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Bioresource Technology 95 (2004) 145–150
BIORESOURCE TECHNOLOGY

Low pH as an inhibiting factor in the transition from mesophilic to thermophilic phase in composting

C. Sundberg *, S. Smårs, H. Jönsson

Department of Biometry and Engineering, Swedish University of Agricultural Sciences, P.O. Box 7032, SE-750 07 Uppsala, Sweden

Received 3 September 2002; received in revised form 16 January 2004; accepted 18 January 2004
Available online 19 March 2004

Abstract

During composting of household waste, the acidity of the material affects the process during the initial phase of rising temperature. In this study, the effects of temperature (36–46 °C) and pH (4.6–9.2) on the respiration rate during the early phase of composting were investigated in two different composts. A respiration method where small compost samples were incubated at constant temperature was used. The respiration rate was strongly reduced at 46 °C and pH below 6, compared to composts with a higher pH or lower temperature. The combination of high temperature and low pH is a possible adverse factor in large-scale composting of food waste.

Keywords: Organic waste; Household waste; Compost; pH; Temperature; Carbon dioxide; Organic acids; Mesophilic; Thermophilic

1. Introduction

Composting is a method that is increasingly used for treatment of organic household waste. Source-separated household waste is often rather acidic, and this can cause process problems at composting facilities. The development of pH during composting is closely linked to the variations in temperature, but this interaction has not been well investigated.

Centrally collected household waste is often acidic, with pH normally ranging between 4.5 and 6 (Eklind et al., 1997). The acidity is due to the presence of short-chain organic acids, mainly lactic and acetic acid (Beck-Friis et al., 2001). These acids are found in the raw material, and their concentrations increase during the initial phase of composting (Nakasaki et al., 1993; Beck-Friis et al., 2003). The presence of short-chain fatty acids under acidic conditions and their absence during alkaline conditions indicate that they are a key factor regulating the pH in composts (Choi and Park, 1998; Beck-Friis et al., 2003). During successful and fully developed composting, the pH often rises to 8–9.

A number of authors have noted stagnation or decline in microbial activity in the transition from mesophilic to thermophilic conditions in laboratory-scale compost reactors (Day et al., 1998; Schloss and Walker, 2000; Beck-Friis et al., 2001; Weppen, 2001). There is no common definition of mesophilic and thermophilic, but mesophilic generally refers to temperatures up to approximately 40 °C, and thermophilic to temperatures from 45 up to 70 °C (Miller, 1996). The stagnation in the microbial activity has in some cases been observed to coincide with low pH in the material (Day et al., 1998; Beck-Friis et al., 2001). Beck-Friis et al. (2001) noted that the change from mesophilic to thermophilic conditions during the initial stage of composting coincided with a change in pH from acidic (pH = 4.5–5.5) to alkaline (pH = 8–9).

Different methods have been used to increase the rate of degradation when acidic materials are composted. Nakasaki et al. (1993) composted organic household waste at 60 °C and observed an increased degradation rate when pH was prevented from decreasing below 7 through liming. Nakasaki et al. (1996) demonstrated that the degradation rate at the initial stage of composting can be significantly increased by inoculation with acid-tolerant thermophilic bacteria. Choi and Park (1998) observed that the growth of thermophilic bacteria in food waste compost at 50 °C was stimulated by an

* Corresponding author. Tel.: +46-18-67-18-11; fax: +46-18-67-18-88.
E-mail address: cecilia.sundberg@lt.slu.se (C. Sundberg).

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doi:10.1016/j.biortech.2004.01.016

addition of thermophilic yeast that breaks down organic acids. In recent experiments in a composting reactor, Smårs et al. (2002) showed that the time of the initial acidic phase could be reduced if the process temperature was kept below 40 °C until the pH value in the condensate is above 5. The reason for this was that the microbial respiration in the well-controlled composting reactor was seriously inhibited if the temperature increased above 40 °C while the substrate was still acidic.

The main objective of the experiments described here was to investigate whether low pH combined with high temperature inhibits the microbial respiration when the composting conditions and substrate are similar to those of large composting plants, i.e. under conditions very different from those where Smårs et al. (2002) made their observations. A further objective was to find the pH below which the inhibition in the thermophilic range occurs. A third objective was to develop and verify a rapid and simple method of measuring the microbial respiration of small samples, enabling replicated studies of the influence of pH and temperature on the microbial respiration of many samples from the same batch.

2. Methods

To thoroughly compare and analyse the effects of different process conditions on compost respiration, we developed a method for investigation of CO_2 production using small samples. Similar methods to study effects of different environmental conditions on compost samples from the same batch have been reported to be successful before (Jeris and Regan, 1973; Richard et al., 1999). Our new respiratory method based on small compost samples in closed bottles is used to measure the microbial activity in the compost during short periods of time. Samples from the initial phase of two different composts, where the pH values were set between 4.6 and 9.2, were composted at 36–46 °C.

2.1. Raw material and pre-treatment

Respiration experiments were carried out with source-separated organic household waste from two different sources. One compost (A) was made from source separated organic waste from Uppsala that was collected, minced and frozen in 1995. This waste was thawed slowly at room temperature for 3–4 days and mixed with chopped wheat straw (10:3, dry weight). The total solids content of the mixture was 35% and the ash content was 24% of the dry weight. It was composted in a 200 l experimental composting reactor as described by Smårs et al. (2001). The oxygen level in the reactor was controlled at 16%. The waste material in the insulated reactor was self-heated from room temperature to 37 °C and was subsequently controlled at this temperature. The samples for experiment A were extracted after 1 day, when 7% of the total organic carbon had been emitted as carbon dioxide. The pH of the extracted material was 5.4. The other compost (experiments B1 and B2) was made from source separated organic waste from the composting plant in Sala, Sweden, which was mixed (3:1, wet weight) with shredded green waste from parks and gardens. It was pre-treated just as at the full-scale plant, and had a total solids content of 34% and an ash content of 24% of the dry weight. The samples were extracted after composting for 4 days (compost B1) and 6 days (compost B2) in a static column 2 m high with a diameter of 0.6 m, with forced aeration (Sundberg and Jönsson, 2003). By this time, they had reached a temperature of 35 °C and the pH was 4.6 (B1) and 5.1 (B2).

Before the respiration measurements, the compost materials, with exception of the untreated controls, were treated with sodium hydroxide (7 M) for pH adjustment. The extracted samples, approximately 100 g per experiment, were stirred throughly manually, and 15 g sub-samples were used for each sodium hydroxide treatment. The material attained pH values ranging from 4.6 to 9.2. The added amounts of sodium hydroxide and the resulting pH values are presented in Table 1.

2.2. Experimentation and analysis

To facilitate measurement of the respiration rate, the compost samples were placed in 118 ml airtight bottles, 3.0 g in each. The bottles were placed in water baths that were held at 36 ± 1 and 46 ± 1 °C, respectively. All respiration experiments were performed in duplicate. Gas samples (5.0 ml) were taken from the bottles with a plastic syringe (Omnifix, B. Braun, Germany) at intervals of 3–4 h during the experiments. When the carbon dioxide concentration was above 15%, the bottles were

Table 1
The amount of sodium hydroxide (7 M) added to each sample, and the pH obtained after addition of the base

Experiment	Added NaOH (mg/g wet weight)	pH
A	0	5.4
	4.9	5.6
	8.6	6.2
	13.5	6.7
	21.0	7.8
B1	0	4.6
	4.1	4.9
	9.1	5.4
	13.8	5.9
	22.0	6.2
B2	0	5.1
	21.3	6.0
	44.3	9.2

rinsed with 350 ml of air at room temperature to restore aerobic conditions.

The compost gas was analysed for CO_2 with Einhorn's Fermentation-Saccharometer no. 1370 (Assistent, Germany) filled with 7 M sodium hydroxide. Samples of compost gas (5.0 ml) were passed through the liquid. The carbon dioxide was absorbed by the solution while the remaining gas was collected in the meter. The volume of gas absorbed was recorded as a measure of the respiration.

The pH of the bottled compost was analysed before and after each experimental session. This was done by mixing the compost with deionised water at a weight ratio of 1:5. The pH was measured with a pH meter (Metrohm Herisau, E150, Germany) and a standard electrode.

The results were analysed statistically using analysis of variance models. The rate of carbon dioxide production was modelled as a dependent variable, with temperature and initial pH as independent variables. Furthermore, the pH change during the experiment was modelled as a dependent variable, with temperature and rate of carbon dioxide production as independent variables. For the statistical analysis, the GLM procedure in the SAS system (SAS Institute, USA, 2001) was used.

3. Results

Typical time series of CO_2 production at different temperatures and pH values are shown in Fig. 1 and the average CO_2 production of all compost samples is displayed in Fig. 2. At 36 ± 1 °C, the CO_2 production in the compost samples was high irrespective of the pH. There was a small but significant ($P < 0.0001$) variation between initial pH values, with lower CO_2 production at higher initial pH values. At 46 ± 1 °C, there was a different correlation between composts with different initial pH. In samples with an initial pH lower than 6.0, the CO_2 production was very small (Table 2), whereas it was significantly ($P < 0.0001$) larger in samples with initial pH higher than 6.5. Consequently, at initial pH values below 6.0 the activity was significantly ($P < 0.0001$) lower at 46 °C than at 36 °C, but for pH values higher than 6.5 there was no significant difference ($P = 0.54$) between the two temperatures. For initial pH values between 6.0 and 6.5 the results were ambiguous. The variation between the duplicate samples was small, with a coefficient of variation of 8.2%.

The pH was recorded before and after the respiration experiments, and the changes in pH for compost samples with initial pH below 6.5 are shown in Fig. 3. In compost samples treated at 36 °C the pH increased

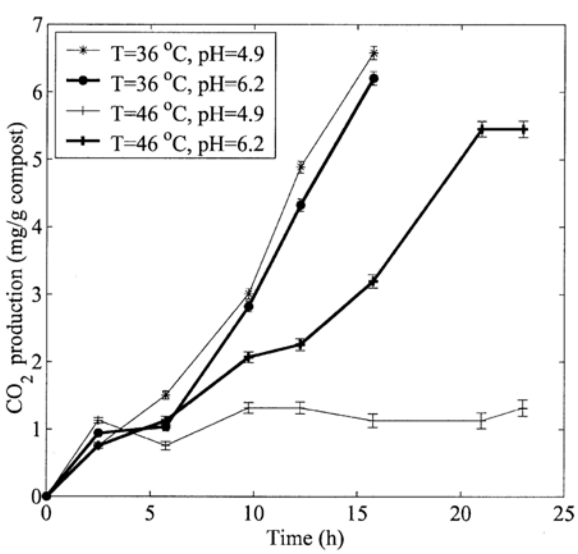

Fig. 1. Time series showing the cumulative carbon dioxide production in compost B1 kept at 36 and 46 °C. The thick lines indicate samples that had been treated with NaOH to raise the pH value. The uncertainty of the observations is indicated by bars showing the mean error estimated from all experiments.

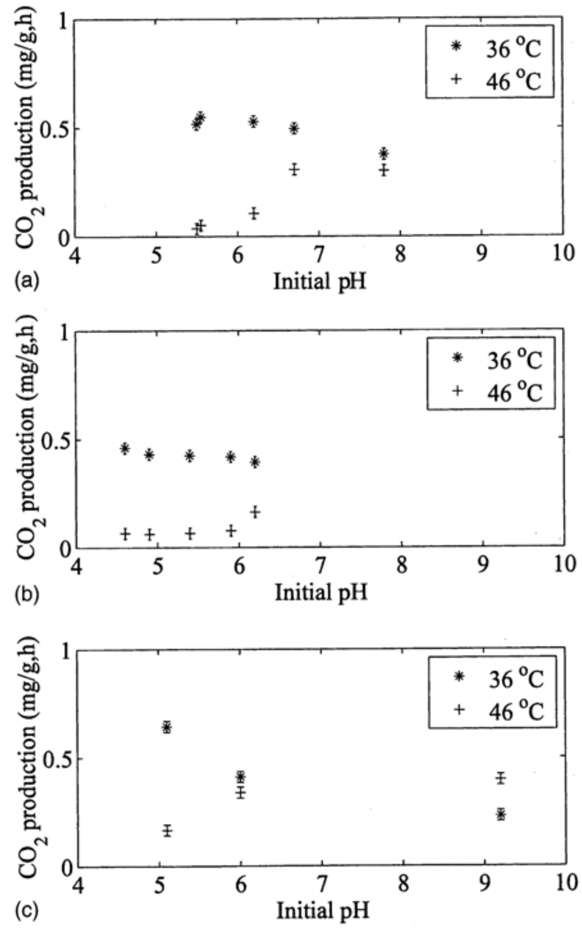

Fig. 2. The average rate and mean error of carbon dioxide production (mg/g (wet weight), h) as a function of initial pH in the composts. Top: experiment A; middle: experiment B1; bottom: experiment B2. 36 °C (∗) and 46 °C (+).

Table 2
CO_2 production in differently treated compost samples. Average of all samples (A, B1 and B2)

Temperature (°C)	Initial pH	CO_2 production (mg/g, h)
36	<6.0	0.48 ± 0.08
36	6.0–6.5	0.44 ± 0.07
36	>6.5	0.37 ± 0.12
46	<6.0	0.11 ± 0.09
46	6.0–6.5	0.20 ± 0.12
46	>6.5	0.34 ± 0.05

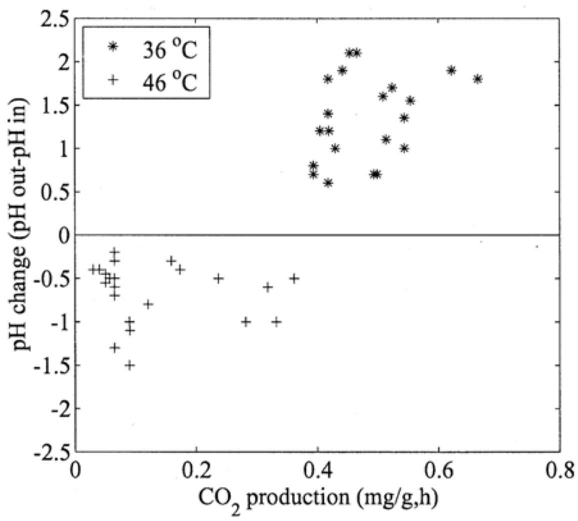

Fig. 3. The change in pH versus the total respiration during the experiment for all samples from experiments A, B1 and B2 with an initial pH below 6.5.

during the experiment, while in all compost samples at 46 °C, the pH decreased during the experiment. The change in pH was well explained by a model with the temperature as independent variable ($r^2 = 0.85$).

4. Discussion

4.1. Activity, pH and microorganisms

At 36 °C, the degradation rate of municipal waste in the initial phase of composting differed only slightly for pH values ranging from 5 to 8, with slower degradation at higher pH (Figs. 1 and 2). The disturbance of the system through addition of sodium hydroxide is one possible explanation for the observed reduced activity at higher pH. At 46 °C, however, the degradation rate at the naturally occurring pH of 5 was very low. Under these conditions the activity was much lower than at 36 °C. The activity increased substantially if the pH was artificially raised above 6.5 (Fig. 2; A and B2). Also, in the experiments presented here, the pH values increased during composting at 36 °C and decreased at 46 °C (Fig. 3). This explains the findings of Smårs et al. (2002) that the initial phase of low pH was substantially longer if the temperature was allowed to rise above 40 °C during the acidic phase, than when it was kept below 40 °C until the acids disappeared.

The large difference in activity between 36 and 46 °C is probably due to the sensitivity of the microbial communities to the combined effects of acidic conditions and temperature. One hypothesis is that the microorganisms can withstand one extreme environmental factor, high temperature or low pH, but not both simultaneously (Strom, 1985; Deacon, 1997). Another possibility would be the existence of two microbial communities, a mesophilic acid-tolerant community and a thermophilic community that does not tolerate acids. This is supported by the fact that fungi are generally more tolerant to acids and less tolerant to temperatures above 35–40 °C than bacteria (Atlas and Bartha, 1998). Fungi have been reported to be an important group in the early phase of composting (Klamer and Bååth, 1998). The thermophilic phase of composting is dominated by bacteria (Strom, 1985), which are generally not as acid tolerant (Atlas and Bartha, 1998). Choi and Park (1998) showed that the growth of thermophilic bacteria in food waste compost was stimulated by the addition of yeast that eliminated the organic acids. Our observation that the changes in pH values during the experiment were different at different temperatures (Fig. 3) may indicate that fundamentally different metabolic paths are predominant at the different temperatures. This supports the hypothesis that different microbial groups are active at the different temperatures.

4.2. Respiration measurement method

The method of measuring the respiration in small airtight bottles at constant temperature was found to function well. Extraction of gas for measurement of CO_2 gave a clear indication of the microbial activity in the compost sample. The duplicate samples gave close results, indicating that the sample preparation procedure gave representative compost samples.

The solubility of CO_2 in water is highly pH dependent due to the carbonic acid system; and the solubility increases sharply at higher pH (Sawyer et al., 2003). Taking the volumes of gas and liquid in the bottles in into account, the solubility in the liquid was low compared to the amounts in the gas phase at pH less than 6.5. At pH above 6.5 the solubility was high, which might have lead to an underestimation of the CO_2 production. However, the measured CO_2 levels were high in all samples with high pH, so any underestimation of the CO_2 production would not alter but reinforce our conclusions.

Measuring differences in respiration of small, parallel samples from the same batch of a larger composting experiment allows the effects of specific process parameters, in this case temperature and pH, to be investigated. This detailed investigation of a part of the process can give additional insight to the dynamics of the larger composting process.

For laboratory-scale composting research, it is valuable to find methods for experimentation on small volumes of compost extracted from the laboratory-scale process. Many other respiration methods require large quantities of compost (Haug, 1993), but one compost respiration method using small samples, 3–8 g, has been reported (Lasaridi and Stentiford, 1998).

4.3. Lag phase

Many authors have noted a decline in microbial activity in the transition from mesophilic to thermophilic conditions when composting food waste or other acid wastes (Haug, 1993; Day et al., 1998; Schloss and Walker, 2000; Beck-Friis et al., 2001; Weppen, 2001; Reinhardt, 2002). The inhibition of thermophilic microorganisms at pH below 6 observed in the present experiment occurred for material from a controlled and well-aerated process (A), as well as for compost from a less controlled process (B). The composts studied also differed in pre-treatment, particle size and amendments used. It is thus likely that the observed relationships are general for composts containing easily degradable organic matter, with low pH caused by organic acids. The inhibition of thermophilic activity at low pH that we describe here, and that has also been observed under other conditions by Reinhardt (2002), is thus a likely explanation for the lag phase observed in the transition from mesophilic to thermophilic composting of food wastes.

4.4. Large-scale composting

In large-scale composting of household waste the incoming material is often of low pH (Eklind et al., 1997), and the temperature often rises quickly to thermophilic levels (Das and Keener, 1997; Sesay et al., 1998). This is because large volumes of compost material are self-insulating and are essentially only cooled by aeration and evaporation of water carried by the ventilated air (Haug, 1993). Thus, if the aeration rate is low, high temperatures can be maintained even if the microbial activity declines to very low levels. Our results show that the microbial activity can be very low in composts at high temperatures and low pH, and that the pH in the material does not seem to increase at those conditions. Instead a decrease in pH was observed (Fig. 3). Thus, there is a risk in large-scale composting that unfavourable conditions with low rates of degradation are conserved for long periods of time, even if the material has a high temperature.

As an alternative to the well known method of adding alkaline substances to raise the pH, the findings presented in this article and in Smårs et al. (2002), show that the process can be accelerated if the compost is cooled to stay below 40 °C until the organic acids have been consumed and the pH has risen. Since alkaline amendments have other disadvantages such as resource use and risks of increased ammonia emissions (Nakasaki et al., 1993), the strategy of keeping the temperature down seems promising.

5. Conclusions

During the initial phase of household waste composting, the process is inhibited if the temperature is 46 °C while the pH is below 6.0. The process is not inhibited at 36 °C, or if the pH is raised artificially above 6.5. This was shown to be valid for two different household waste composts of different origins, amendments, pre-treatments and from different composting processes. We therefore conclude that inhibition of the microbial activity at temperatures near 46 °C and pH below 6.0 is a common problem in the initial phase of food waste composting.

The inhibition of thermophiles at low pH is an important key to explain the often observed lag phase in the transition from mesophilic to thermophilic conditions in the initial phase of composting. The observed decrease in pH when the temperature was 46 °C and the initial pH was below 6.5 implies that in large-scale composting with limited cooling there is a risk that conditions with low degradation rates at low pH and high temperature are maintained for long periods of time.

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