Increased aeration for improved large-scale composting of low-pH biowaste

Förbättrad storskalig kompostering av bioavfall med lågt pH-värde genom ökat luftflöde

Cecilia Sundberg

SLU
Institutionen för biometri och teknik

Rapport – miljö, teknik och lantbruk 2005:06

SLU
Department of Biometry and Engineering

Uppsala 2005
ISSN 1652-3237

ABSTRACT

Biowaste composting at several plants in Scandinavia has been troubled by low pH in the collected waste as well as after the composting process. Our hypothesis was that increased aeration would give a higher and faster rise in pH during the composting process, and that this would give a higher decomposition rate. The objective was to test this hypothesis by experiments in full scale, with an emphasis on the role of temperature in the transition from acidic to neutral pH.

Experiments were carried out at two large composting plants. At one plant the temperature and CO_2-concentration were similar during the early processes regardless of aeration rate. At higher aeration rates the pH, decomposition rate and stability became higher. At the other plant higher aeration rates during the first two weeks resulted in much higher pH and intensive decomposition. That compost also received a large water addition to keep the compost moist, and the product from the process was stable.

At both composting plants, increased aeration rates at the start of the process resulted in higher microbial activity and a rapid rise in pH. The increased aeration also gave a more stable end product. The main recommendation for process improvement is therefore to increase the aeration. Increased aeration at the start improved the decomposition, but increased aeration later in the process may also be important.

Increased aeration lead to severe drying of the compost. Heat is produced by microbial activity, and is transported from the compost with the air, mainly by evaporation. Drying is thus a result of decomposition activity. If the aeration is reduced in order to avoid drying of the compost, the activity is also reduced and the product will not become stable. The recommendation thus is to keep the compost moist by adding water, not by reducing aeration.

SAMMANFATTNING

Bakgrund och syfte

Ett antal komposteringsanläggningar i Norden har problem med lågt pH på både ingående avfall och färdig kompost. Dessutom är nedbrytningen långsam och komposten hinner inte stabiliseras under den intensiva, inneslutna processen.

Labskaleförsök vid SLU har visat att pH-ökningen och nedbrytningen i kompostprocessen kan påskyndas avsevärt av höga syre(oxygen)halter och låg temperatur (under 40°C) under den inledande sura fasen. Syftet med de försök som redovisas här var att undersöka om samma effekt kan uppnås i storskaliga anläggningar.

Metod och resultat

Försök genomfördes vid två komposteringsanläggningar. På båda anläggningarna följdes två satser från inlastning till utlastning vid kompostering i en hall där komposten luftas med fläktar och vänds automatiskt med en vändmaskin. Påverkan av olika luftmängder på processparametrar som pH, temperatur, torrsubstanshalt (TS), stabilitet (SOUR), CO_2- och O_2-halt undersöktes.

Vid en anläggning gav olika luftmängder under första veckan i stort sett samma temperatur och CO_2-halt i frånluften, men vid högre luftning blev pH högre liksom nedbrytningen och den uppnådda stabiliteten. Uttorkningen blev kraftig i den kompost som luftades mest.

Vid den andra anläggningen fick man ett betydligt högre pH-värde och intensiv nedbrytning i den kompost som luftades mer under de första två veckorna. Den komposten fick också en stor tillsats av vatten så att TS-halten hölls på en lämplig nivå. Produkten blev stabil. I den kompost som fick mindre luft under de första två veckorna tillfördes också mindre vatten, så TS-halten blev för hög. Den komposten behöll ett lågt pH och nedbrytningen under processen var betydligt sämre.

Diskussion

I rapporten diskuteras sambanden mellan olika processparametrar, bland annat

- hur pH påverkas av temperatur och luftning.
- hur nedbrytningen hänger samman med CO_2, O_2 och temperatur.
- hur uttorkningen beror av nedbrytning och luftning.

Slutsatser och rekommendationer

Den viktigaste rekommendationen för processförbättring är att öka luftningen. Ökad luftning gav ökad nedbrytning och snabbare pH-stigning vid båda anläggningarna. Viktigast är ökad luftning i början av processen, men ökad luftning senare är också av betydelse. Ingen av anläggningarna utnyttjar idag sin fulla luftningskapacitet.

Effekten av temperatur på pH och processutveckling har inte klarlagts fullt ut. I den ena anläggningen hade alla bingar oavsett luftning samma temperatur, 48-56 °C, under den tidiga sura perioden. I den andra anläggningen hade ett stort område i en

binge temperaturer under 40 °C under de första tre dagarna, och detta var förmodligen orsak till den snabba pH-stigningen i den bingen.

Komposten bör hållas fuktig genom att man tillsätter vatten, inte genom att luftningen minskas. Värme bildas vid nedbrytningen och transporteras bort med luften, främst genom avdunstning. Uttorkningen är därför ett resultat av nedbrytningen. Om luftningen minskas för att minska uttorkningen kommer också nedbrytningen att minska och man får inte en stabil produkt. Vid båda anläggningarna finns möjlighet att tillsätta vatten och den möjligheten bör utnyttjas.

Temperaturen är inte en bra processindikator. En hög temperatur kan bero på en hög aktivitet, men det kan också bero på för liten kylning, vilket ger hög temperatur även vid låg aktivitet. En låg temperatur kan bero på för mycket kylning, eller på låg aktivitet orsakad av uttorkning eller brist på syre(oxygen).

En bra processindikator är pH-värdet. Ett högt eller stigande pH betyder att processen fortskrider väl. Ett lågt eller sjunkande pH tyder på att aktiviteten är låg, och då kan man inte vänta sig att få en stabil produkt.

Andra bra processindikator är koldioxidavgången och syreförbrukningen. Denna är ett direkt mått på nedbrytningsaktiviteten. Enbart koncentration av CO_2 eller O_2 säger dock ingenting om nedbrytningsaktiviteten, utan det är koncentrationen multiplicerad med luftmängden som är en användbar processindikator.

PREFACE

Biowaste composting has increased in recent years. Many plants have been constructed and they still need to improve their processes. The project presented in this report is the result of an encounter between practitioners and researchers who had approached the same issue from two different directions. Composting of waste at low pH was fairly unknown and had become an interesting research issue for the compost research group at SLU. At many plants, including the two plants involved in this project, problems with low pH in waste and compost have been faced for several years.

At both Hogstad and Støleheia there is a note on the wall with the following text:

> "Theory is when you know everything and nothing works.
> Practice is when everything works but nobody knows why.
> Here we combine theory and practice: nothing works and
> nobody knows why. "

To me this project proves that the note on the wall is not a guideline for the work at the plants. By combining theory and practice we can understand how the composting process works, and that knowledge can be very useful – both in theory and in practice.

I want to thank everybody at RKR and IVAR for all help with digging up compost, weighing, sampling, measuring, planning experiments and trips as well as many other things. A special thanks to Erik Norgaard for introducing me to the Norwegian composting facilities and making this project possible, and for valuable comments on the report. I also want to thank my advisor Håkan Jönsson for inspiring support through the whole process from the first ideas to the final report.

This work is a part of the project “Improved process control in large-scale composting“ which is financed by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS). RKR and IVAR have also contributed financially to the investigation.

Uppsala, April 2005

Cecilia Sundberg

TABLE OF CONTENTS

1. INTRODUCTION

Composting of biowaste (source-separated biodegradable waste) is an important part in the European Union waste management strategy, which aims at reducing the amounts of waste to landfill and increase recycling of materials and energy. Many composting plants for biowaste have been built in recent years.

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. In active compost, any 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.

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 controlling the microbial activity are moisture, temperature, oxygen, pH and substrate composition (Miller, 1993).

Each microbial species can only grow within a certain temperature range, and most microorganisms are killed by excessive 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).

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).

Biowaste composting in Scandinavia has been troubled by the low pH of the collected waste. The pH is often in the range of 4.5-5.1 (Eklind et al., 1997; Norgaard and Sorheim, 2004). The low pH is caused by short-chain organic acids, mainly lactic acid and acetic acid. These acids are formed anaerobically by microorganisms. The acids can also be decomposed microbially, but the decomposition is slow if the pH is very low. This is especially the case at thermophilic temperatures (Sundberg et al., 2004).

Disadvantages of the low pH of the composting waste include corrosion, odour, slow decomposition and thus inefficient use of the facilities, low compost quality, and difficulties in attaining temperatures high enough for sanitization.

The formation and decomposition of organic acids is dependent on the oxygen level and the temperature. More oxygen gives lower maximum concentrations of organic acids 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 a mesophilic range (below 40 °C) initially, until the pH in the condensate from the outgoing air is above 5 (Smårs et al., 2002). The intention with the experiments reported here was to investigate whether this strategy, to keep the temperature down until pH rises, would function also in large-scale composting. In a small composting reactor, a large proportion of the heat released during composting is lost through surface cooling, but in a large-scale plant the major means of cooling is by aeration and evaporation of moisture. It is thus more difficult to cool large compost volumes, and there is a risk of excessive and premature drying of the compost.

In this report, results from experiments carried out in June-October 2004 at two Norwegian composting plants are reported.

1.1. Objective

Our hypothesis was that increased aeration would give a higher and faster rise in pH during the composting process, and that this would give a higher decomposition rate. The objective was to test this hypothesis by experiments in full scale, with an emphasis on the role of temperature in the transition from acidic to neutral pH. Would the aeration capacity be high enough to keep the temperature below 40°C during the low-pH-phase? Would the aeration rate affect pH even if the temperature increased above 40°C?

A further objective was to evaluate the value of different parameters as indicators of microbial activity in the investigated composting processes. Finally, we wanted to investigate the extent of drying caused by the increased aeration, and thus the need for water addition.

2. MATERIALS & METHODS

2.1. The composting plants

The Støleheia composting facility, managed by the municipal company Renovasjonsselskapet for Kristiansandsregionen (RKR) in Vennesla municipality near Kristiansand, Norway, treats biowaste (source-separated household food waste, 11 000 tons in 2004) from a region with about 100 000 inhabitants. The substrate is prepared by mixing the biowaste with crushed yard waste and wood waste as structural amendments. The waste mixture is then loaded into reinforced concrete bays in which air is blown from below. The composting bays are 2.8 m wide, 2.2 m deep and 64 m long. They are aerated in 5 separate zones (A-E) and the material is turned by mechanised agitators at intervals of 2-3 days, and each time moved 4.2 m towards the end of the hall. The residence time in each zone is 5-7 days. After 30-40 days of composting the compost is cured indoors in aerated piles for about a month, before being screened, cured outdoors for several months and then used in soil mixtures.

The Hogstad composting facility, managed by the municipal company IVAR in the Stavanger region in Norway treats 25 000 tons of biowaste per year. The substrate is prepared from biowaste mixed with crushed wood waste as a structural amendment. The waste mixture is composted in reinforced concrete bays 5 m wide, 42 m long and 2.5 m high, though they are only filled to 2 m height. They are aerated by negative aeration, drawing the gases out through perforated floors below the bays. The aeration is in 4 zones, 7-15 m long along the length of the hall. The material is turned every 2-4 days and moved 4.7 m each time. After 9 turns, 20-30 days of composting, the compost is moved to piles where it is cured indoors for 3-4 weeks.

2.2. Experimental set-up

At RKR, two successive batches in three composting bays were monitored. Each bay had a different aeration scheme whereas other factors were kept as similar as possible. The variations between the bays were due both to different fan sizes and to different on/off intervals (Table 2.1). The same substrate was used in all three bays, although it differed between the batches. All bays were turned on the same days. Water was added in different amounts (see section 3.2.2) since drying differed between the bays. Water was added by spraying on top of the bays for 5-20 min per hour during nighttime.

At IVAR, three batches in two composting bays were monitored. Each bay had a different aeration scheme, whereas other factors, such as turning frequency, were kept as similar as possible. The aeration was continuous in all bays, but valves were used to vary the rates. Negative aeration (drawing the gases out through perforated floors below the bays) was used in all zones except for the first zone in Bay 8, where air was blown into the material from below. Water was added in different amounts (see section 4) since the aeration rate and thus the drying differed between the bays. Water was added and mixed in during turning of the compost.

Table 2.1 Aeration scheme at RKR

	Bay 1	Bay 2	Bay 3
Zone A	2 min on 10 min off	Continuous[1]	Continuous[2]
Zone B	1 min on 10 min off	1 min on 10 min off	5 min on 10 min off
Zones C-E	2 min on 60 min off	2 min on 60 min off	2 min on 60 min off

[1] Maximum fan capacity: 2500 m^3/h.

[2] Maximum fan capacity: 5000 m^3/h.

2.3. Substrate preparation procedure

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 at arrival to open the bags. At RKR, the waste (73 % on wet weight basis) was mixed with recirculated compost (>10 mm, 11%), garden and park waste (8%), and wood chips (coarse 5% and fine 3%), which provided structure to the composting substrate. At IVAR, a mixture of waste (72 % on wet weight basis), recirculated structure material (>20mm, 14 %) and crushed wood (13 %) was used. At both RKR and IVAR the mixture was sieved in a drum sieve to remove plastic bags before being entered into the composting bays.

2.4. Sampling

2.4.1. RKR

From the substrate mixture for Batch 1, 10 one-litre grab samples were taken from the pile during loading. The intention was to get diverse samples, so that the sample variance would be a measure of the variation within the substrate mix. (In that case, variations between the different treatments could be related to the variance of the substrate, i.e. a between-treatment variation larger than the within-substrate variance could be judged as significant.) Substrate samples from Batch 2 were taken according to a different method– a 10-litre bucket was filled with samples from various places in the pile. These samples were mixed thoroughly by hand, and one-litre samples were taken out. Samples from the composting process were taken as one-litre grab samples.

Off-gas was collected in 0.4 m high upside-down trays covering 0.95*1.15 m, with a hole (diameter 0.14 m) for the gas to flow through. Gas samples were taken from within the tray. Condensate samples (10-100 millilitres) were collected with a sponge from inside the trays.

2.4.2. IVAR

Five 5-litre grab samples were taken of the substrate during loading. Samples from the composting process were taken as three 5-litre grab samples from each batch.

From Bay 8, zone A, off-gas was collected in a 0.5 m high circular tray with diameter 0.7 m with a hole (diameter 0.07m) for the gas to flow through. Gas samples were taken from the volume covered by the tray. Condensate samples (5-100 millilitres) were collected from inside the trays. In the other bays and zones the gas concentrations were measured in the off-gas pipes and no condensate samples were collected.

2.5. Physical and chemical analyses

Temperature was measured with encapsulated sensors and loggers (Tiny Splash, Geminiloggers, INTAB, Sweden), which were placed in the compost at 0.3 m depth (RKR) and 0.5-1 m depth (IVAR) from the surface. Temperature was recorded every 5 minutes. Temperature was also measured manually with temperature probes placed in the compost mass. At IVAR, temperature was also registered in the off-gas channels with pre-installed sensors connected to the process computers.

Oxygen and carbon dioxide concentrations were measured with a multi-gas analyser, GA 2000 (Geotechnical Instruments, UK). The instrument measures oxygen with a galvanic cell sensor and carbon dioxide 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). Substrate and compost samples of 12 g were mixed with 60 ml of deionised water. Samples for pH was taken randomly from the large samples, but pieces larger than 2-3 g were avoided. The samples were shaken for a few seconds and pH was measured after 1 hour. The pH was also measured on the condensate, either on pure condensate or, in case of small samples, diluted with deionised water.

At RKR airflow was measured with a vane anemometer (Testo 435, Testo, Germany) in the inlet air pipes. At IVAR, a VelociCalc Plus Multi-Parameter Ventilation Meter was used to measure airflow and relative humidity in the exhaust gas pipes. Airflow was also measured with a hot-wire anemometer (SwemaAir 300, Swema, Sweden) at IVAR.

At RKR, dry matter concentration was determined on 30-90 g samples dried at 105 °C for 24 h. At IVAR, dry matter was also determined by drying 1 kg samples at 105 °C for 72 hours. Volatile solids concentration was determined as ignition loss in dry sieved (10 mm) samples kept at 550 °C for 3 hours.

The soluble oxygen uptake rate (SOUR) was measured on sieved (10 mm) samples mixed with water, according to the method described in Lasaridi & Stentiford (1996), though without nutrient amendments.

Nitrogen (Kjeldahl-N) was measured on materials samples by Jordforsk.

2.6. Statistical and mathematical analysis

The carbon dioxide emissions were calculated from airflow and the CO_2 concentration in the gas outflow. The heat flow was estimated from the specific heat capacities of dry air and steam, the enthalpy of evaporation and measured values of airflow, input and output temperature (Sundberg, 2003). The relative humidity was assumed to be 100% on both inflow and outflow.

The degree of decomposition can be estimated from the volatile solids (VS) content:

$$k = \frac{(VS_i - VS_o)\cdot 100}{VS_i \cdot (100 - VS_o)} \qquad \text{(Haug, 1993)}$$

The degree of decomposition, k, is calculated from the volatile solids of the input and output (VS_i and VS_o) given as % of TS. This method is based on the assumption that the inert matter (ash) of the material is conserved during the process, and thus the VS percentage of the compost decreases as organic matter is decomposed.

The nitrogen data from IVAR were statistically analysed by analysis of variance performed with the GLM procedure in the SAS System 8.01 (SAS Institute, 1999-2000) statistical software. The correlation between heat and carbon dioxide values at RKR were analysed by linear regression with the function *polyfit* in MATLAB 6.5 (The Mathworks, 2003).

3. RESULTS AND DISCUSSION OF EXPERIMENT AT RKR

3.1. Early process

3.1.1. Aeration

The measured aeration rates during the beginning of the process are presented in Figure 3.1. In Bay 1 the aeration was intermittent, and the average aeration rate is presented. In Bays 2 and 3 the aeration was continuous. The bays (1,2 and 3) are referred to in order of aeration rate with the lowest rate in Bay 1.[1]

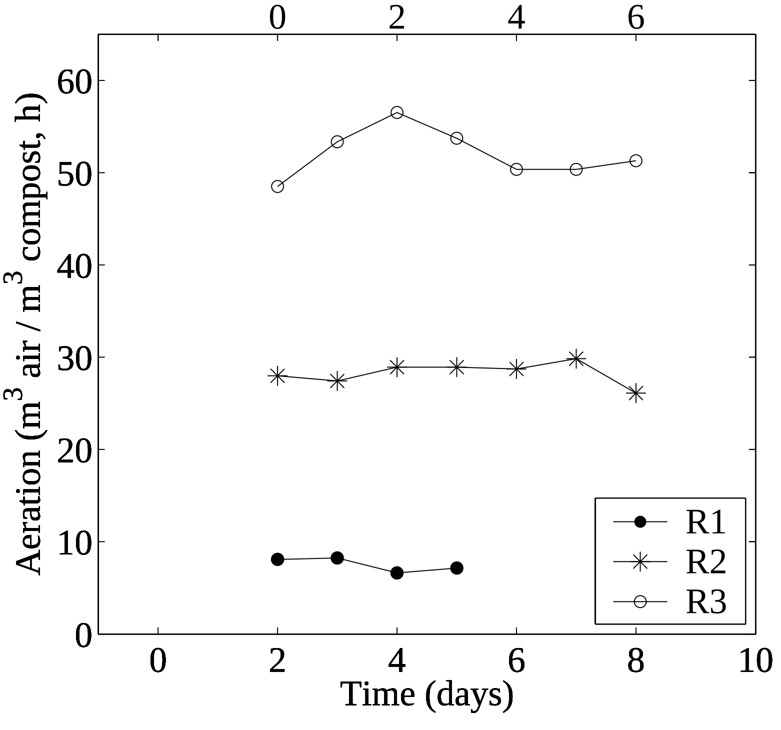


Figure 3.1. Airflow at RKR in Bay 1 (.), Bay 2 (*) and Bay 3 (o). Time for batch 1 and 2 below and above figure, respectively.

---

[1] Internal RKR numbering: Bay 9 = 1, Bay 7 = 2, Bay 6 = 3.

3.1.2. Temperature, CO_2, O_2 and pH

Some parameters were very similar in all bays and batches. The temperature increased rapidly to 40-50°C within a day or two, then stayed near 50°C, and in some cases increased to 60-70°C after about a week (Figure 3.2). Although the temperatures in the material at 0.5 m depth were quite similar in all bays, the temperatures in the exhaust air were considerably lower in Bay 1. This may be an effect of the intermittent aeration in this bay, which affected the measurements of the off-gas temperature.

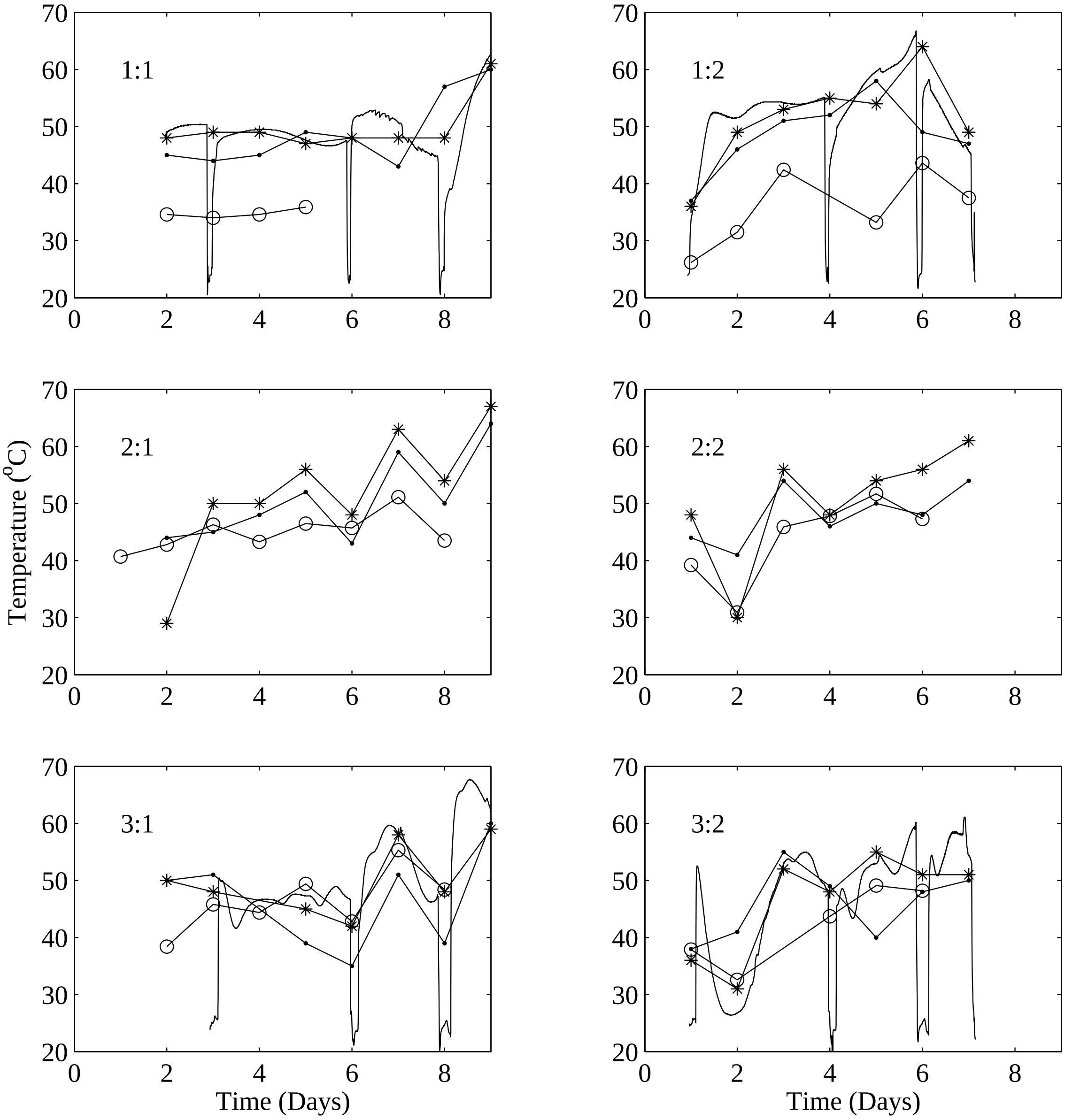


Figure 3.2. The temperature during the first 9 days at RKR. Bay 1 (top), Bay 2 (middle) and Bay 3 (below); Batch 1 (left) and Batch 2 (right). The temperatures were measured at the center of the bay at 0.5 m depth (*), near the edge of the bay at 0.5 m depth (.) and in the off-gas across the bay (o). In Bay 1 and Bay 3 the temperature was also logged every 5 min. at 0.5 m in the center of the bay (solid line). The short periods of 20-30 °C indicate turning of the compost.

The carbon dioxide concentrations in the exhaust gas were 0.5-2% in most cases and there were no distinct trends (Figure 3.3). The oxygen concentrations were 17-20%, indicating aerobic conditions in the compost. The pH values, however, varied over time and between batches, and this information, which is presented in Figures 3.4-3.6 and discussed below, can be used to evaluate the process in the different bays.

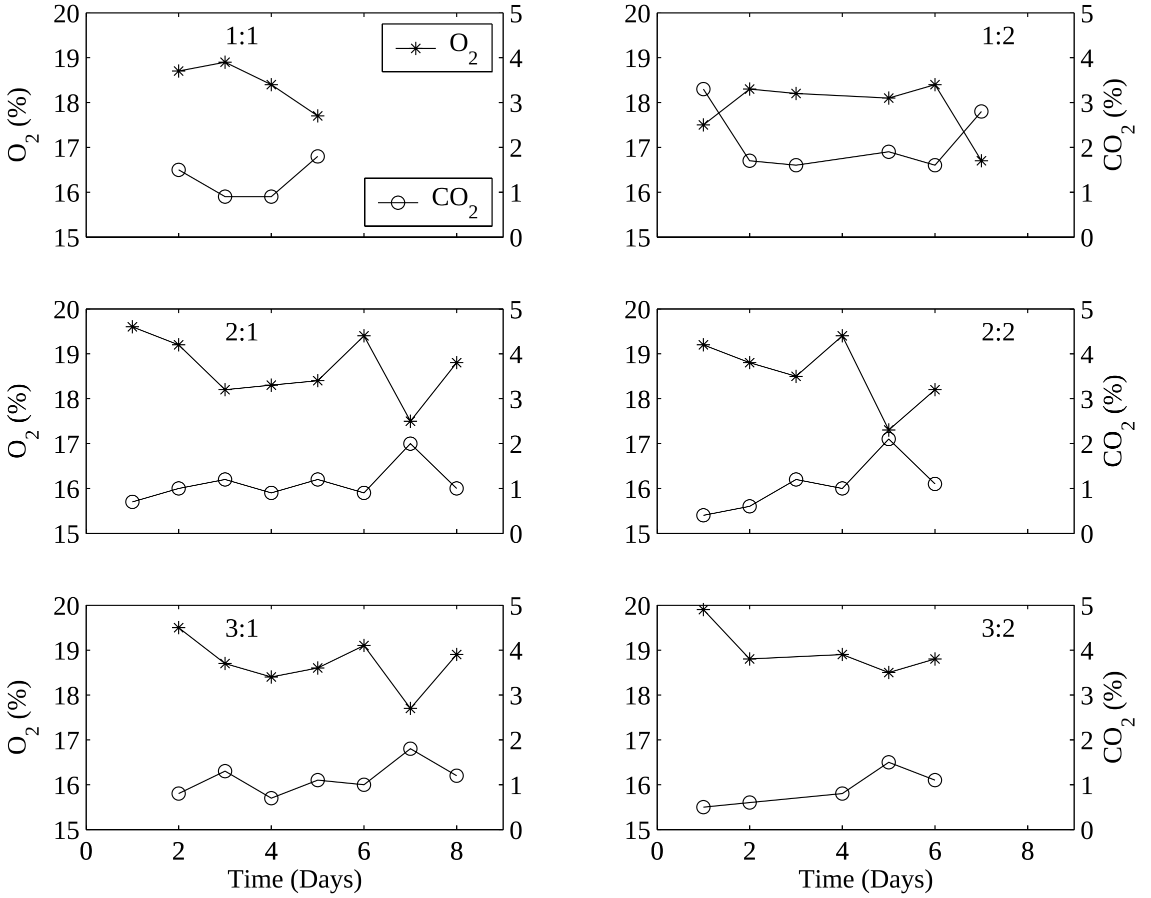


Figure 3.3. Oxygen (*) and carbon dioxide (o) concentrations in the exhaust gases at RKR. Bay 1 (top), Bay 2 (middle) and Bay 3 (below); Batch 1 (left) and Batch 2 (right).

3.1.3. Bay 1 – Low aeration rate

The process in Bay 1, batch 1, showed little activity during the first week. The temperature was constant between 45-50 °C (Fig 3.2), the dry matter concentration only increased slightly (Fig 3.4) and the pH in the material did not change much (Fig 3.6). There were problems with the gas analysis, so there is only data from days 2-5 (Fig 3.3). This gas data shows that although there was a CO_2 content of 1-2% in the exit air, this was not a sign of high activity, and this is related to the low airflow (this is further discussed in section 5.6). During Days 8 and 9, however, there was an increase in both temperature and condensate-pH (Fig 3.2 and 3.4). This indicates that the process was starting, after one week of very little activity.

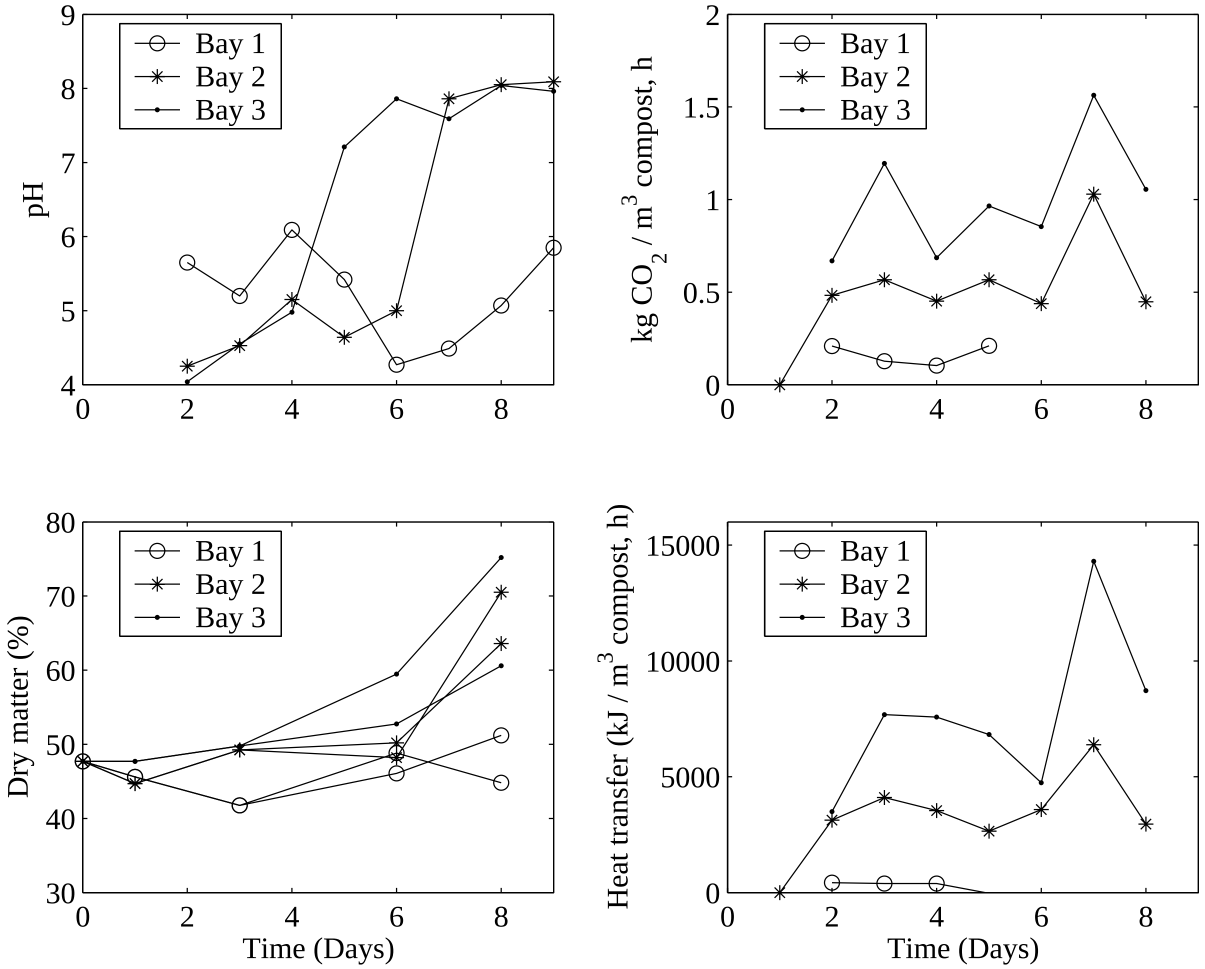


Figure 3.4. Physical and chemical data from Batch 1 at RKR: pH in the condensate (top left), dry matter concentration (bottom left), carbon dioxide emissions (top right) and heat emitted with exhaust air (bottom right). Dry matter in samples from both edge and centre are presented.

The second batch in the same bay developed similarly. There was very little activity until Day 6-7, when the temperature and the pH in the condensate started to rise (Fig 3.2 and 3.5).

3.1.4. Bay 2 – Medium aeration rate

Bay 2 received 3-4 times as much air as Bay 1, and this aeration was continuous. In this bay the temperature showed an increasing trend in both batches. The trend was irregular, probably because of the turning of the compost (Fig 3.2). During the first two days the temperatures were lower than in Bay 1, but thereafter they were higher. The dry matter content increased drastically on Day 8 in batch 1, and less drastically on Day 6 in batch 2. The pH in the condensate increased sharply after 6-7 days. The increasing temperature is an indication of increasing activity, and this is confirmed by the carbon dioxide emissions (Figures 3.4 and 3.5). The CO_2 emissions were considerably higher in Bay 2 than in Bay 1.

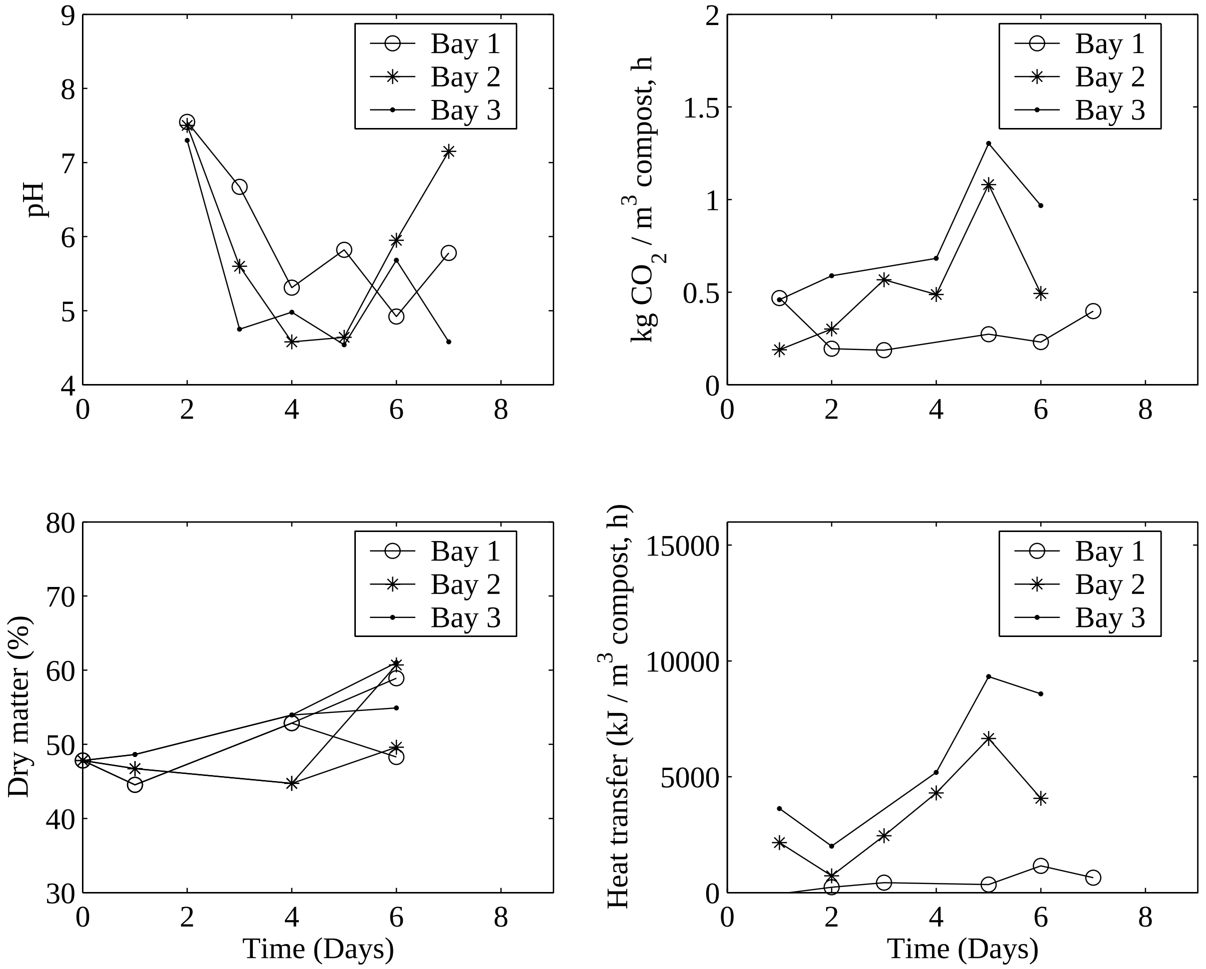


Figure 3.5. Physical and chemical data from Batch 2 at RKR: pH in the condensate (top left), dry matter concentration (bottom left), carbon dioxide emissions (top right) and heat emitted with exhaust air (bottom right). Dry matter in samples from both edge and centre are presented.

3.1.5. Bay 3 – High aeration rate

Bay 3 received almost twice as much air as Bay 2. In the first batch, the temperature was rather variable, with a constant or slowly decreasing trend followed by an increase on Day 7 (Figure 3.2). The dry matter content increased and reached very high levels, probably enough to cause inhibition of the process, on Day 8 in Batch 1. The pH in the condensate increased from acidic to alkaline already on Day 5, and the pH in the material increased during the following days (Figure 3.6). The carbon dioxide concentration in the exhaust gas was similar to Bay 2, but due to the higher aeration rate (Figure 3.3), the carbon dioxide emissions were much higher, especially in Batch 1 (Figure 3.4). This is sign of considerable activity in the compost.

The second batch in Bay 3 was similar to the first, but the temperature had a rising trend during the first few days, and the increase in pH was not as evident as in the first batch (Figure 3.6).

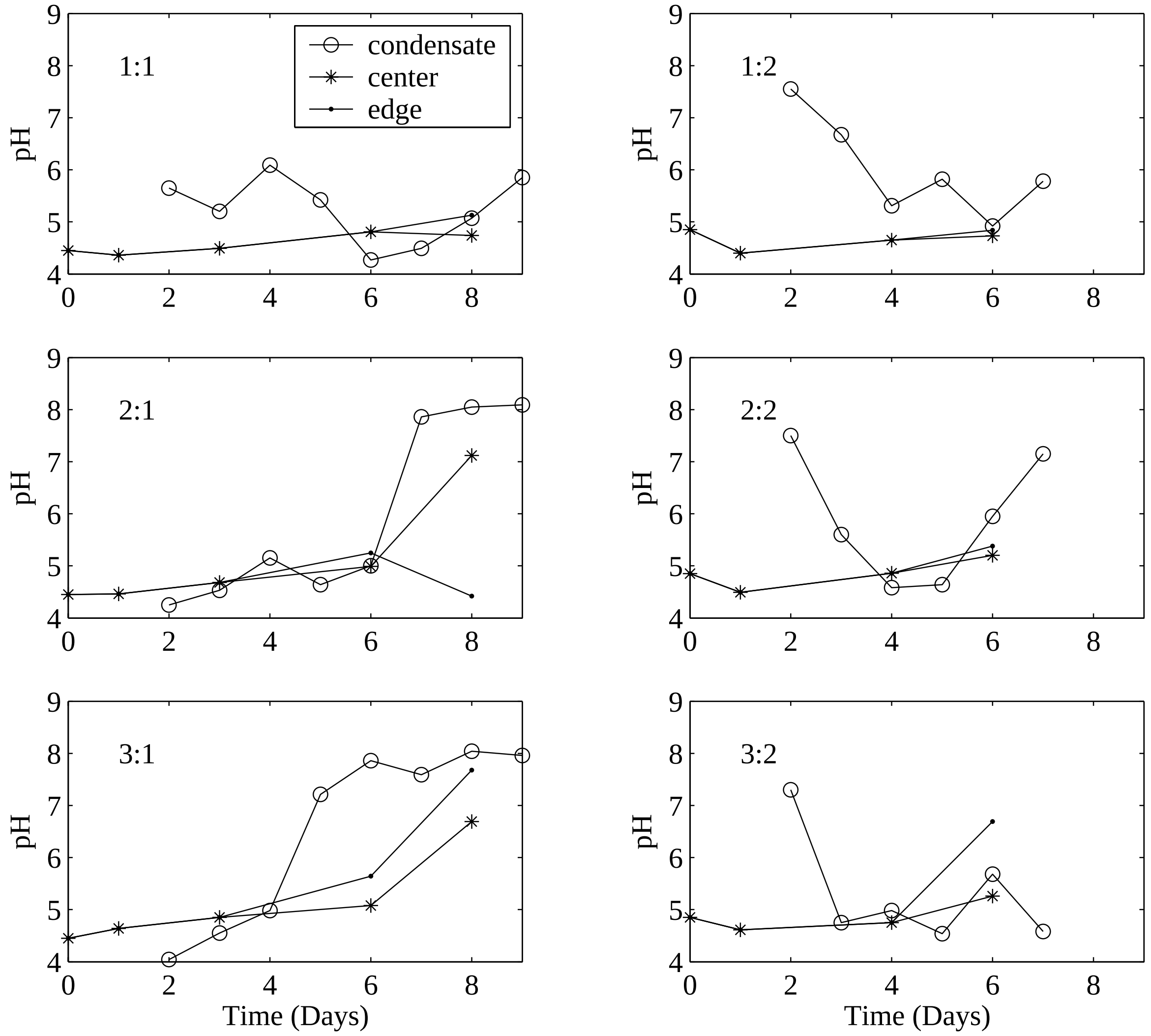


Figure 3.6. The pH in the condensate (o) and in material samples; in the center(*) and edge (.) of the bays. Bay 1 (top), Bay 2 (middle) and Bay 3 (below); Batch 1 (left) and Batch 2 (right).

In almost all batches, high temperatures and high carbon dioxide emissions were recorded on the 22nd of June, Day 7 (Batch 1) or 5 (Batch 2). A possible cause for this was the turning of the compost on the day before (on the 21st), which may have activated the processes. This hypothesis is supported by the fact that the temperature increased also on the 24th in the first batch in Bays 2 and 3 (Fig 3.2), and that was also the day after turning.

3.2. Later process

3.2.1. Temperature and gas concentrations

During the later part of the process, only a few measurements were made. The temperature in the mass was measured, as well as the gas concentrations in the exhaust. Since the bays were only aerated for two minutes every hour, the aeration resulted in a short peak in CO_2 emissions. The data are thus rather unreliable, but the temperatures and maximum CO_2 emissions are shown in Figure 3.7. The temperatures were higher in Bay 2 and Bay 3 and the CO_2 emissions were highest in Bay 3. Thus there was more decomposition in this bay, which had the highest pH rise and the fastest decomposition during the initial phase (see above, section 3.1.5).

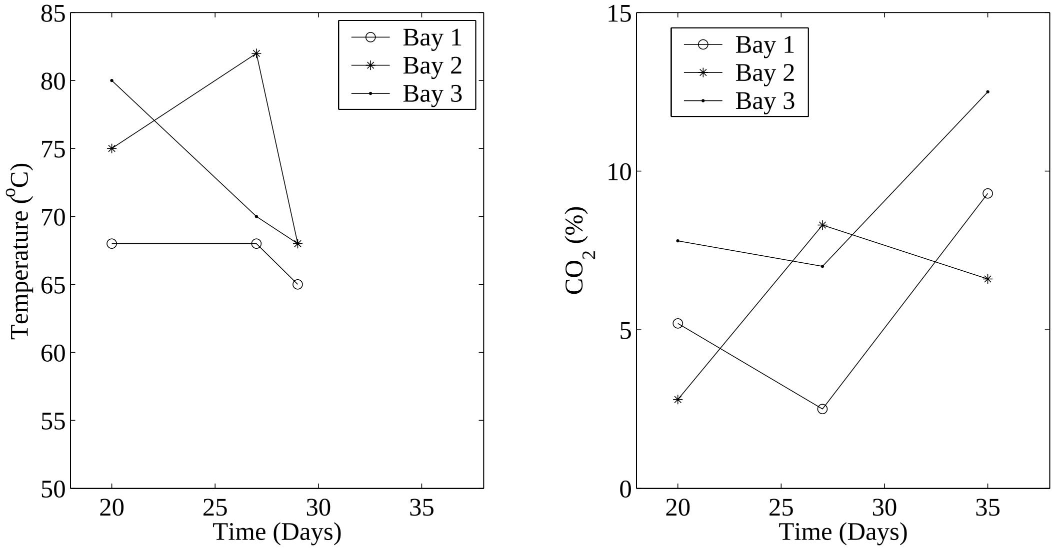


Figure 3.7. Later part of process at RKR. Temperature (left) and peak carbon dioxide concentration in exhaust (right).

3.2.2. Dry matter and water

The dry matter concentration increased in all batches. The smallest increase was in Bay 1 and the largest in Bay 2. The water addition was set to give more water to the bay that received more aeration. The dry matter concentration in the end product was similar to the values measured after 8-9 days of composting (Figures 3.4 and 3.5), so most of the drying occurred during the initial phase. During the later stages the aeration rate and the drying was smaller, and it was countered by the water addition.

Table 3.1. Dry matter concentration in substrate and finished compost, as well as total water addition, in the different bays and batches at RKR. Standard deviations in parenthesis

	Dry matter (g/g fresh weight)	Added water (m^3/batch)	Added water (m^3/ m^3 waste)
Substrate 1	0.477 (0.024)	-	-
Substrate 2	0.478 (0.033)	-	-
Batch 1:1	0.483 (0.052)	4.1	0.16
Batch 1:2	0.528 (0.083)	4.1	0.16
Batch 2:1	0.604 (0.115)	8.2	0.32
Batch 2:2	0.607 (0.068)	8.2	0.32
Batch 3:1	0.581 (0.049)	11.5	0.44
Batch 3:2	0.562 (0.101)	11.5	0.44

3.2.3. Decomposition and stability

During the process the SOUR decreased by 20-50% in the bay with least aeration (Bay 1) and by more than 60 % in the bay with intermediate aeration (Table 3.2). The final values (4.7-9.8 g O_2/kg VS,h) still indicate rather unstable compost. Unfortunately, SOUR was not determined for the bay with the highest aeration rate. However, the development during the first week, as well as the final neutral pH in this bay, are signs that this compost was more stable than the other two. From the volatile solids content it was estimated that 31-42% of the organic matter was decomposed in Bay 1 and 45-52% in Bay 2. The result that there was higher decomposition in Bay 2 than in Bay 1 is more reliable than the absolute values.

Table 3.2. Properties of waste substrate and compost output from the enclosed process at RKR. Standard deviations in parenthesis

	Volatile solids (g/g dry matter)	pH	SOUR (g O_2/kg VS,h)
Substrate 1	-	4.5 (0.1)	-
Substrate 2	0.844 (0.086)	4.8 (0.2)	12.2 (2.4)
Batch 1:1	0.789 (0.043)	5.4 (0.3)	9.8 (1.7)
Batch 1:2	0.759 (0.061)	6.3 (0.6)	5.8 (2.6)
Batch 2:1	0.750 (0.011)	6.2 (0.4)	4.7 (0.2)
Batch 2:2	0.728 (0.002)	6.4 (0.1)	4.7 (0.2)
Batch 3:1	-	7.0 (0.2)	-
Batch 3:2	-	7.1 (0.5)	-

4. RESULTS AND DISCUSSION OF EXPERIMENT AT IVAR

No major differences were observed between the two batches in Bay 8 and the three batches in Bay 1, respectively. Therefore the 2-3 batches in each bay are discussed together.

4.1. Aeration

In Zone A the aeration rate was about three times higher in Bay 8 than in Bay 1 (Figure 4.1). Bay 8 also received more air than Bay 1 in the next zone. In both bays the aeration rate was much higher in Zone A than in later zones. No distinct differences in aeration rate between the two bays were seen after 10 days (in zones C-E).

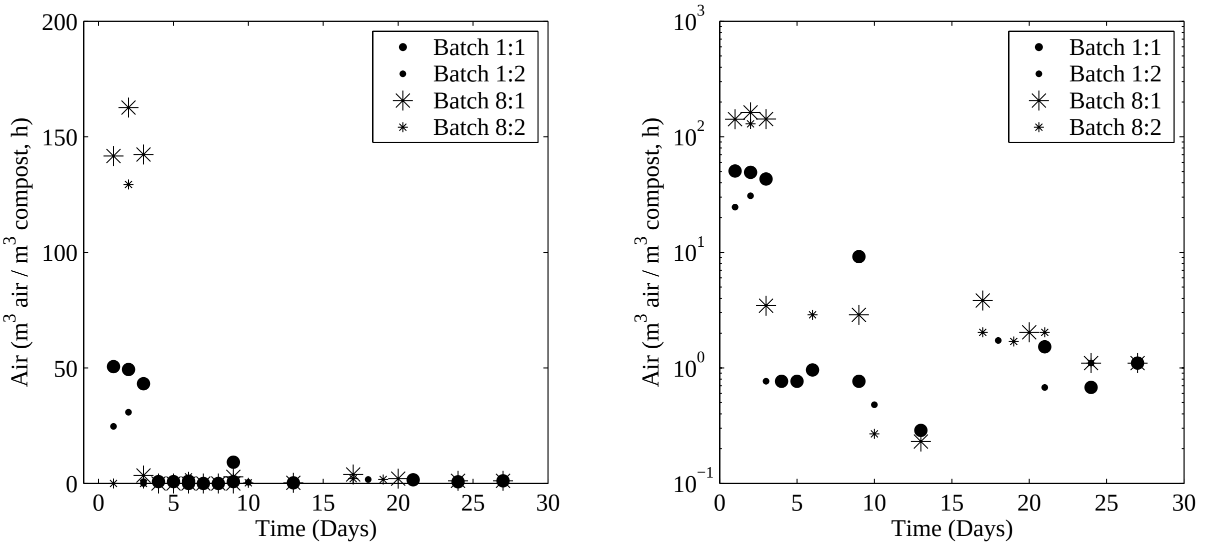


Figure 4.1. Air volumes (m^3/h per batch) at IVAR. The same data is shown both with a linear scale (left) and a logarithmic scale (right).

The measurement of air volumes was troubled by problems with the instruments. This was because the air volumes were measured on the exhaust from the compost, which was hot and humid. Furthermore, air volumes were often measured shortly after turning, and decreased aeration due to compaction between turnings was not investigated. Therefore there are large uncertainties as well as many gaps in the data, and it can thus not be used for estimations of the carbon dioxide emissions or oxygen consumption, as was done with the data from RKR (section 3.1).

4.2. pH

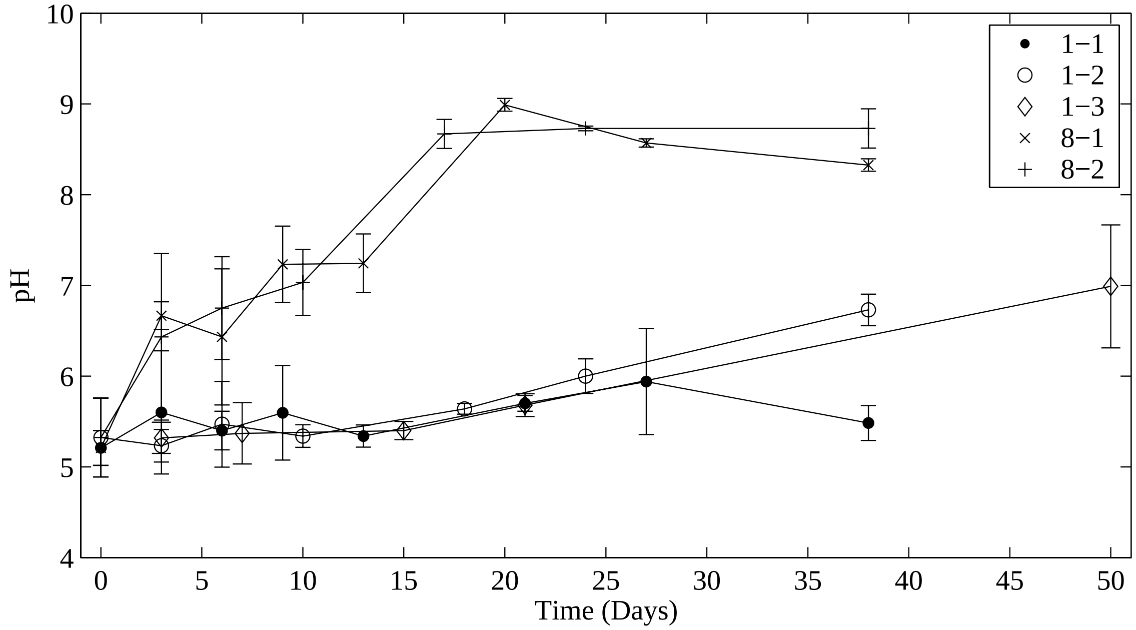


Figure 4.2. The pH development in the different batches during the composting process at IVAR. The standard deviation is shown in errorbars.

In Bay 1, the pH did not change significantly during the first 25 days. After that it increased (in two of the three batches) but still remained below 7 (Figure 4.2). In Bay 8, on the contrary, there was a significant rise in pH from the start, which continued for 2-3 weeks. Already after 3 days, the pH had increased by more than one pH-unit.

Two major factors, oxygen supply and temperature, have been shown to be important for the pH rise in acidic composts (Smårs et al., 2002; Beck-Friis et al., 2003). In this case it is clear that there was a larger oxygen supply to Bay 8 during the first week (Figure 4.1) but the oxygen concentration in the exhaust gas was not higher. The temperature effect is not evident, as discussed below.

4.3. Temperature

The on-line temperature measurements in Bay 8 had a repeated pattern in the two successive batches, but with large variations within the mass in each batch (Figure 4.3). In one part of the batch, the temperature was kept cool, 16-36°C. In another part, closer to the previous batch, the temperature was higher, 46-54 °C after a 24 h heating period. The cool temperatures in this batch were confirmed by the manual temperature measurements at 6 places (depth 0.5-1.3 m deep), which gave temperatures ranging from 22 to 36°C. Since that bay was aerated from below, the top half of the mass was most likely warmer than the lower part.

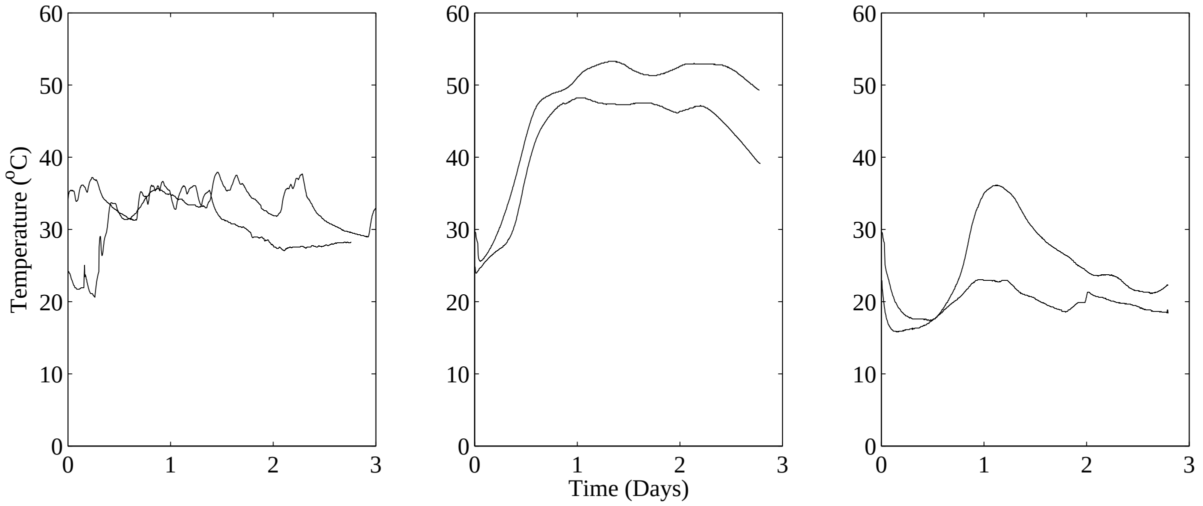


Figure 4.3. Temperature in the mass during the start of composting in Bay 1, Batch 1 and 3 (left) and at two different sites in Bay 8, Batch 1 and 2 (center and right).

In Bay 1, the different temperature measurements gave diverging results. The sensors for on-line temperature measurement, which were placed at 0.5-1 m depth, measured temperatures below 38°C in both batches (Figure 4.3). The manual measurements (5 places at 0.5-1.3 m depth), however, measured 42-68°C. The temperature in the exhaust gas was about 50°C after a heating period of about 12 hours, in the two batches were the temperature was measured at that time (Figure 4.4). Those measurements indicate that most of the mass in Bay 1 was not cooled enough to remain mesophilic. The low temperature measured by the buried sensors may be explained by the fact that they were placed rather high, and since in this bay the air was sucked down, the highest temperatures were in the lower part.

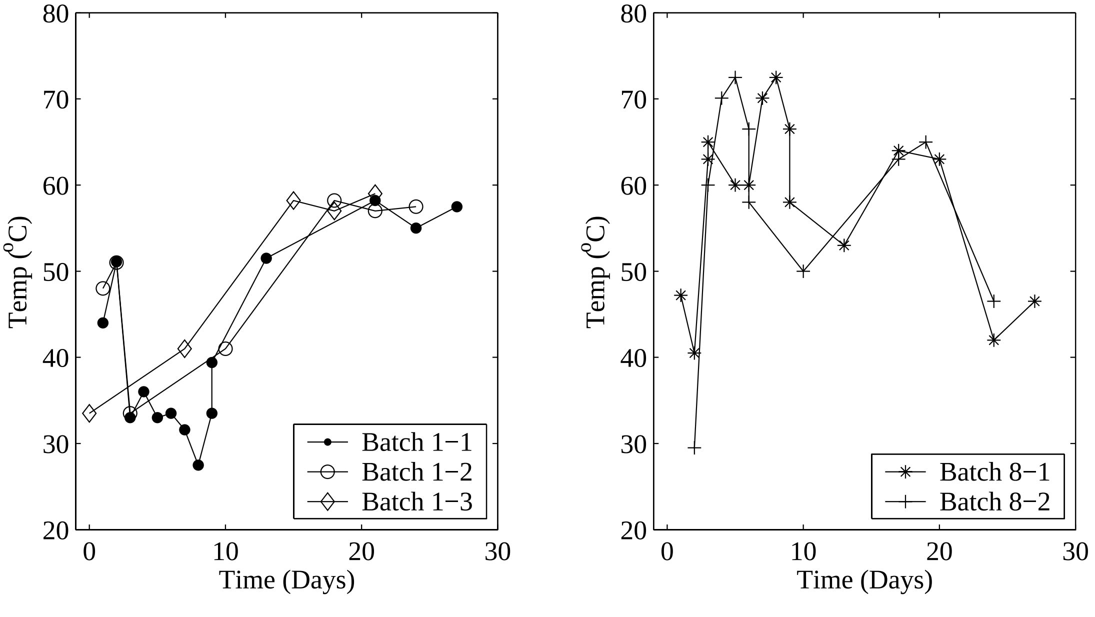


Figure 4.4. Temperature in the exhaust gas from Bay 1(left) and Bay 8 (right).

In summary, the interpretation of the temperature data given above gives at hand that the temperature was below 35-40°C in a large part of Bay 8 during the first 3 days, whereas it was between 40 and 60°C in most of Bay 1 during that time period.

All temperatures measured with the buried sensors declined after some time (Figure 4.3). In two cases this occurred after 1 ½ days and in four cases after 2 ½ days. This decline in temperature indicates a declining activity, and this shows that 2-3 days is a suitable time period for turning and /or water addition, since such measures will increase the activity.

Later during the process the temperature in the off-gases was below 60°C during most of the time in Bay 1 and above 60°C during half of the time in Bay 8 (Figure 4.4). In Bay 1, temperatures below 40 °C were measured during the second week (in Zone B). It is suspected that there was something wrong with the aeration, that part of the airflow did not pass through the compost mass, but by-passed it somehow. That would explain the low off-gas temperatures.

4.4. Oxygen and carbon dioxide

The oxygen and carbon dioxide concentrations add up to 20-21%, indicating that the process was aerobic (Figure 4.5). Nevertheless, the carbon dioxide concentrations were high, often more than 5%.

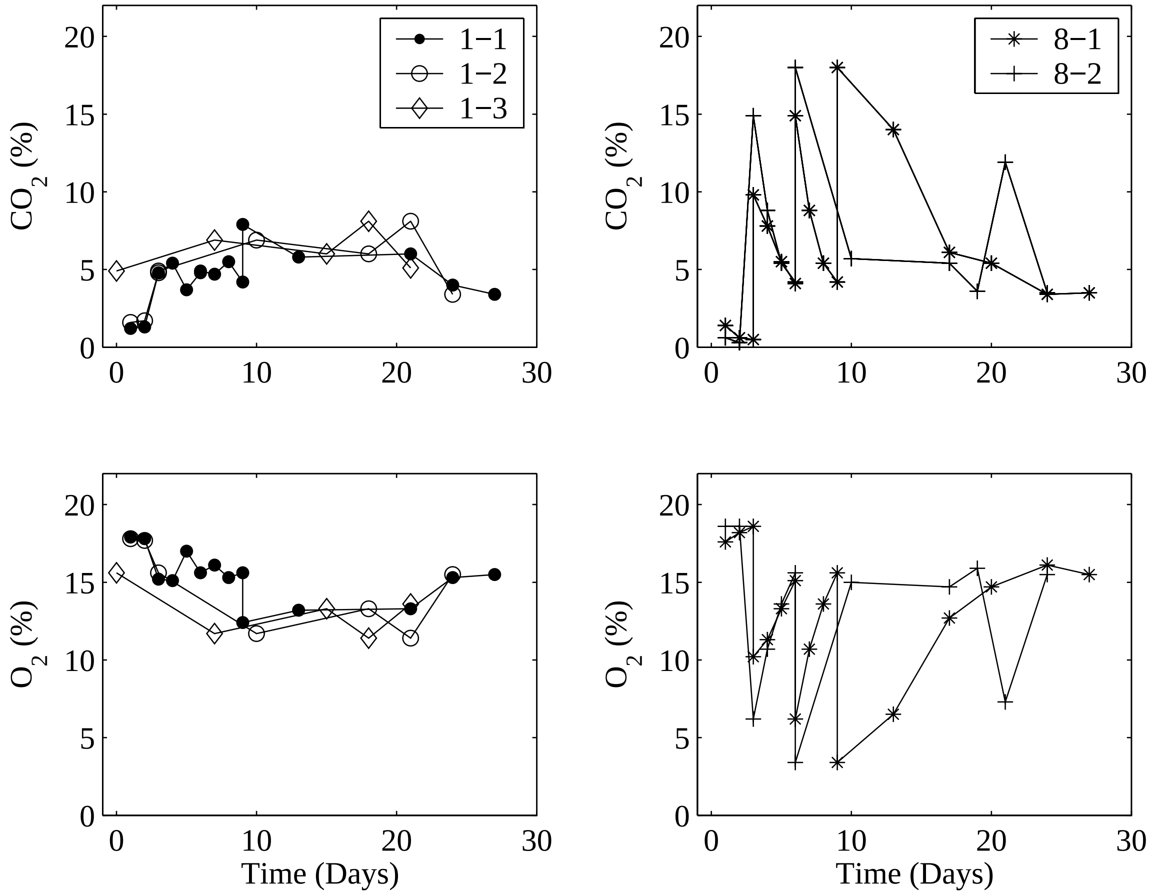


Figure 4.5. Carbon dioxide (top) and oxygen (below) concentrations in the exhaust from the compost mass in Bay 1 (left) and Bay 8 (right). The results are given as volume percentage of dry air.

In Bay 8 there were peaks in carbon dioxide emissions and oxygen consumption after turning. This was because the process was 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 (Appendix 1). There was no such pattern in Bay 1, neither in carbon dioxide nor temperature, so there was no obvious sign of reaction upon turning.

4.5. Dry matter and water

During the process there was a large increase in dry matter concentration in Bay 1 but not in Bay 8 (Figure 4.6). This is explained by the larger water addition to Bay 8 (Table 4.1). In Bay 1, large amounts of water were added at unloading, resulting in only slighter higher solids content in the output compost.

Table 4.1. Water addition at IVAR

	Water (m^3/batch)	Water (m^3/ton wet weight in)	Water (m^3/ton dry weight in)	Water (m^3/ m^3 waste in)
Batch 1:1	3.7	0.09	0.21	0.08
Batch 1:2	6.3	0.22	0.46	0.13
Batch 8:1	24.6	0.65	1.5	0.52
Batch 8:2	23.0	0.78	1.7	0.49

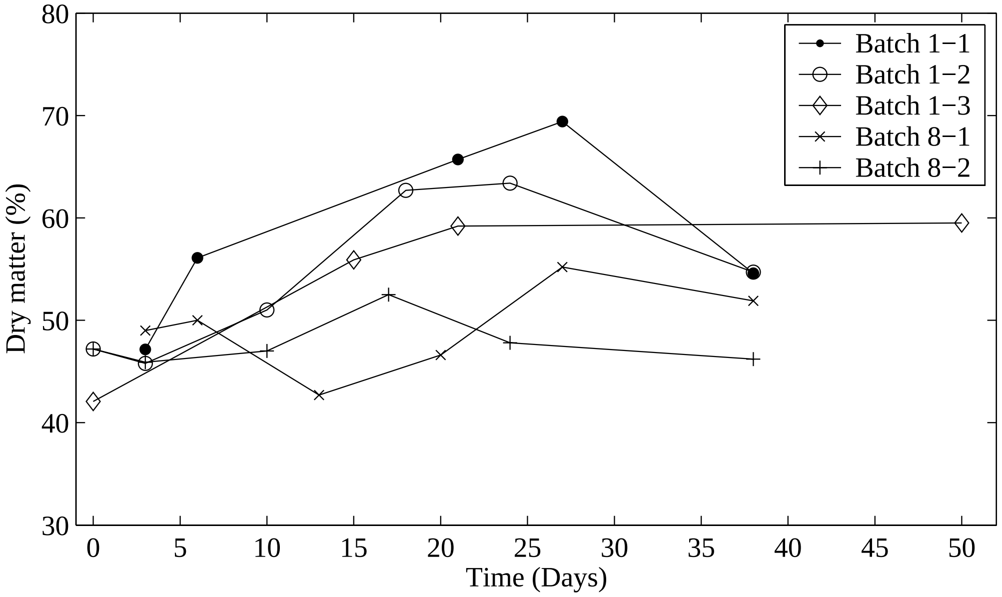


Figure 4.6. Dry matter content during the composting process at IVAR.

4.6. Decomposition and stability

During the composting process the specific oxygen uptake rate (SOUR) decreased by less than 30% in Bay 1 and by 80-90% in Bay 8 (Table 4.2). The resulting SOUR of 1.0 in Bay 8 Batch 1 is indicative of stable compost (Lasaridi and Stentiford, 1998).

Table 4.2. Properties of waste substrate and finished compost from the enclosed process at IVAR. Standard deviations in parenthesis

	Dry matter (g/g fresh weight)	Volatile solids (g/g dry matter)	pH	SOUR ($g\ O_2/kg\ VS,h$)
Substrate 1	0.394	0.712	5.21 (0.19)	10.6
Substrate 2	0.400	0.631	5.32 (0.43)	16.3
Substrate 3	0.415	0.717	-	18.0
Batch 1:1	0.552 (0.032)	0.661 (0.023)	5.48 (0.19)	9.4 (1.1)
Batch 1:2	0.522 (0.006)	0.647 (0.017)	6.73 (0.17)	9.4 (1.1)
Batch 1:3	0.604 (0.032)	0.614 (0.022)	6.99 (0.68)	4.9 (1.1)
Batch 8:1	0.503 (0.010)	0.548 (0.018)	8.33 (0.07)	1.0 (0.2)
Batch 8:2	0.469 (0.009)	0.567 (0.037)	8.73 (0.22)	2.3 (1.2)

By the volatile solids loss method it was estimated that 11-16% of the organic matter was decomposed in Bay 1 and 40-45% in Bay 8. From the mass balance (Table 4.3) it is estimated that 28 % of the organic matter was decomposed in Bay 1 and 44% in Bay 8. However, the mass balance is very uncertain (see section 5.8). Nevertheless, judging from the temperature, pH, CO_2 emissions and SOUR there is no doubt that the decomposition was larger in Bay 8 than in Bay 1.

Table 4.3. Mass balance wet mass, dry mass and volatile mass of two batches at IVAR. No mass balance was done for batch 1:3. Input and output masses in tonnes (t) and mass losses as % of input mass

	Wet mass			Dry mass			Volatile mass		
Batch	Input (t)	Output (t)	Loss (%)	Input (t)	Output (t)	Loss (%)	Input (t)	Output (t)	Loss (%)
1:1	41.7	19.3	53.7	17.6	10.5	40.1	12.1	7.0	42.4
1:2	29.2	24.0	17.7	13.8	13.1	4.7	9.5	8.5	10.2
1:1+1:2	70.9	43.3	38.9	31.4	23.7	24.6	21.6	15.5	28.3
8:1	38.0	20.7	45.6	16.0	10.7	33.1	11.0	5.9	46.7
8:2	29.2	21.3	27.1	13.8	9.8	28.7	9.5	5.6	41.1
8:1+8:2	67.2	42.0	37.6	29.8	20.6	31.1	20.5	11.5	44.1

4.7. Nitrogen

The nitrogen concentration (Kjeldahl-N) expressed as a percentage both of dry matter and of volatile solids, increased during the process (Table 4.4). This is normal during the composting process, as nitrogen remains in the compost to a larger extent than organic carbon, which is emitted as carbon dioxide.

Table 4.4. Nitrogen content in waste substrate and output compost at IVAR. Standard deviations in parenthesis. Nitrogen was not analysed on Batch3

	Kjeldahl-N (% of DM)	Kjeldahl-N (% of VS)[1]
Substrate 1	1.91 (0.35)	2.78 (0.44)[2]
Substrate 2	1.91 (0.31)	2.78 (0.44)[2]
Batch 1:1	2.47 (0.25)	3.73 (0.38)
Batch 1:2	2.43 (0.22)	3.76 (0.35)
Batch 8:1	2.09 (0.17)	3.81 (0.32)
Batch 8:2	2.31 (0.19)	4.07 (0.33)

[1] Standard deviation is calculated only from the nitrogen analysis. It does not include standard deviation of VS determinations.

[2] Average for both substrates due to few determinations of VS.

The final nitrogen concentration as percentage of dry matter was higher in Bay 1 than in Bay 8. However, the final concentration of nitrogen as percentage of VS was not significantly different between the bays. There was thus no difference in nitrogen concentration in the remaining organic matter in the composts from Bay 1 & Bay 8, although the compost from Bay 8 was more degraded and more mature.

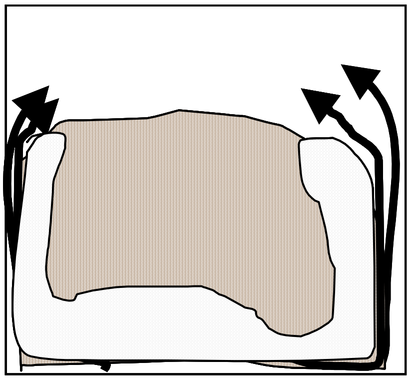
In Bay 8, the temperature was higher (except for the first few days), the aeration rate was higher and the pH was higher. All these are factors that contribute to increasing ammonia emissions from compost. However, if there were higher ammonia emissions, they were balanced by higher decomposition of carbon constituents, leaving equal nitrogen content in the organic matter. The nitrogen losses from the compost cannot be deduced from this data. That would require either direct measurements of ammonia in the exhaust, or reliable mass balances. Mass balances are discussed in section 5.8.

5. GENERAL DISCUSSION

5.1. The processes at RKR and IVAR

At RKR in Bay 1, a week passed before the composting activity started. The pH remained low, the CO_2 emissions were lower than in the other two bays and the temperature was rather constant at 48-56°C. In Bay 2, which received more aeration, the temperature and CO_2 emissions increased steadily, and the pH increased from Day 5-6 onward. The increasing values are signs of a well-functioning process. The higher aeration rates caused more drying, but this could be abated by adding water to the compost. In Bay 3, which had the highest aeration rate, the process started off even faster, with a quicker pH-change and higher carbon dioxide emission. However, the drying was severe. In total, more aeration gave an earlier rise in pH and a faster decomposition, measured as CO_2 emission and heat evolution. Initially, while pH was low in all bays, the temperature was very similar in all bays, 48-56°C. Later, higher temperatures were observed, in combination with faster decomposition, in the batches where the pH had risen. Moreover, rapidly increasing dry matter concentrations were observed when the pH and temperature increased.

At RKR the aeration is not distributed evenly through the mass. More air finds a path through the loosely packed material near the edges, and less goes through the more compact material in the middle (Figure 5.1). The process is therefore variable not only vertically but also horizontally, and sampling of temperatures and materials were done both at the centres and the edge. The observed temperatures were similar, but the edge parts became drier, and pH increased faster there. This indicates that the composting process was more active near the edges than in the centres.



Figur 5.1. View of the aeration system at RKR. More air finds a path through the loosely packed material near the edges, and less goes through the more compact material in the middle.

At IVAR, the bays are aerated by suction from below. This has the advantage that the exhaust can be sampled individually for each zone, but a major drawback is the fact that the aeration channels can be blocked by compact compost at the bottom of the bays. The bay floors in Zone A were cleared and covered with new base material just before the experiments, but the later zones were not cleared. The cool temperature measured in Bay 1, Zone B, indicate that the aeration in this zone was not functioning (see section 4.3).

At IVAR, the processes in the two bays differed clearly from the start through the whole process. In the bay that received more air and a larger water addition the pH increased to above natural and the product became stable. In the other bay, the pH remained below neutral and the product was not stable. The two subsequent batches that were monitored were very similar, indicating a good repeatability of the process.

The aeration rate in Zone A in Bay 1 at IVAR was comparable with the aeration rates at RKR, whereas the aeration rate in Bay 8 was much higher. It is therefore not surprising that the process in Bay 8 at IVAR differed from all the other processes.

5.2. Sampling

It was difficult to obtain representative samples of the waste and compost material. The sample types can be classified into three groups. Firstly, there was the waste substrate, which was highly heterogeneous. It was more heterogeneous at IVAR than at RKR due to differences in the shredding and mixture procedure. At RKR, an attempt was made to use a sampling procedure involving turning and dividing heaps of waste until a small enough sample is obtained (Lundeberg et al., 1999), but this method stratified material of different particle sizes, and was obviously not appropriate for such a heterogeneous sample. The method described in la Cour Jansen et al. (2004) could be more appropriate for waste substrates, since it involves grinding of the samples before taking sub-samples, but the method is much more laborious. Secondly, sampling during the process involves great difficulties in attaining representative samples. Samples were taken directly after turning, to minimise the effects of vertical stratification. The work environment in the compost hall is not suitable for manual labour, so taking a few grab samples was considered to be the only reasonable sampling method. At RKR there was a considerable horizontal difference across the bays. This was handled by taking samples both in the middle and at the edges of the bays.

Thirdly, the end product unloaded from the bays is much more homogeneous than the substrate, and the compost is mixed when it is unloaded. However, the waste/compost has been turned several times during the process, and then the batches have become mixed, so individual input batches can no longer be distinguished. This problem is more pronounced at RKR, where the batches are smaller and the compost is turned more times than at IVAR. For example, the differences between the two investigated batches at RKR, which were obvious at loading as well as after one week, could not be distinguished at unloading.

5.3. pH

More aeration gave a faster rise in pH, both at RKR and IVAR. At low aeration rates the pH did not increase, and in some cases it even decreased, whereas high aeration rates gave increased pH as well as faster decomposition. This development can be explained by different oxygen needs for acid consumption and acid production (Fig 5.2).

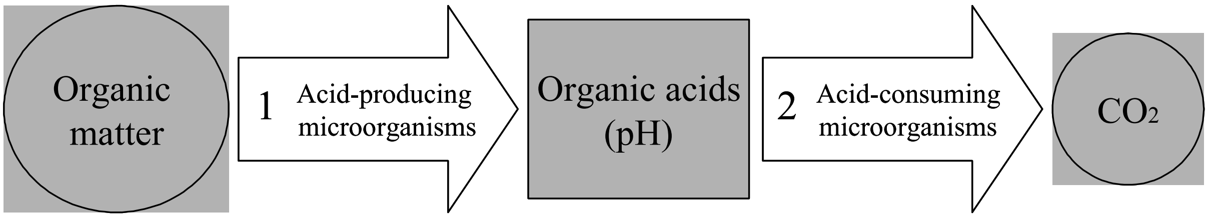


Figure 5.2. Schematic figure of microbial production and decomposition of organic acids during composting. High concentrations of organic acids correspond to low pH.

Both production and consumption of organic acids are microbial processes, and the resulting acid concentration is reflected in pH, and also affects the microorganisms. The acid production step (1) is robust, does not require oxygen and proceeds whenever there is an abundant supply of easily degradable substrate. The acid consumption (2) is aerobic (requires oxygen) and is sensitive to low pH in combination with high temperature (above 40°C) (Sundberg et al., 2004). However, when it functions well, Step 2 is faster than the anaerobic acid production (Step 1), and this is why organic acids are reduced to very low levels and the material is neutralized during efficient composting. Step 1 starts already during waste generation and collection, so the incoming substrate has a low pH and high acid concentration, so it is essential that conditions favouring Step 2 are established at the initiation of composting.

5.3.1. Measuring pH

Two methods were used to measure pH in this project, one measured the pH of the condensate (in all Bays at RKR and Bay 8 zone A at IVAR) and the other measured the pH of material samples mixed with water. These two methods gave different results. At RKR in Batch 1 the pH of the condensate rose above neutral earlier than that of the materials (Figure 3.6), 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. Therefore, pH in the condensate can be used as an early indicator of a pH change in the material. However, a high pH in the condensate does not always reflect an eventual pH change in the material. In Batch 2 at RKR, the condensate pH was high during the first days and then decreased (Figure 3.6), whereas the pH of the material was low from the start. The reason for this is not clear, but this phenomenon has been observed before in reactor experiments (Beck-Friis et al., 2001). A possible explanation is the fact that the organic acids are not very volatile at low temperatures (lactic and acetic acid have higher boiling points than water). Thus less acids would evaporate during the first 2 days in Batch 2 at 30-40 °C than during the first days of Batch 1 at 40-50 °C, even if the actual acid concentration 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.

An advantage of measuring the pH in the condensate is that it gives an indication of the pH value in a large volume of compost, whereas it is often difficult to take representative materials samples during the process. In these experiments, the representativity of materials samples was maximised by sampling the material during the process just after turning of the compost.

5.4. Temperature, pH and decomposition

One aim of the project was to determine whether it was possible to reduce the temperature at the start of the process, and if this would have a positive effect on process development. At both plants increased aeration had clear positive effects on decomposition at the start of the process, whereas the effect on temperature was not as evident.

At IVAR there was probably a reduced temperature caused by the increased aeration in Bay 8 (See section 4.2) and this contributed to the rapid rise in pH. At RKR however, all bays had the same temperature during the first few days. As long as pH was low (below 6), all bays had temperatures in the range of 48-56 °C (Fig. 3.2) and carbon dioxide concentrations in the off-gas of 1-2% (Fig 3.3). Since this was early in the composting process, when there is much degradable substrate, this stable process indicates that there was some kind of limitation to the process. The oxygen and carbon dioxide concentrations were rather constant, but they were not at a level that could inhibit the process. The temperature however, was inhibiting the process, even though 48-56 °C is generally not too hot for composting. On the contrary, the normal optimum temperature is about 52-60 °C, and composting can proceed efficiently at 70 °C or above. However, this is only true for composting at pH values near neutral. It has been shown that at pH below 6, composting is inhibited also at moderately thermophilic temperatures (Smårs, 2002). In laboratory experiments, the composting activity was very low at 46 °C at pH below 6, compared with higher pH or a lower temperature (Sundberg et al., 2004). Furthermore, a transition to higher pH occurred rapidly at 36 °C but not at 46 °C. These findings explain why temperatures of 48-56 °C occurred at RKR during the acidic phase, regardless of aeration rate. The process activity increased until a temperature was reached at which the microbial activity was inhibited, and when the pH is low, this occurs already a t 48-56 °C.

The temperature measurements at RKR were all done in the top 0.5-1 m, but the mass was 2 m deep and aerated from below with air at about 25°C. The temperatures measured are thus higher than the average within the mass, and there were regions with considerably lower temperatures in the lower parts of the bay, but it is not known if these were large enough to impact the process as a whole.

5.5. CO_2, O_2 and heat

When organic matter is decomposed, heat is released. The heat production is proportional to the oxygen consumption and to the carbon dioxide production (Figure 5.3). Carbon dioxide emissions (airflow multiplied by exhaust air carbon dioxide concentration) and heat transport (a function of airflow, input and exhaust air temperature and humidity) are thus two different ways of estimating the activity of the compost. Both methods were used to calculate the activity at RKR (Figure 5.4). They were correlated in Bay 2 and Bay 3, but in Bay 1 there was no significant correlation. This is due to the intermittent aeration in Bay 1, which introduced errors in the measurement of carbon dioxide, airflow and off-gas temperature. Heat flow and carbon dioxide flow were correlated by a factor of 9.2 kJ/ g CO_2, or 404 kJ/ mol CO_2 (Figure 5.3). This can be compared with literature values of 440 kJ/mol O_2 (Weppen, 2001).

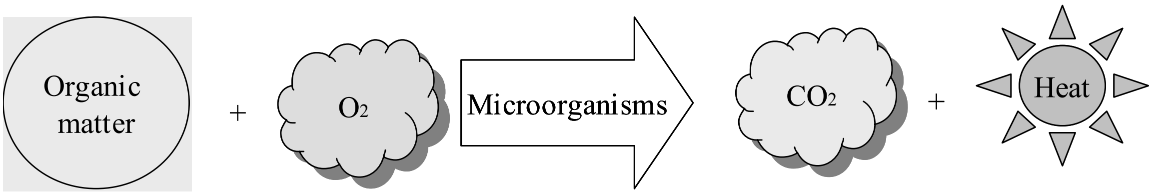


Figure 5.3. Simplified view of aerobic decomposition during composting.

There was also a correlation between the measurements of temperature and CO_2-concentration in Bay 2 & 3. In Figure 5.4 (right) it is obvious that the data from Bay 1 are not correlated.

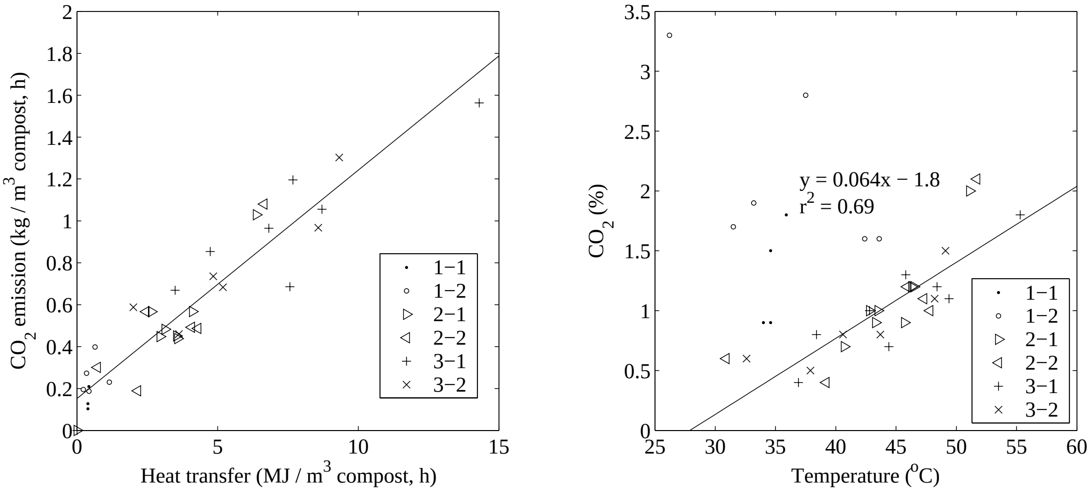


*Figure 5.4. Correlations of heat and CO_2 at RKR during the first 8-9 days of the process; heat flow vs. CO_2 emission (left) and temperature vs. CO_2 concentration (right). Linear regression lines calculated from Bay 2 (triangles) and Bay 3 (*x *and +) data.*

The diagram of heat flow and carbon dioxide flow (Figure 5.4, left) gives a measure of the activity in the compost; high values mean high activity. The data of temperature and CO_2 concentration do not reveal any such information (Figure 5.4, right).

At RKR, all bays had similar temperatures (45-50°C) and CO_2 concentration (1-2%) during the initial phase, although there was a variation in airflow. This can be explained by the temperature inhibiting the process (see section 5.4), and the relation between heat production, carbon dioxide production and oxygen consumption was the reason for this inhibiting temperature to occur at carbon dioxide concentrations in the off-gas of 1-2%, regardless of the aeration rate. It was thus the aeration rate that directly determined the decomposition rate, with more aeration giving more decomposition. However, since the temperatures and gas concentrations were very similar regardless of decomposition rate, neither would be a reliable process indicator or control variable.

5.6. Process indicators

There are two essential requirements for a process indicator: it should be possible to measure and it should say something about the process. Measurements should preferably be done on-line and at a reasonable cost. There are several possible process indicators for composting activity. The activity is manifested as heat release, oxygen consumption and carbon dioxide emission. Heat and CO_2 are removed by aeration and oxygen is supplied by aeration. Process indicator candidates are thus measurements of heat, carbon dioxide, oxygen and aeration rate.

The aeration systems at RKR and IVAR differ, and thus the ways to measure are different. At IVAR the exhaust is collected separately for each zone, and the temperature of the exhaust is measured on-line. It is theoretically possible to measure the concentrations of the off-gases, though it may be difficult and costly in practice, especially considering the high temperature and humidity of the off-gases. At RKR, the exhaust is not collected separately for each zone, so it is not possible to measure the temperature or gas concentration. Temperature is measured on-line by sensors in the walls, but the quality of these measurements is questionable. To use airflow as a process indicator, high accuracy is not necessary in this case. Thus data based on information on fan characteristics, vault settings and on/off-time for fans may be a useful low-cost alternative to direct airflow measurements.

It is the rates of heat release, O_2 consumption and CO_2 emission that indicate the activity of the compost, not the states of temperature, O_2 or CO_2 within the compost or the exhaust. For examples, during the first week in the RKR investigations the temperature and the concentrations of O_2 and CO_2 were very similar in all bays, but the activities varied, due to the different airflow rates. It is thus important to note that possible indicators of process activity must combine measurements of temperature, CO_2 or O_2 with airflow data.

5.7. Drying

At RKR the compost became dry in the bays with more aeration. Some water was added to these bays, but not enough to counteract the drying. At IVAR, large amounts of water were added to the bay with higher aeration, and drying occurred mainly in the bay that received less aeration as well as less added water.

The water addition systems are different at the two plants. At RKR, water is sprinkled on top of the compost at nighttime. The seepage of water down the compost is countered by the aeration, which is directed upwards. It is thus more difficult to distribute the added water evenly at RKR than at IVAR, where water is added by the turning machine during turning of the compost.

Increased aeration will normally lead to more evaporation and thus to faster drying of the waste. Aeration is essential for compost cooling, and processes with higher activity require more aeration. Evaporation, driven by aeration, is the most important mechanism for cooling, and this cannot be avoided. Water addition 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).

The heat taken up by a given volume of air increases with temperature, and this is mainly because hot air can carry more moisture at higher temperatures (Table 5.1). If the compost gas is heated to 70°C and becomes saturated it removes approximately 2.5 times more heat than if it is only heated to 55°C, and it also removes 2.5 times more moisture. Consequently, removing a given amount of heat requires more air at lower temperatures, but approximately the same amount of moisture is removed. Moreover, if increased aeration results in increased evaporation, it is a consequence of increased decomposition.

Table 5.1. Uptake of energy and moisture by 1 m^3 of saturated air at 20 °C, when it is heated to 40 °C, 55 °C or 70 °C. Theoretical values, calculated with the method described by Sundberg (2003).

Temperature [°C]	Energy in dry air [kJ]	Energy in steam [kJ]	Total energy [kJ]	Evaporation [m^3]
40	24	97	120	0.04
55	41	278	320	0.12
70	59	718	777	0.30

The increased drying that results from increased aeration is thus a result of higher decomposition rates, but it is often perceived as a problem at the facilities. However, both plants in this project have equipment for water addition. Trying to save on air and water at a composting facility reduces the efficiency of the process and results in a poorer product quality. Thus, saving air and water is very wasteful and results in inefficient use of the investment that has been made at the composting plant.

5.8. Mass balances

The volumes and weights of the input and output materials were noted at IVAR, in an attempt to make a mass balance of the system. The attempted mass balance at RKR was not finalised, since some weights were not determined. The data from IVAR are presented in Table 4.3. However, the data are not reliable, and not relevant to use in a further analysis. Firstly, only some material was weighed, and the total weight was then estimated from the total volume. Due to variations in density of the input material, and unreliable volume measurements, the uncertainties in the weights are quite large, possibly about 10 %. Secondly, the batches are mixed during the process, so it is necessary to weigh several consecutive batches and calculate an average. Weighing only two consecutive batches, as was the case here, is not enough. This can be concluded from the large variations between Batch 1 and Batch 2 Thirdly, the dry matter determination is an important source of error. At IVAR, large samples (1 kg) were used, and this reduces the error that is introduced when sieved samples are used. However, the substrate is very heterogeneous and it is difficult to get a representative sample. At IVAR, only one sample was used for the dry matter analysis, and there was an uncertainty, possibly about 3 % (on wet weight basis). Fourthly, volatile solids (VS), which is used to determine the organic matter content, is measured on very small samples (a few g). In our analyses, VS was determined on sieved samples, which are not representative of the whole mass, and thus of limited value for a mass balance. The errors in the individual wet, dry and volatile mass determinations combine to large uncertainties in the estimations of mass losses, since these are calculated as the difference between two uncertain values.

Mass balances are of great value in compost process investigations, but making reliable mass balances requires improved weighing facilities (at IVAR), long time series (one or two batches is not enough) and further development of the sampling procedures for dry matter and VS determinations.

5.9. Final remark: Increase the aeration rate!

Composting is aerobic decomposition of waste, a process where organic matter and oxygen is microbially converted to carbon dioxide, water, heat and microbial biomass. Aeration is essential to this process both for supply of oxygen and for removal of heat. A lack of aeration can cause problems for three reasons: lack of oxygen, too high temperatures and too low pH value. (A low pH as such is only limiting in extreme cases, but low pH makes the process less temperature-tolerant, and temperature inhibition sets in at lower temperatures (Sundberg et al., 2004).) Most of the time, at both plants, at least one of these factors was inhibiting the process, and the simplest and most efficient measure should be to increase the aeration rate.

At both IVAR and RKR the full aeration capacity is used in the first zone, but later much less than the full aeration capacity is supplied. This would be an appropriate strategy if the activity had peaked already in the first zone, but this is not the case. At least two strategies can therefore be considered. One would be to increase the aeration rate even more in the first zone, but this would involve costly reconstructions at the plants. The second strategy would be to increase the aeration rate in the later zones. I would strongly recommend this as a next step in process improvement.

6. CONCLUSIONS AND RECOMMENDATIONS

- At both composting plants, increased aeration rates at the start of the process resulted in higher microbial activity and a rapid rise in pH. The increased aeration also gave a more stable product in the end. The main recommendation for process improvement is therefore to increase the aeration. Increased aeration at the start improved the decomposition, but increased aeration later in the process may also be important. Neither at RKR nor at IVAR is the full aeration capacity of the facility used.
- The effect of temperature on pH and process development in the beginning of the process remains somewhat unclear. At IVAR a large proportion of the bay in which a sharp pH increase occurred was mesophilic (below 40 °C) during the first 3 days. This probably accelerated the pH-change. At RKR however, all bays had the same temperature, 48-56°C, during the early acidic period.
- Increased aeration caused severe drying at RKR. At IVAR, however, large amounts of water were added in the highly aerated Bay 8, and the mass was kept moist. It was also clear that the process proceeded better in the moist compost at IVAR than in the dry compost at RKR. The recommendation thus is to keep the compost moist by adding water, not by reducing aeration. Heat is produced by microbial activity, and is transported from the compost with the air, mainly by evaporation. Drying is thus a result of decomposition activity. If the aeration is reduced in order to avoid drying of the compost, the activity is also reduced and the product will not become stable.
- Temperature by itself is not a good indicator of microbial activity. A high temperature can indicate high activity, but it can also indicate low activity due to insufficient cooling. A low temperature can indicate too much cooling, or deficient oxygen supply, or too dry compost. However, a process indicator combining temperature and airflow rate may be very useful.

- pH is a good process indicator. A high or rising pH means that the process is proceeding well. A low or declining pH indicates that the activity is low and that you cannot expect to get a stable product.
- Other useful process indicators are the CO_2 emissions and the O_2 consumption. This the product of the air volume and the difference between input and output gas concentration. It is a direct measure of the activity in the compost. At RKR it is difficult to measure the concentration in the exhaust air, but at IVAR it is easier. However, the concentration by itself is not a good indicator of microbial activity. It is only useful in combination with the aeration rate.

7. 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**(4): 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**(1): 41-50.

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**(4): 167-178.

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

la Cour Jansen J., Spliid H., Lund Hansen T., Svärd Å., Christensen T.H. 2004. Assessment of sampling and chemical analysis of source-separated organic household waste. *Waste Management* **24**(6): 541-549.

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. and Papi T.(ed). *The Science of Composting*. Blackie Academic & Professional. Glasgow. pp. 274-285

Lasaridi K.E., Stentiford E.I. 1998. A simple respirometric technique for assessing compost stability. *Water Research* **32**(12): 3717-3723.

Lundeberg S., Johansson C., Kron E., Sandström M., Klingstedt E., Brohede L., Norin E., Carlsbaeck M., Palm O., Brunes L., 1999. *Sjösättning av certifieringssystem för kompost och rötrest*. Naturvårdsverket**.** AFR-REPORT 257. Stockholm, Sweden.

Miller F.C. 1993. Composting as a Process Based on the Control of Ecologically Selective Factors. In: Metting F.B.J.(ed). *Soil Microbial Ecology*. Marcel Dekker. New York. pp. 515-544

Norgaard E., Sorheim R., 2004. *Tiltak for å sikre rask etablering av varmkompostering ved behandling av bioavfall*. Norsk Jordforbedring & Jordforsk. Grimstad /Ås, Norway.

Smårs S., 2002. *Influence of Different Temperature and Aeration Regulation Strategies on Respiration in Composting of Organic Household Waste*. Department of Agricultural Engineering. Uppsala, Sweden, Swedish University of Agricultural Sciences: 27.

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**(3): 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., Smårs S., Jönsson H. 2004. Low pH as an inhibiting factor in the transition from mesophilic to thermphilic phase in composting. *Bioresource Technology* **95**(2): 145-150.

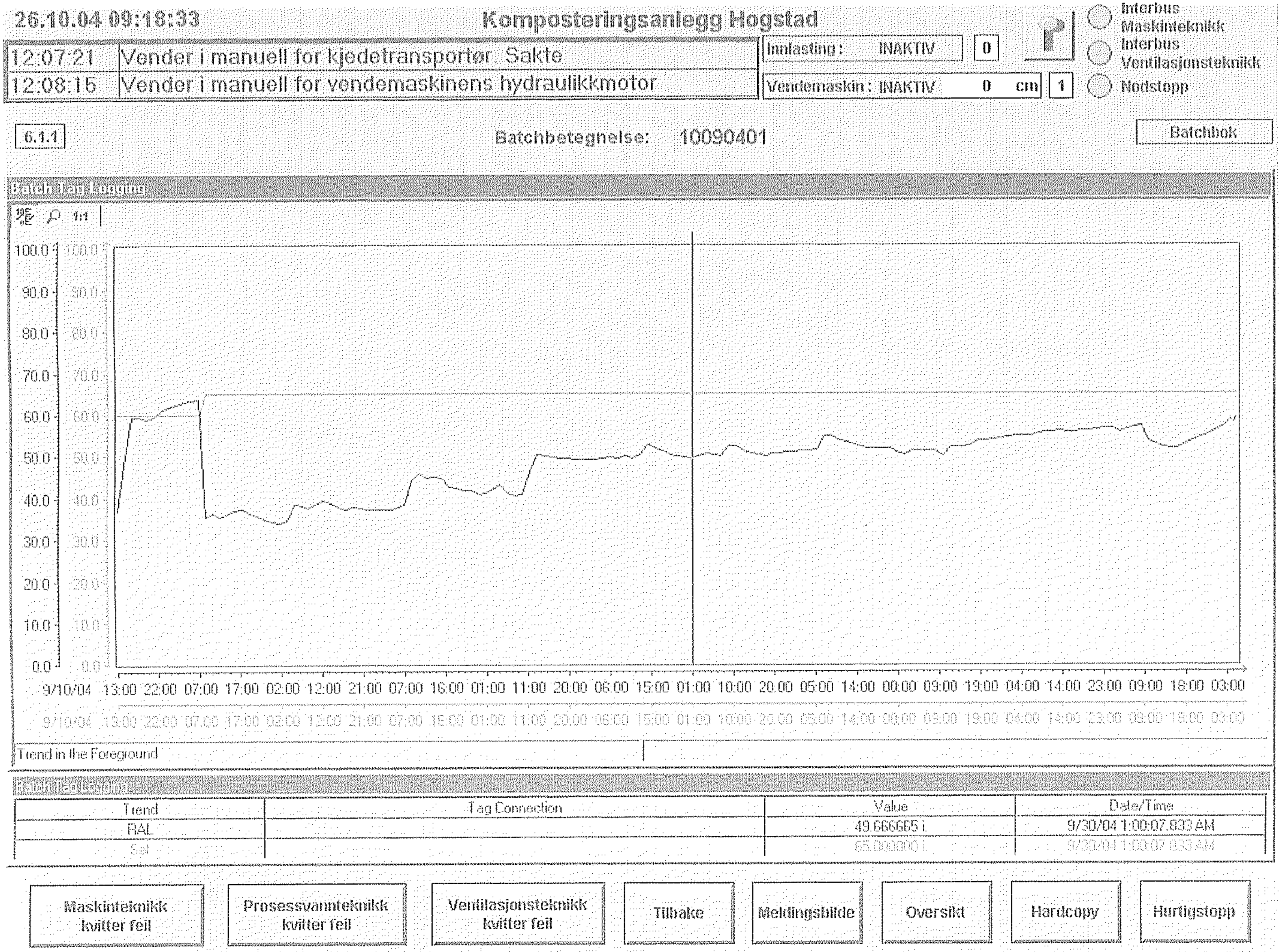
Weppen P. 2001. Process calorimetry on composting of municipal organic wastes. *Biomass and Bioenergy* **21**(4): 289-299.

APPENDIX 1 – TEMPERATURE AT IVAR

Temperature measurements in exhaust from IVAR, on-line measurements recorded in process computer.

First page: Batch 1:2

Second page: Batch 8:2



26.10.04 09:18:33

Komposteringsanlegg Hogstad

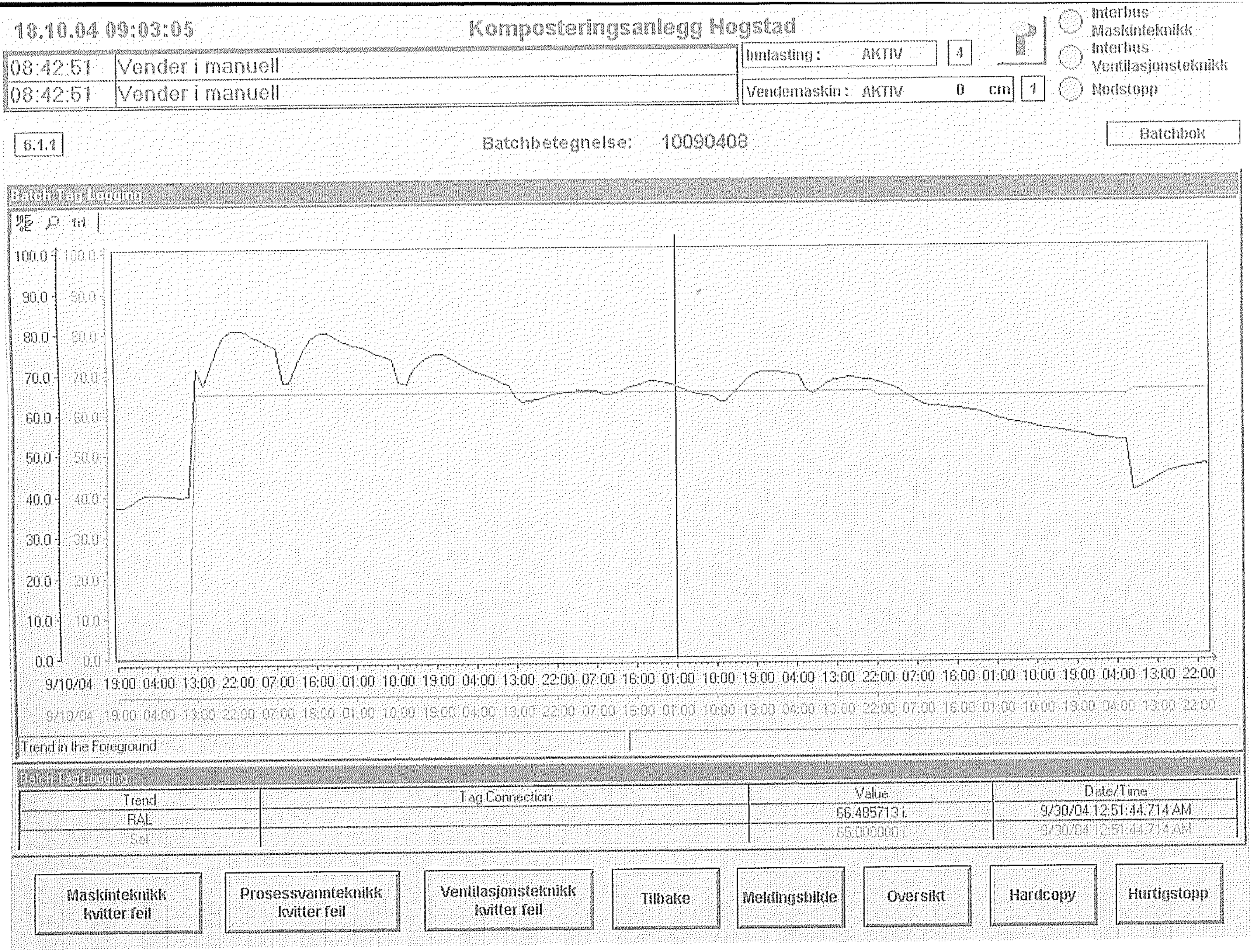
12:07:21 Vender i manuell for kjedetransportør. Sakte
12:08:15 Vender i manuell for vendemaskinens hydraulikkmotor

Innlasting: INAKTIV 0
Vendemaskin: INAKTIV 0 cm 1

Batchbetegnelse: 10090401

Trend in the Foreground

Trend	Tag Connection	Value	Date/Time
RAL		49.666665 i	9/30/04 1:00:07.833 AM
Sel		65.000000 i	9/30/04 1:00:07.833 AM



18.10.04 09:03:05

Komposteringsanlegg Hogstad

08:42:51 Vender i manuell

08:42:51 Vender i manuell

Innlasting : AKTIV 4

Vendemaskin : AKTIV 0 cm 1

○ Interbus Maskinteknikk

○ Interbus Ventilasjonsteknikk

○ Nodstopp

6.1.1

Batchbetegnelse: 10090408

Trend in the Foreground

Trend	Tag Connection	Value	Date/Time
RAL		66.485713 i	9/30/04 12:51:44.714 AM
Set		65.000000	9/30/04 12:51:44.714 AM

TIDIGARE PUBLIKATIONER

2003-07-01 skedde en sammanslagning av Institutionen för biometri och informatik och Institutionen för lantbruksteknik.

Biometri och teknik

Examensarbeten

2005:01 Hårsmar, D. Bättre enskilda avlopp i Sigtuna kommun – möjligheter för bebyggelse i Odensala socken.

2005:02 Svensson, M. Desalination and the environment: Options and considerations for brine disposal in inland and coastal locations.

2005:03 Jakobsson, D. Retention av tungmetaller i en anlagd våtmark – Studier av Vattenparken i Enköpings kommun.

2005:04 Leonardsson, J. & Östensson, E. Inverkan av torrsubstanshalt och temperatur på kompostens syrabildning.

2004:01 Ericsson, N. Uthållig sanitet i Peru – En förstudie i staden Picota.

2004:02 Ekvall, C. LCA av dricksvattendesinfektion – en jämförelse av klor och UV-ljus.

2004:03 Wertsberg, K. Behandling av lakvatten med kemiska oxidationsmedel för att delvis bryta ned oönskade organiska föreningar – En studie utförd vid Hovgårdens avfallsanläggning i Uppsala.

2004:04 Degaart, S. Humanurin till åkermark och grönytor: avsättning och organisation i Göteborgsområdet.

2004:05 Westlin, H. Utvärdering av ett silotorksystem för spannmål utrustat med omrörare.

Rapport – miljö, teknik och lantbruk

2005:01 Jönsson, H., Vinnerås, B. & Ericsson, N. Källsorterande toaletter. Brukarnas erfarenheter, problem och lösningar.

2005:02 Gebresenbet, G. Effect of transporttime on cattle welfare and meat quality.

2005:03 de Toro, A. & Rosenqvist, H. Maskinsamverkan – tre fallstudier.

2005:04 Vinnerås, B. Hygienisering av klosettvatten för säker växtnäringsåterförsel till livsmedelsproduktionen.

2005:05 Tidåker, P. Wastewater management integrated with farming – environmental systems analysis of modern city of Surahammar.

2004:01 Bernesson, S. Life cycle assessment of rapeseed oil, rape methyl ester and ethanol as fuels – A comparison between large- and smallscale production.

2004:02 Elmquist, H. Decision-Making and Environmental Impacts.

Rapport – biometri

2004:01 Gustafsson, L. Tools for Statistical Handling of Poisson Simulation: Documentation of StocRes and ParmEst

Licentiatavhandling

02 Sundberg, C. 2004. Food waste composting – effects of heat, acids and size.

Kompendium

2004:01 Publicering 2000-2003.

2005:01 Publicering 2000-2004.

Biometri och informatik

Institutionsrapporter

81 Olsson, U. & Sikk, J. Fourth Nordic-Baltic Agrometrics Conference, Uppsala, Sweden, June 15-17, 2003. Conference proceedings.

80 Edlund, T. Pluripolar Completeness of Graphs and Pseudocontinuation. Licentiatavhandling.

79 Nilsson, K. Macrolide antibiotics – mode of action and resistance mechanisms. Licentiatavhandling.

78 Sahlin, U. Analysis of forest field data with a spatial approach. Examensarbete.

77 Seeger, P. Nested t by 2 Row-Column-Designs suitable for bridge competitions.

76 Wörman, A. Low-Velocity Flows in Constructed Wetlands: Physico-Mathematical Model and Computer Codes in Matlab-Environment.

75 Huber, K.T., Moulton, V. & Steel, M. Four characters suffice to convexly define a phylogenetic tree.

74 Ekbohm, G. Induktion, biometri, vetenskap.

73 Huber, K.T:, Moulton, V. & Semple, C. Replacing cliques by stars in quasi-median graphs.

72 Huber, K.T. Recovering trees from well-separated multi-state characters.

71 Holland, B.R., Huber, K.T., Dress, A. & Moulton, V. δ-plots: A tool for analyzing phylogenetic distance data.

Lantbruksteknik

Institutionsrapporter

255 2003 Nilsson, D. Harvesting and handling of flax for the production of short fibres under Swedish conditions. A literature review.

254 2003 Sundberg, C. Food waste composting – effects of heat, acids and size.

253 2003 Wikner, I. Environmental conditions in typical cattle transport vehicles in Scandinavia.

Institutionsmeddelanden

03:01 Sjöberg, C. Lokalt omhändertagande av restprodukter från enskilda avlopp i Oxundaåns avrinningsområde.

03:02 Nilsson, D. Production and use of flax and hemp fibres. A report from study tours to some European countries.

03:03 Rogstrand, G. Beneficial Management for Composting of Poultry Litter and Yard-Trimmings- Environmental Impacts, Compost Product Quality and Food Safety.

03:04 Lundborg, M. Inverkan av hastighet och vägförhållande på bränsleförbrukning vid körning med traktor.

03:05 Ahlgren, S. Environmental impact of chemical and mechanical weed control in agriculture. A comparing study.

03:06 Kihlström, M. Possibilities for intermodal grain transports in the Mälardalen region – environmental and economical aspects.

2005:06 Sundberg, C. Increased aeration for improved large-scale composting of low-pH biowaste