Biodegradation (2005) 16: 205–213 © Springer 2005

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

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Accepted 10 June 2004

Key words: aerobic decomposition, organic waste, pH

Abstract

Inhibition of the degradation during low pH conditions has been observed in fed-batch composting systems. To analyse this phenomenon, fed-batch composting of food waste with different amounts of starting culture was examined in laboratory reactor experiments. Changes in temperature, carbon dioxide evolution, pH, solids, ash and short chain organic acids were measured. In reactors with a daily feed rate of 24% or less of the starting culture, thermophilic temperatures occurred and the pH and carbon dioxide evolution were high and stable after a starting period of 4–5 days. In reactors with a daily feed rate of 48% or more of the starting culture the composting process failed, as the pH dropped below 6 and remained there and the temperature and carbon dioxide evolution were low. It was concluded that the use of adequate amounts of starting culture consisting of active compost can efficiently prevent low pH conditions and process inhibition in fed-batch composting of food waste.

Introduction

In fed-batch composting, the substrate is added intermittently, often on a daily basis, while the compost is removed as a batch at longer time intervals. The treatment, which sometimes is called sequentially fed or continuous composting as a clear terminology is lacking, is often done in two stages, one for high-rate degradation and one for curing. Fed-batch composting is traditionally used in backyard composting and is now also increasingly used for on-site treatment of food wastes, e.g. in restaurants or housing areas. Mechanised equipment for on-site composting is commercially available in Scandinavia, Korea, Japan and other countries. These composting machines are often small, designed for 1–300 kg day^{-1} (Hwang et al. 2002). Whereas composting of various wastes in batch processes, where all substrate is introduced at the start of the process, is well described in the literature, there are few reports on intermittently fed composting (Choi et al. 2001; Hwang et al. 2002; Nakasaki et al. 1998; Schulze 1962), in spite of its widespread use.

Organic acids, mainly lactic and acetic acid, are frequently produced during initial microbial degradation of food waste, in a process that reduces the pH to 4–5 (Eklind et al. 1997). This acid-producing process has been observed during storage and collection of waste (Eklind et al. 1997) and during the initial phase of batch composting (Beck-Friis et al. 2003; Day et al. 1998). During successful composting, the acids are decomposed and pH increases (Beck-Friis et al. 2003; Day et al. 1998).

Use of recycled compost as a starting culture for composting is common in both batch and fed-batch composting. Recycled compost provides a diverse microbial culture that can accelerate the start-up process (Nakasaki & Akiyama 1988). Compost can also provide structure and dilute the fresh waste, reducing the risk for oxygen depletion

and subsequent anaerobic conditions. It is thus likely that the quality and amount of starting culture has a large influence on the success of fed-batch composting.

In preliminary studies on fed-batch composting of food waste from a restaurant in a full-scale composting machine, the pH value and temperature declined, degradation ceased and severe odour problems occurred. The aim of the experiments described here was to study fed-batch composting of food waste, with emphasis on the role of organic acids in process failure. The experiments were performed in laboratory reactors and the effects of starting culture on temperature development, carbon dioxide emissions and organic acids were investigated.

Materials and methods

An experiment on continuous composting with four treatments, two of which were duplicated, was carried out in laboratory reactors (Figure 1). Food waste and water were added daily to reactors with different amounts of starting culture. Three identical cylindrical rotating reactors, made of 3-l insulated Dewar vessels, were used for the experiments. The reactors had 8 mm thick non-insulated plastic lids. The reactors were placed horizontally and rotated 220° one way and back, every 10–20 min. Each was aerated with 0.7 l min^{-1} by negative aeration driven by air pumps (RENA301, France). The airflow was measured with rotameters (Kytola, Finland). The exhaust gas was bubbled through a sodium hydroxide solution (1–2.5 mol l^{-1}) to absorb the carbon dioxide produced. The absorbed carbon dioxide (CO_2) was later determined by titration with hydrochloric acid. The temperature in the reactors was monitored with thermocouples connected to an AAC-2 logger (INTAB, Sweden) recording the temperature every 2 min.

The reactors were filled with 20, 100, 200 and 400 grams (g) respectively of a starting culture sieved through a mesh (10 mm × 10 mm). The experiments with 100 and 200 g of starting culture were performed in duplicate (100A, 100B, 200A and 200B), making six process runs in all. The starting culture was compost originating from the same wastes as used in the experiment – restaurant waste and sawdust (Table 1). Food waste from a restaurant, 50 g (wet weight) of a mixture of bread, fried potatoes, cooked meat, vegetables and cheese, was added to the reactors every day (d). The food waste was prepared in batches of 250–1500 g and minced for 5–15 s in a food processor (Philips) to make the particles small without losing the porous structure of the material and it was refrigerated (0–7 °C) for up to 7 days before being used. Sawdust (5 g d^{-1}) was added as a structural amendment and water (10–50 ml d^{-1}) was added to keep the moisture content between 45 and 55%. The reactors were opened once every day for weighing, sampling, observation of odour and structure and addition of fresh waste and water. Before sampling, the material in the reactors was thoroughly stirred by hand to homogenise the material. Solid samples (15–22 g) were extracted

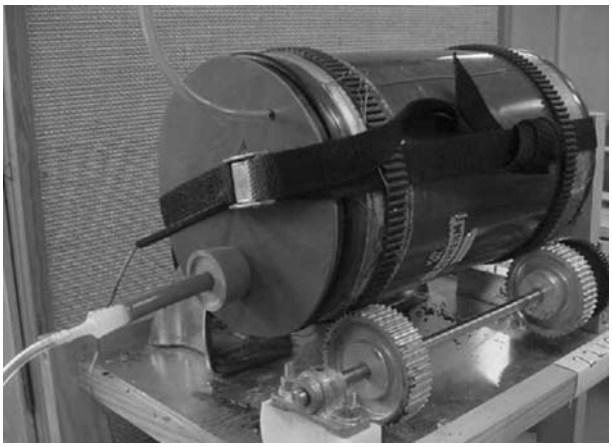

Figure 1. A composting reactor; a 3-l rotating Dewar vessel.

Table 1. Substrate properties: solids content, ash content and pH in starting culture, food waste and sawdust

Substrate	Solids content (% of fresh weight)	Ash content (% of solids)	pH
Starting culture	54.8 ± 0.3	8.9 ± 0.6	8.2
Food waste	53.4 ± 1.7	3.8 ± 0.3	5.8 ± 0.2
Sawdust	93.5	0.5	4.7

daily and the moisture content and pH were measured on fresh samples. The pH was measured using a standard electrode and a pH meter (inoLab, WTW, Germany) on compost diluted with deionised water (1:5) and kept at room temperature for 1 h. Moisture content was determined after drying at 105 °C for 22 h. Ash content was determined on dry samples heated to 550 °C for 4 h. Short-chain organic acids (acetic, butyric, lactic and propionic acid) were analysed by high-pressure liquid chromatography (HPLC), after extracting with water (1:4), shaking for 30 min and filtering with 0.45 μm PVDF filters. For the HPLC an ion-exchange column (HC-75, Hamilton, USA) at 60 °C and refractive index detection at 40 °C were used. The mobile phase was 5.0 mM sulphuric acid (H_2SO_4).

Results

Moisture and ash

The average moisture contents in the compost reactors were between 46.7 and 56.7% (Table 2). The lowest moisture content was in the composts with 200 g of starting culture, and the highest was in those with 20 or 100 g. The ash content average was between 4.2 and 8.0%, where the higher ash content was in composts with more starting culture (Table 2).

Table 2. Average solids and ash content in the reactors, which are identified by the amount of starting culture

Reactor	Solids content (%)	Ash content (% of solids)
400	47.2 ± 5.1	8.0 ± 0.5
200A	53.3 ± 2.7	6.7 ± 0.3
200B	50.2 ± 1.2	7.0 ± 0.3
100A	43.3 ± 2.7	6.1 ± 0.7
100B	44.0 ± 1.9	5.9 ± 0.9
20	43.9 ± 1.3	4.2 ± 0.3

Temperatures

In the reactors with 200 and 400 g of starting culture the temperature rose rapidly, and after 4–5 days the process temperatures stabilised (Figure 2). There was a consistent temperature pattern with rapidly increasing temperatures after mixing and feeding, followed by declining temperatures until the next feeding time. During the stable period, the daily maximum temperature was 51 ± 3 °C (average ± standard deviation) in the reactors with 200 g of starting culture and 62 ± 3 °C in the reactor with 400 g. Distinct odours of meat and ammonia developed in these reactors.

In the composts with 100 g of starting culture the temperature increased during the first few days, with daily maximum values rising from 30 to 40 °C, but thereafter the temperatures did not become higher (Figure 2). These two reactors had similar temperature development for the first 3 days, but then they diverged. In one reactor (100B) the temperature declined to just above room temperature after 5 days and it did not rise again. In the other reactor (100A), the temperature increased slowly each day, from 30–32 °C directly after mixing and feeding to 35–40 °C 24 h later. The odours from these reactors also differed during the latter part of the experiment. Reactor 100A smelled of yeast, but reactor 100B smelled of vinegar (acetic acid). In the reactor with 20 g of starting culture the temperature increased slightly during the first few days, and then varied irregularly between 24 and 35 °C during the rest of the experiment (Figure 2). The odour from this reactor was sour, and it also smelled of yeast.

Carbon dioxide and solids loss

In the reactors with 200 and 400 g of starting culture, the CO_2 production increased during the first 4–5 days and then reached a steady level (Figure 3). In the reactors with 20 and 100 g of starting culture the CO_2 production also increased

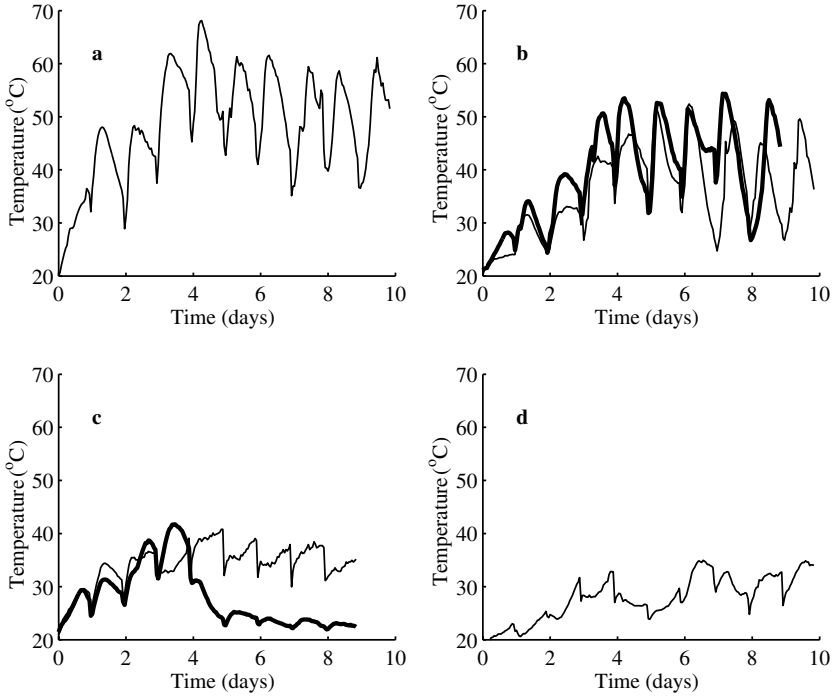

Figure 2. Temperature (°C) development in the reactors: (a) 400 g of starting culture, (b) 200 g of starting culture. Thin line: 200A; Thick line: 200B, (c) 100 g of starting culture. Thin line: 100A; Thick line: 100B, (d) 20 g of starting culture.

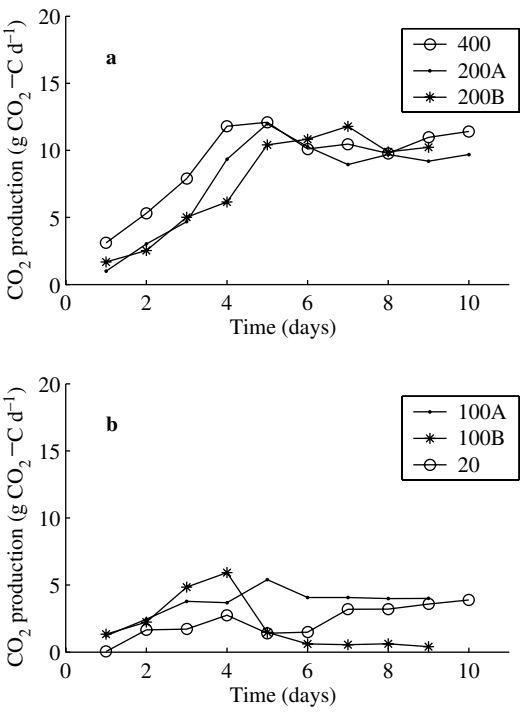

Figure 3. Carbon dioxide development (g d^{-1}) in the reactors: (a) 400 and 200 g of starting culture, (b) 100 and 20 g of starting culture. The figures represent total daily values.

during the first 4–5 days, but not as much. Then the CO_2 production levelled out, except for 100B where it decreased to very low levels. The degradation rates were also calculated from the changes in solids content in the reactors (Figure 4) and they correlated well with the cumulative CO_2 production.

Acids and pH

In all reactors, the pH declined during the first 2 days, from 8.2 in the starting culture to 6–7 after 2 days (Figure 5). In the reactors with 200 or 400 g of starting culture, the pH value reached a minimum of 6.1–6.5 on Day 3 or 4 and then increased and remained between 7.7 and 8.7 during the rest of the experiment. In the reactor with 400 g of starting culture the shift in pH occurred within a period of 24 h, whereas it took several days in the reactors with 200 g. In the reactors with 20 or 100 g of starting culture, the pH continued to decline to minimum values of 4.6–5.2. Towards the end of the experiment the pH values increased slightly in the reactor with 20 g of starting culture and in 100A, while it continued to fall in 100B.

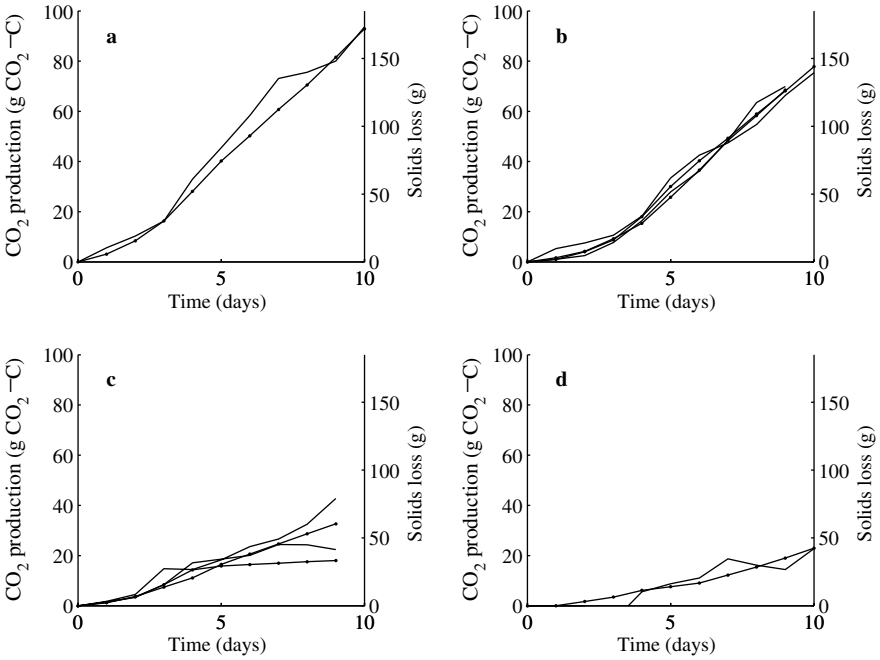

Figure 4. Accumulated carbon dioxide production (dotted line) and solids loss (solid line). (a) 400 g of starting culture, (b) 200 g, (c) 100 g, (d) 20 g.

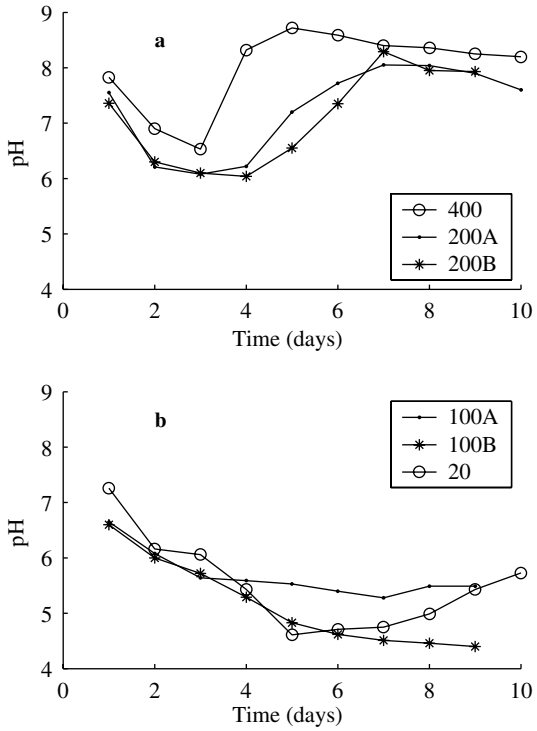

Figure 5. pH development in the reactors: (a) 400 and 200 g of starting culture, (b) 100 and 20 g of starting culture.

The concentrations of organic acids differed between these three reactors (Figure 6). In the reactor with 20 g of starting culture, there was a succession of acids, from acetic and propionic acid to propionic and butyric acid from Day 4 to Day 12. In reactor 100A, where the pH was about 5.5 during the second half of the experiment, the total acid concentration was much lower and no acid dominated. In reactor 100B, which had continuously falling pH values, the acid concentration increased continuously, with acetic acid as the dominating acid.

The reactor with 20 g of starting culture showed signs of possible improvement towards the end of the experiment, with rising temperature (Figure 2) and pH (Figure 5). That experiment was therefore continued for three more days. During that time the temperature and pH declined.

Discussion

Moisture and ash

The moisture content was only slightly higher than the intended range of 45–55%, so the moisture

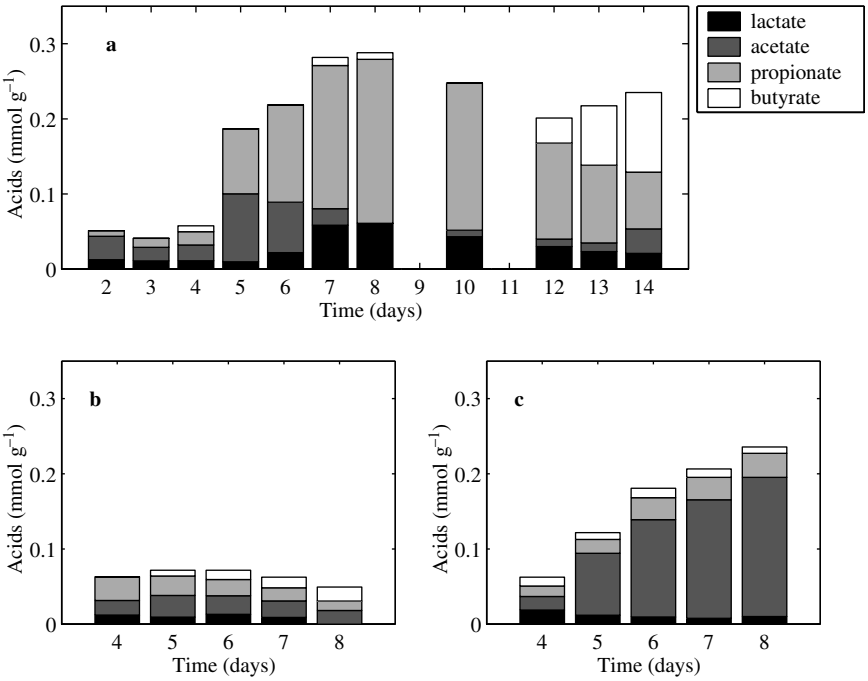

Figure 6. Content of organic acids (lactic, acetic, propionic and butyric acid) at selected times: (a) 20 g of starting culture, (b) 100 g of starting culture (100A), (c) 100 g of starting culture (100B).

content was adequate and would probably not cause any major differences in process performance. The moisture in the samples does not represent an average daily value, but the lowest value for each day, since sampling was done just before adding water. During high temperature conditions, the evaporation was considerable, and therefore the lower moisture content measured in the high temperature reactors (Table 2) does not necessarily reflect a lower average moisture content.

Much water was added to the composts. Food waste contains high concentrations of easily degradable organic substances such as sugars, starches, lipids and proteins, and the initial water content was in this case only 47%. Since water evaporates as a result of the elevated temperature and aeration during composting, food waste compost is susceptible to drying, and it is therefore often necessary to add water to keep the degradation rate high (Keener et al. 1996). In these experiments, water was added to keep the moisture high enough to avoid limitations in degradation rate due to drying. The ash content was higher in the reactors that contained more starting culture and that had higher degradation. This is because the ash fraction increases when organic matter is decomposed and because the starting culture had a higher ash content than the feed.

Temperatures and degradation rates

We assumed that a larger starting culture would give a more robust process with higher temperatures and degradation rates, and we observed stable composting processes in the reactors with 200 and 400 g of starting culture. The main difference between those processes was that with 400 g of starting culture, higher temperatures were obtained throughout the experiment (Figure 2). A daily temperature variation of about 20 °C was observed in all these composts. The rapid temperature rise after feeding and turning indicates the presence of an active microbial community that immediately started to degrade the energy-rich substrate supplied, which had a small particle size and was thus easily available to microorganisms. The decline in temperature that followed indicates that the rapidly degradable organic matter had been depleted. This daily pattern is

consistent with the quick response to feeding of fed-batch composts observed by Nakasaki et al. (1998). For each reactor, the CO_2 production followed the temperature closely, with increasing CO_2 production at higher temperatures. However, during the second half of the experiment, the reactor with 400 g of starting culture did not have a larger CO_2 production than the reactors with 200 g, even though the temperature was higher.

The reactors with less starting culture (20 and 100 g) did not produce thermophilic temperatures. Moreover, the processes did not respond immediately to feeding, in the way that the well-functioning composts with more starting culture did. The average degradation was small, as is shown both by the CO_2 and solids loss measurements (Figure 4).

The solids losses had the same trends as the CO_2 production (Figure 4), but had a larger day-to-day variability and some obviously faulty negative values. Sampling error in the moisture measurements was the main cause of these deviations. Solids losses are therefore considered to be less reliable in this case, but they did give an adequate indication of the degradation rate when averaged over several days. The average solids losses in the reactors with 200 and 400 g of starting culture during the stable phase were 71.7 and 79.6%, respectively, of the volatile solids in the daily added food waste. Clearly 200 and 400 g of starting culture, 4.1 or 8.2 times the daily feed (on dry basis), corresponding to initial feed rates of 24 and 12% respectively, sufficed to establish a well-functioning process, while only 20 or 100 g did not.

Acids and pH

We expected that processes with little starting culture would fail, and that organic acids and low pH values would be important indicators of a failing process. This clearly occurred for the composts with 20 and 100 g of starting culture, where the pH values fell rapidly and remained acidic during the remainder of the experiment. The low pH values originate from short-chain organic acids such as lactic, acetic, propionic and butyric acid (Robertsson 2002). These acids are normally formed in anaerobic microenvironments during rapid decomposition of organic matter, but may also be formed under aerobic conditions (Enfors & Häggström 2000). Organic acids are also a readily available substrate for microorganisms. In successful composting, the degradation of acids is very efficient, and large amounts of acids can be rapidly decomposed under optimal conditions (Beck-Friis et al. 2003). However, organic acids are also toxic to microorganisms, and the toxicity depends on pH, acid type and concentration and microbial species. The tolerance to acidic conditions is generally higher in acidogens than in other microorganisms, and therefore the balance between formation and degradation of acids depends on pH and acid concentration. This balance developed differently in the two reactors with 100 g of starting culture. In reactor 100A a steady process was formed from Day 5 onwards, with a low but steady CO_2 production (Figure 3), pH near 5.5 (Figure 5) and steady acid concentration (Figure 6). In reactor 100B, however, the total concentration of acids increased to a higher level, and the CO_2 production and pH decreased to lower values than in 100A. This lower CO_2 production indicates a lower rate of degradation of acids, due to inhibition of aerobic acid-degrading microorganisms.

During the period of decreasing pH, the acetic acid concentration increased markedly in both 100B and 20, and that observation is consistent with the fact that acetic acid is more toxic than e.g. lactic acid (Ray 2004). This is because the toxic effect is mainly from the undissociated form of the organic acids, which are lipophilic and enter freely through the cell membranes, and then dissociate within the cell, causing a decrease in internal pH. As an acid with higher pK_a has more undissociated molecules at a given pH, it is more toxic. Therefore, under similar conditions, acetic acid is more toxic to microorganisms than propionic acid, which is more toxic than lactic acid.

The temperature in the reactors was clearly correlated to pH. In the reactors with 20 and 100 g of starting culture, which maintained pH values below 6 throughout the experiment, the temperature stayed below 42 °C and did not rise to thermophilic levels. Moreover, during the start-up of the composts that later achieved successful degradation, low pH conditions were also formed initially, and the rise in pH coincided with a rise in temperature to more than 45 °C. This is in agreement with the results reported by Smårs et al. (2002) for batch composting, that thermophilic conditions inhibit the degradation process during an initial low pH phase, but not at high pH.

The compost reactors were well aerated, with 0.7 l min^{-1} (1 m^3 d^{-1}). The oxygen supply was thus 160 g O_2 d^{-1} and the maximum CO_2 production was 12.1 g C d^{-1}. This is equivalent to an oxygen consumption of 20% of the oxygen supplied, which indicates that the aeration was sufficient to maintain high oxygen levels in the reactors even during peak degradation. However, this does not mean that the whole compost mass was aerobic all of the time. Since oxygen transport into the heterogeneous composting particles is limited, there are normally anaerobic zones on the microscale in compost, even if it is well aerated (Hamelers 1993). Composting can therefore be described as an aerobic/anaerobic co-process, and such a perspective is fruitful for understanding the dynamics of acids in composting (Reinhardt 2002).

Repeatability

To investigate the repeatability of the experiments, the sets with 100 and 200 g of starting culture were performed in duplicate. We expected that the processes in the reactors would repeat well since the substrate was well defined and conditions such as aeration and turning were similar in all cases. In the experiments with 200 g of starting culture, the processes did develop similarly, with the same daily temperature pattern (Figure 3) and pH development (Figure 5) during the stable second half of the experiments. During the first few days, however, one reactor (200B) had a faster increase in maximum daily temperature, while the other (200A) had a faster increase in pH and CO_2 production.

The repeatability was not good in the reactors with 100 g of starting culture. During the first 3 days, the temperature and pH developed in the same way in both reactors, but later one reactor achieved temperatures and pH values that were significantly lower than in the other. In the reactor with low pH (100B) acetate accumulated during the process, whereas in the other reactor (100A) the acid composition was mixed and smaller (Figure 6), which might be due to differences in formation and/or decomposition of acids. More importantly, however, neither of these reactors obtained a functioning composting process.

The failure of some processes and success of others may seem predetermined by the different initial conditions, but this is inconsistent with the development during the first 3 days. During those days the temperature, CO_2 production and pH were very similar in the processes with 100 and 200 g of starting culture, with the exception of pH on Day 3. However, these reactors still developed in three different ways from Day 4 onwards. This suggests that there was a strong influence of positive feedback processes, where a small increase in pH leads to a further increase in pH, whereas a small decrease in pH leads to a further decrease in pH. In that way, small variations in initial conditions, feed, moisture, mixing etc. can lead to large differences in the resulting process.

Starting culture

A starting culture has several stabilising effects on the composting process. First, it provides a structure that ensures that aeration of the matter is possible. Second, it dilutes the fresh waste, decreasing the readily available energy per volume and thus reducing the risk of odours and inhibiting concentrations of organic acids resulting from local oxygen depletion caused by rapid degradation of easily degradable matter. Third, a starting culture supplies microorganisms, and this reduces the time for colonisation and thus for the start of high-rate degradation. Finally the starting culture may provide a chemical pH buffer, reducing the inhibitory effect of the organic acids. All these factors may contribute to the positive effects of starting culture during the start-up of fed-batch composting.

The starting culture used in the experiments was 0.41–8.2 times the size of the daily fresh waste feed (on a dry weight basis). This is low compared to other reported experiments with fed-batch composting where the starting culture has often been 10 times the size of the daily feed (Hwang et al. 2002; Nakasaki et al. 1998). We achieved a well-functioning process with starting cultures of at least 4.1 times the daily feed, but the processes failed when the starting culture was 2.1 times the daily feed or less.

Odours

Since there were clearly discernable and distinctly different smells from all processes, odours may be a useful indicator of process performance. Well-functioning processes smelled of meat and ammonia, whereas failing processes smelled of yeast and vinegar.

Conclusions

Fed-batch composting depends on rapid establishment of a process with high degradation rate that can handle the intermittent feed of degradable matter. If a well-functioning process is not established, the result can be a process that largely produces organic acids, which further reduces the microbial activity. Low temperature, low degradation rate and odours of yeast and acid characterise such a system.

One way to establish a process with high degradation rate is to use a large enough starting culture of active compost. In this study, in well-aerated laboratory-scale composting reactors, well-functioning fed-batch composting was established with a starting culture 4.1 times larger than the daily feed, whereas a starting culture of 2.1 times the daily feed was not sufficient.

It is evident from our experiments that pH is a key indicator of process performance. In a well-functioning fed-batch composting process, pH may decline to about 6.0, but it recovers to neutral or slightly alkaline levels within a few days. If the pH continues to decline below 6.0, it is a clear sign that the composting process is not working properly. With continued addition of fresh waste at the same rate the composting process will stay acidic and it will not recover.

These experiments suggest that positive feedback processes, where small decreases in pH lead to further decreases in pH and vice versa, are important during the establishment of the process. In that way, small initial deviations lead to very different process developments.

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