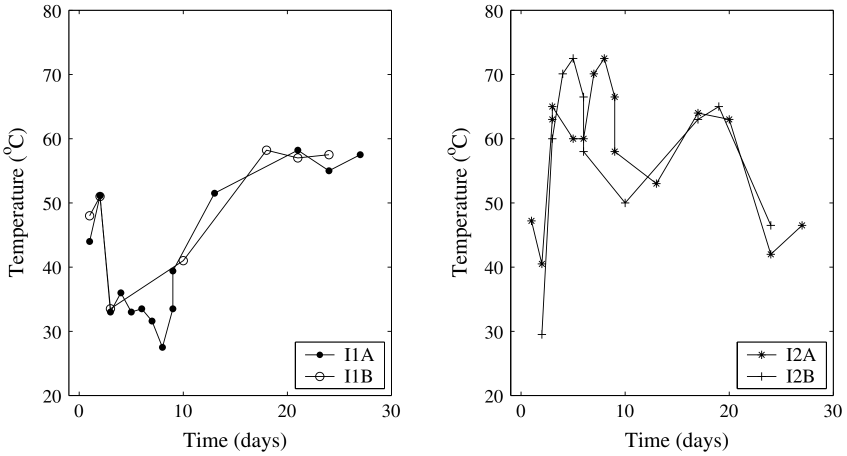

Fig. 6. Temperature in the exhaust gas from I1 (left) and I2 (right) at IVAR.

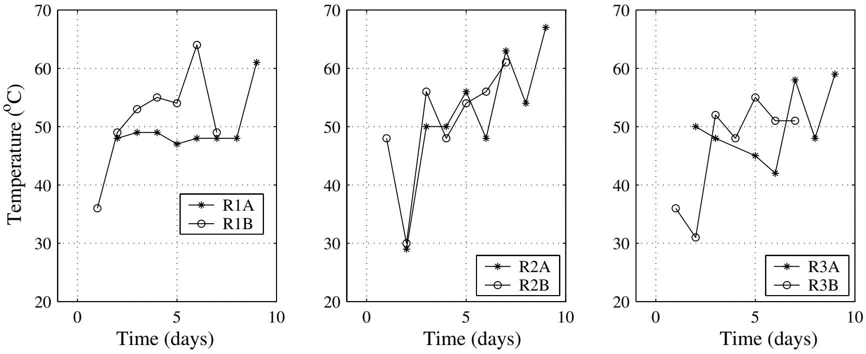

Fig. 7. Temperature at RKR, measured in the centre of the bays at 0.3 m from the upper surface.

Table 4

The number of temperature readings at different intervals at RKR, measured in the centre of the bays 0.3 m from the upper surface

Temperature	pH < 7	pH > 7
<48 °C	4	4
48–56 °C	26	3
>56 °C	2	5

Data from when pH in the condensate was below and above 7, respectively.

in some cases it even decreased, whereas high aeration rates gave increased pH as well as faster decomposition and more stable products. The aeration rates in the first zone in R2, R3, I1 and I2 were higher than the rates formerly used at the plants, and higher than rates normally used in the composting industry, as reported by VanderGheynst et al. (1997). However, the rates applied were within the range for required peak aeration reported by Haug (1993).

In I2 there were peaks in carbon dioxide emissions and oxygen consumption after turning (Fig. 5). This can be explained by the process being boosted by the turning and water addition. This is also evident from the temperature curves, which have a distinct pattern of rapidly rising temperatures followed by a slow decline (Fig. 6). In I1, where pH values were lower, there was no such pattern,

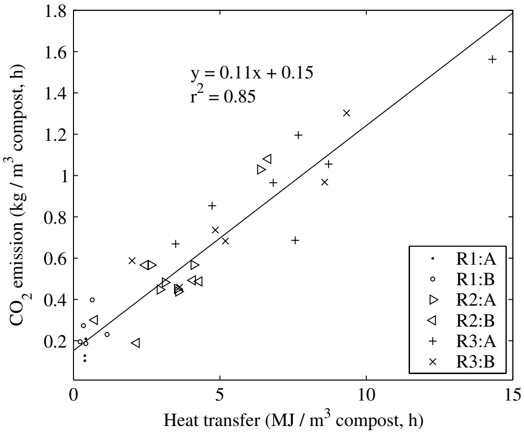

Fig. 8. Correlations of heat and CO_2 at RKR during the first 8–9 days of the process; heat flow vs. CO_2 emission. Linear regression lines calculated from R2 (triangles) and R3 (*x* and +) data.

Table 5

Dry matter (g/g fresh weight) at RKR after 6 days of composting in samples taken at the centre and the edge of the bay

	R1	R2	R3
Centre	0.48	0.50	0.54
Edge	0.52	0.54	0.60

Average of 2 batches. DM at start was 0.48 g/g.

Table 6
Properties of compost from the enclosed process at IVAR and RKR in the first (A) and second (B) batches

Batch	Dry matter (g/g fresh weight)	Volatile solids (g/g DM)	pH	Nitrogen (% of DM)	SOUR (g O_2/kg VS, h)
I1:A[a]	0.55 ± 0.02	0.66 ± 0.01	5.5 ± 0.1	2.5 ± 0.1	9.4 ± 0.5
I1:B[a]	0.52 ± 0.01	0.65 ± 0.01	6.7 ± 0.1	2.4 ± 0.1	9.4 ± 0.5
I2:A[a]	0.50 ± 0.05	0.55 ± 0.01	8.3 ± 0.1	2.1 ± 0.1	1.0 ± 0.1
I2:B[a]	0.46 ± 0.01	0.57 ± 0.02	8.7 ± 0.1	2.3 ± 0.1	2.3 ± 0.5
R1[b]	0.51 ± 0.03	0.77 ± 0.02	5.8 ± 0.3	n.d.[c]	7.9 ± 1.4
R2[b]	0.61 ± 0.04	0.74 ± 0.01	6.3 ± 0.1	n.d.[c]	4.7 ± 0.1
R3[b]	0.57 ± 0.03	n.d.[c]	7.0 ± 0.1	n.d.[c]	n.d.[c]

[a] Average of 3 samples.
[b] Average of 2 samples.
[c] Not determined.

which is an indication of a process inhibition. The O_2 concentration in the exhaust was more than 15% and the sum of O_2 and CO_2 was about 21% for most of the time in all processes, with major exceptions only when pH was rising in I2 and during the later stages of intermittent aeration in R1–R3. However, even though the composts were well aerated, the pH remained low for prolonged periods, especially in bays with less aeration. The most common explanation for low pH is anaerobic conditions, which favour production of organic acids (Brinton, 1998; Robertsson, 2002), and anaerobic conditions during collection and storage are probably the main reason for the low pH of the incoming waste. Anaerobic conditions may also continue during the process in poorly aerated interiors of compost aggregates. However, this is not enough to explain the consistently low pH in the studied processes, since the exhaust gas from the bays where pH remained low had only slightly lower (although statistically significant) oxygen concentrations than in bays where pH increased (Table 3). Since the pH increased faster in bays with higher decomposition rates and remained low at lower decomposition rates, the difference in pH between bays was more likely due to higher aerobic decomposition of acids in bays with rising pH than to higher anaerobic production of acids in bays with consistently low pH.

The temperature, CO_2 and O_2 concentrations at RKR indicate a stable process with small fluctuations during the first week (Table 3, Fig. 7). This is unexpected in the beginning of the composting process. Stable conditions normally occur later, during curing, and are caused by substrate limitation, which is not the case early in the process. Oxygen deficiency could be a limiting factor, but the overall O_2 concentration was above 15% at all times, indicating good oxygen supply. The most likely explanation for the stable process conditions is a temperature limitation, even though the observed temperatures (48–56 °C) are generally not too hot for composting. At pH below 6, however, composting is inhibited at moderately thermophilic temperatures (Smårs, 2002). In laboratory experiments, the activity has been found to be very low at 46 °C at pH below 6, compared with higher pH, and a transition to higher pH occurs rapidly at 36 °C but not at 46 °C (Sundberg et al., 2004). A plausible explanation for the temperature development at RKR is thus that during the acidic phase the process activity increased until a temperature was reached at which the microbial activity was inhibited, and as the pH was low, this occurred at less than 56 °C (Table 4).

Several methods were used to measure the temperature, but it was still difficult to get a full picture of the temperature in the bulk mass. Daily measurements were made in the exhaust gas (IVAR) or in the mass (RKR). Temperature was also measured at both plants with buried sensors incorporated into the compost but not in all bays or at all times (Sundberg, 2005). Both plants also had temperature sensors for process control, but those data were too unreliable to be used in this evaluation. The aeration systems differed; at IVAR the air was drawn from below whereas it was blown from below at RKR. The temperature gradients consequently differed, with the lowest temperature at the bottom at IVAR and at the top at RKR, and these vertical temperature gradients were large most of the time. At IVAR there were also large horizontal differences within the aerated zones during the beginning of the process. In total, it was not possible to get a full view of the temperature in the bulk mass from the collected data. This was especially the case at IVAR and it was difficult to tell how the temperature affected the processes there.

The pH was measured both in the condensate and in material samples, and the two methods gave different values but similar trends (Fig. 4). In batch A at RKR, the pH of the condensate increased above neutral earlier than that of the materials, and this has also been previously documented (Beck-Friis et al., 2001). In the condensate there are acids and bases that have evaporated from the surface of the compost particles, which may have different pH than the insides of the particles. Since acids are mainly produced anaerobically and decomposed aerobically, it is likely that the acid concentration is first reduced on the surfaces of the particles, which are in contact with the oxygenated compost gas. Therefore, pH increases in the condensate earlier and faster than in the material samples. However, a high pH in the condensate did not always reflect an eventual pH rise in the material. In batch B at RKR, the condensate pH was high during the first days and then decreased (Fig. 4), whereas the pH of the material was low from the start. This phenomenon has been observed previously in reactor experiments (Beck-Friis et al., 2001). A possible explanation is that the organic acids are not very volatile at low temperatures (lactic and acetic acid have higher boiling points than water). Thus, less acid would evaporate during the first 2 days of batch B at 30–40 °C than during the first days of batch A at 40–50 °C, even if the actual acid concentrations in the composts were the same. In total, these results show that pH in the condensate can be used as an early indicator of a pH change in the material, if the temperature is high enough. Another advantage of measuring the pH in the condensate is that it gives an indication of pH in a large volume of compost, whereas it is often difficult to take representative samples of the material during the process.

When organic matter is decomposed, heat is released. In aerobic decomposition, the heat production is essentially proportional to the oxygen consumption and to the CO_2 production. CO_2 emissions (airflow multiplied by exhaust air CO_2 concentration) and heat transport (a function of airflow, input and exhaust air temperatures and humidities) are thus two different ways of estimating the activity of the compost. The correlation between heat flow and carbon dioxide flow (Fig. 8) shows that either CO_2 emission or heat emission can be used as an indicator of process activity in composts when the aeration is continuous. This is in contrast to the CO_2 and O_2 concentrations and the temperatures, which at RKR showed very little variation even when the aeration and decomposition rates were not the same. CO_2 emission and heat emission are thus much better process performance indicators than temperature or CO_2 or O_2 concentration.

Aeration is essential for cooling compost, and processes with higher activity require more cooling and thus more aeration. Evaporation, driven by aeration, is the most important mechanism for cooling of large composts, and thus drying cannot be avoided if there is degradation. Addition of fresh water or recycled condensate is therefore necessary in order to obtain stable compost from organic household waste. This is evident from mass and energy balances of composting processes (Sundberg, 2003). Increased aeration normally leads to more evaporation and thus to faster drying of the compost. This is particularly the case if the increased aeration leads to increased decomposition. At IVAR, but not at RKR, water addition was able to cope with the drying of the waste. The added water in I2 corresponded to, on average, 72% of the wet weight of the incoming waste (Table 1). The evaporated water corresponded to 170% of the water in the incoming waste.

5. Conclusions

At both composting plants, increased aeration rates at the start of the process resulted in larger heat losses, higher microbial activity, faster decomposition and a faster rise in pH. The increased aeration also gave a more stable end product.

The O_2 concentrations were high (>15%) even at the low aeration rates, so the prevailing low pH was not due to an anaerobic process environment. At RKR all bays achieved similar temperatures during low-pH conditions, regardless of the aeration rate. This indicates that the process was probably limited by the temperature (48–56 °C) in combination with low pH.

The material was dried by the aeration rates that were needed to raise pH and give efficient decomposition, and therefore a water addition of up to 0.7 times the wet weight of the substrate mixture was necessary to achieve stable compost. By increasing the aeration rates and adding water to compensate for drying, it was possible to improve the efficiency of the composting plants by shortening the time needed to produce stable compost.

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References

Beck-Friis, B., Smårs, S., Jönsson, H., 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, 423–430.

Beck-Friis, B., Smårs, S., Jönsson, H., Eklind, Y., Kirchmann, H., 2003. Composting of source-separated household organics at different oxygen levels: Gaining an understanding of the emission dynamics. Compost Science & Utilization 11, 41–50.

Brinton, W.F., 1998. Volatile organic acids in compost: production and odorant aspects. Compost Science & Utilization 6, 75–82.

Eklind, Y., Beck-Friis, B., Bengtsson, S., Ejlertsson, J., Kirchmann, H., Mathisen, B., Nordkvist, E., Sonesson, U., Svensson, B.H., Torstensson, L., 1997. Chemical characterization of source-separated organic household waste. Swedish Journal of Agricultural Research 27, 167–178.

Haug, R.T., 1993. The Practical Handbook of Compost Engineering. Lewis Publishers, Boca Raton.

Johnson, R.A., 1994. Miller and Freund's Probability and Statistics for Engineers. Prentice-Hall, Englewood Cliffs, NJ.

Lasaridi, K.E., Stentiford, E.I., 1996. Respirometric techniques in the context of compost stability assessment: Principles and practice. In: de Bertoldi, M., Sequi, P., Lemmes, B., Papi, T. (Eds.), The science of composting. Blackie Academic & Professional, Glasgow, pp. 274–285.

Norgaard, E., Sorheim, R., 2004. Tiltak for å sikre rask etablering av varmkompostering ved behandling av bioavfall (Measures for the establishment of thermal composting when treating biowaste). Norsk Jordforbedring & Jordforsk. Grimstad /Ås, Norway.

Robertsson, M., 2002. Effects of interrupted air supply on the composting process – composition of volatile organic acids. In: Insam, H., Riddech, N., Klammer, S. (Eds.), Microbiology of Composting. Springer-Verlag, Berlin Heidelberg, pp. 189–201.

Smårs, S., 2002. Influence of different temperature and aeration regulation strategies on respiration in composting of organic household waste. Department of Agricultural Engineering, Swedish University of Agricultural Sciences: Doctoral thesis, Agraria 324, Uppsala, Sweden.

Smårs, S., Gustafsson, L., Beck-Friis, B., Jönsson, H., 2002. Improvement of the composting time for household waste during an initial low pH phase by mesophilic temperature control. Bioresource Technology 84, 237–241.

Sundberg, C., 2003. Food waste composting – effects of heat, acids and size. Swedish University of Agricultural Sciences, Department of Agricultural Engineering: Report 254. Uppsala, Sweden.

Sundberg, C., 2005. Increased aeration for improved large-scale composting of low-pH biowaste. Department of Biometry and Engineering: Report 2005:06. Uppsala, Sweden.

Sundberg, C., Smårs, S., Jönsson, H., 2004. Low pH as an inhibiting factor in the transition from mesophilic to thermophilic phase in composting. Bioresource Technology 95, 145–150.

VanderGheynst, J.S., Gossett, J.M., Walker, L.P., 1997. High-solids aerobic decomposition: pilot-scale reactor development and experimentation. Process Biochemistry 32, 361–375.