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Waste Management 23 (2003) 17–26

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Investigation and optimization of composting processes— test systems and practical examples

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Accepted 12 September 2002

Abstract

To determine the optimal course of composting it is useful to carry out experiments. The selection of the right experimental set-up depends on the question of concern. Each set-up is useful for a particular application and has its limits. Two test systems of different scales (up to 1500 ml; up to 100 l) are introduced. The purpose and importance of each system design shall be highlighted by application examples: (1) Suitability of a liquid industrial residue as composting accelerator; (2) Determination of the compost maturity; (3) Behaviour of odor-reducing additives during waste collection and composting; (4) Production of tailor-made compost with respect to Nitrogen (5) Suitability of O₂-enriched air for acceleration of composting. Small-scale respiration experiments are useful to optimize parameters which have to be adjusted during substrate pre-treatment and composting, with the exception of particle size and temperature, and to reduce the number of variants which have to be investigated in greater detail in larger scale experiments. As all regulation possibilities such as aeration, moistening, turning can be simulated with the technical scale set-up, their complex cooperation can be taken into consideration. Encouraging composting variants can be tested, compared and optimized.

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1. Introduction

Currently, organic feedstocks are composted on an industrial scale in many areas of the world. Therefore, a lot of different composting systems are employed. The steering and regulation possibilities are manifold as well. Very often, assessment, investigation, and optimization of composting processes and their substrates are required. For that purpose mathematical models and experiments can be used. Mathematical composting models are useful to get an idea of how control measures affect different conditions during the process—such as composting time, emissions, and the properties of compost itself. However, since composting models rely heavily on estimated values, it is necessary to verify assumptions used in the models using experimental testing. A wide range of lab-scale composting set-ups including use of different scales, equipment, operation modes, and additional analytical procedures are used

worldwide. Each system offers advantages and disadvantages, but the results that different systems provide are hardly comparable. As a result, the development of standardized methods for composting system research and development are needed, at least on a national scale.

Two advanced examples of different experimental scales (small-scale: up to 1500 ml; laboratory-scale: up to 100 l) and their potential applications are introduced in detail in the following. The purpose and importance of each practice will be pointed out by presentation and discussion of experimental results, which were obtained at the Department of Waste Management over the past several years. These results cover some important practical application areas such as investigation of co-composting substrates, additives for improvement of composting properties, determination of degree of maturity, and testing of new composting methods. The small-scale respiration system, for instance, can be used to demonstrate the general suitability as well as limiting or supporting properties of substrates for composting. A technical-scale composting unit consisting of 100-l bioreactors and peripheral equipment for measurement,

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process control, and regulation can effectively simulate a composting process, including all control operations, commonly used in an industrial composting facility. The efficiency of control methods can be tested and, therefore, be optimized for application on an industrial-scale.

2. Set-up of small-scale experiments

In a respirometer, solids, slurries, and liquid samples can be examined on a very small scale in test vessels from 250 to 1500 ml. This set-up, developed at the University of Stuttgart (Steinicke, 1976), has been sold as a standardized system by Voith (Fa. Voith Sulzer, Heidenheim, Germany). Inside the respirometer, the biochemical oxygen consumption can be measured continuously, and therefore biological degradation can be ascertained as a function of time.

The respirometer (Fig. 1) is designed as a closed system consisting of test vessels (12 in general), an oxygen generator, and a manometer. The system can be operated under temperature conditions from 15 to 35 °C. CO₂—a result of the biochemical degradation processes—is adsorbed on soda lime pellets. This results in a drop in pressure in the vessels. The electrolytic release of oxygen from a CuSO₄-solution begins via a contact in the manometer. When the initial pressure is re-established, the electrolysis is stopped. The amount of the electricity consumed for electrolysis is proportional to the amount of oxygen consumed during microbial degradation. By coupling the measuring unit with a computer, a continuous recording of the oxygen consumption is obtained. In order to describe other parameters concerning the degradation progress of the sample, vessels can be removed during the test and the material inside can be analyzed (Heerenklage and Stegmann, 1997).

3. Practical application of small-scale experiments

Some selected examples of the practical application of respirometer experiments are presented to demonstrate

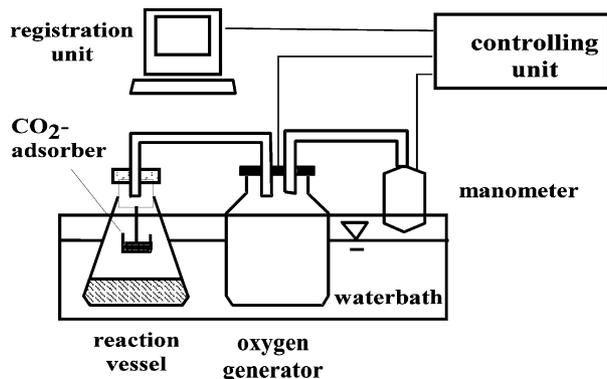


Fig. 1. Scheme of a respirometer (Hupe et al., 1993).

the potential benefits of respirometry in the composting field.

3.1. Investigation into the suitability of a liquid industrial residue as a composting accelerator

A liquid, protein-rich NaOH-solution—a residue of chitosan production—was being considered as a composting accelerator by the generator of the waste and a composting facility due to its high N-content. The aim of the respiration experiments was to investigate the extent and significance of acceleration that occurred (Ritzkowski et al., 1998).

Firstly, the general degradability of the liquid solution was determined by investigating the respiration activity of matured compost with and without the solution. The moisture contents were adjusted to be similar in both cases. The experiments showed (Fig. 2) that the solution was degradable and that an intensive degradation started early and continued at a lower level over a long period of time.

The general acceleration possibility was investigated by measuring the respiration activity of waste with and without solution. The model waste used was composed of different green waste components (C/N with solution: 25; without: 43; similar moisture). These experiments showed (Fig. 2) that addition of the solution increased O₂-consumption during the first day but decreased it in the subsequent period. This finding most likely shows that some easily degradable proteins in the solution were degraded at the beginning of the experiment, but that an inhibition of degradation resulted afterwards.

To find out to what extent the inhibition was caused by NaOH contained in the solution, different amounts of solution and additional NaOH were added to the model waste. The following variants—all adjusted to a similar moisture content—were used:

- A: green waste mixed with water (C/N = 43).
- B: green waste mixed with 34% residual solution (C/N = 26).

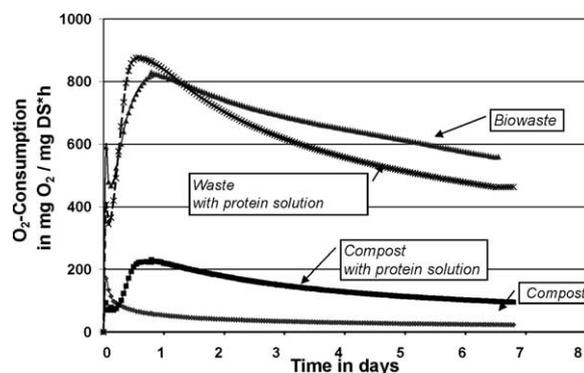


Fig. 2. O₂-consumption of model waste and matured compost with and without addition of the industrial residual solution during a period of 8 days.

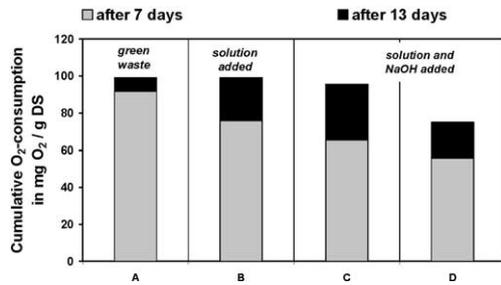


Fig. 3. Cumulative O₂-consumption after periods of 7 and 13 days for substrates with different ratios of model waste, residual solution and NaOH-solution.

- C: green waste mixed with 10% residual solution and 24% NaOH-solution (C/N=35).
- D: green waste mixed with 2% residual solution and 32% NaOH-solution (C/N=39).

The NaOH-content in variants B, C, and D was approximately the same due to the added NaOH solution and the NaOH from the residual solution. Compared to the non-treated variant A, the reduced O₂-consumption after 7 days of NaOH-treated variants C and D shows (Fig. 3) that an NaOH-inhibition took place. On the other hand, the variant with residual solution only (B) showed a higher O₂-consumption than variants C and D, although total NaOH-concentrations were approximately the same. Contradictory effects took place during this study: on the one hand, an improved degradation due to protein addition by the residual solution and on the other a limitation due to NaOH addition. The measurements after 13 days, showed that the total O₂-consumption of most variants were similar, which means that the finally reachable degradation rates were also similar.

Overall, it was shown that the industrial residual solution did not accelerate the process in the long term. Substances in the solution caused a time limiting effect at the beginning of the trial, while the proteins in the solution produced a contradictory effect. Considering both effects, the solution proved to be suitable as a composting co-substrate but not as an accelerator.

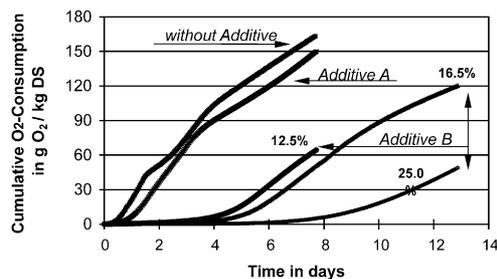


Fig. 4. Oxygen consumption of model biowaste without and with odor-reducing additives A and B (B in three concentrations) in dependence on time.

3.2. Investigation into the behavior of odor-reducing additives during composting

During storage and collection of biowaste, odors, which may be considered unpleasant, may be produced. Two different additives (A and B)—intended to be added to biowaste in a biobin—were developed by a company to solve this problem. Theoretically, the additives could have a limiting or inhibiting effect on composting. Therefore, their influence on microbiological degradation was investigated in a respirometer. Model biowaste as well as matured composts were mixed with the odor-reducing substances A and B in different ratios.

The oxygen consumption of the samples with the odor-reducing substance A was slightly lower compared with the untreated sample (Fig. 4). This led to the conclusion that microbial degradation under aerobic conditions was slightly limited by additive A. Although substance A had a slightly limiting effect on composting, additional experiments showed (Leikam et al., 1996) that it was degradable under anaerobic conditions. Therefore, it is likely that it would be degraded in parts of a biobin or in anaerobic zones occurring in a composting process. Under these conditions, additive A was considered not to be usable, but a verification on a larger scale was necessary (Section 5.1).

The delay in respiration of biowaste samples treated with substance B (Fig. 4) indicated that additive B provoked an inhibition of microorganisms. The higher the concentration of additive B, the lower the rate of oxygen consumption and the longer the period of inhibition. After a time (B_{12.5%}—4 days; B_{16.5%}—5 days; B_{25%}—~12 days) O₂-consumption of variants with additive B proceeded parallel to the non-treated variant. This indicates microbial adaptation and/or the ability to use substance B as a substrate. Additional analyses showed, that additive B was, in fact, completely degraded. To verify the adaptability of microorganisms to additive B, further respiration experiments were carried out. A mature compost was inoculated with substrate from the previous experiment containing adapted microorganisms.

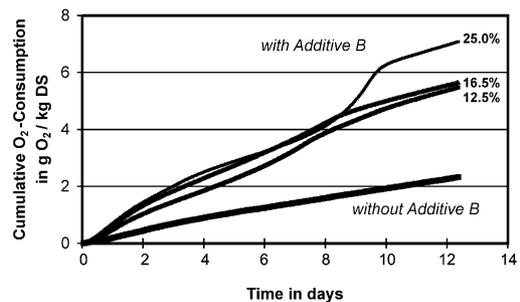


Fig. 5. Oxygen consumption of matured compost inoculated with additive-adapted microorganisms and with different concentrations of the odor-reducing additive B in dependency of time.

Additive B was then added in three different concentrations. Fig. 5 shows that a delay, and thus inhibition, was not detected. Compared with pure compost, the increased respiration activity also showed that the additive was degradable. That means that composting of waste treated with substrate B seems to be possible, however inoculation with adapted microorganisms is suggested.

3.3. Determination of the maturity of composts

The maturity of compost is important for application purposes. In Germany, fresh and matured composts are distinguished for marketing. Usually, the degree of compost maturity is calculated by the maximum self-heating temperature (Table 1) measured in an isolated vessel (BGK, 1998). This method is not feasible for determining the maturity of compost in lab-scale experiments (e.g. with the unit from Fig. 7), since the amount of material needed for the test is too large. Another method—accepted and standardized as well—is the measurement of respiration activity in the respirometer over a period of 4 days. This method requires a considerably lesser amount of material (20 g, compared to 2 l for the self-heating test) and thus is more suitable for lab-scale experiments. The maturity is calculated as described in Table 1, according to Jourdan (BGK, 1998). An improved method for the calculation of the maturity from respiration activity was suggested by Becker (1997, Table 1). A comparison of the three above referenced methods is necessary for examining their consistency.

All three methods in Table 1 were investigated based on 27 composts collected from different composting facilities (Ritzkowski, 1996). In almost half of the samples the results compared well (Fig. 6). In a further third—at least two methods showed the same level of maturity. Only four samples had different results for each method. The method described by Becker had a higher correlation with self-heating (matches with self-heating: 67%) than the standardized method described by Jourdan (matches with self-heating: 56%).

In general, all methods were comparable as far as mature composts are concerned. In the early and middle stages of degradation the degree of maturity can

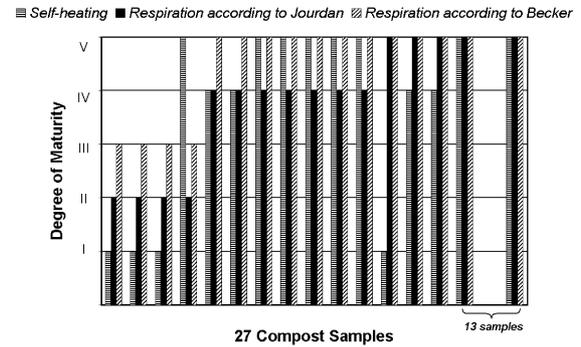


Fig. 6. Degree of maturity of different compost samples calculated by different methods.

strongly vary and a classification with regard to the material status could at times be inaccurate. Overall, respiration measurement can provide useful information for composting experiments, where the progress of degradation and the stage of product quality must be assessed.

4. Set-up of laboratory-scale composting experiments

The laboratory-scale composting unit shown in Fig. 7 allows for the simulation of a composting process with all operating controls (aeration, moistening, turning) common to those in a composting facility. Composting variants can be tested, compared, and optimized and, in this way, the best variants for the industrial-scale can be determined.

Fig. 7 shows the schematic for the laboratory composting unit. A maximum of 10 100-l steel reactors were running simultaneously. Each reactor was equipped with a, water-filled double wall (6), which could heat the contents of the reactor. To guarantee homogeneous water temperatures, a pump (7) was installed. The exterior reactor wall was insulated (5). Heating of the water was achieved either by manual or automatic regulation. To simulate the self-heating of the substrate, for instance, the water was automatically heated up to compensate for heat losses to surroundings. Temperatures at different places within the reactor (e.g. in the centre and at different depths of the substrate, near the

Table 1
The relation between the degree of maturity and some biochemical parameters

Degree of maturity	Maximum temperature (°C)	O ₂ -consumption (mg/g OS) (according to Jourdan)	O ₂ -consumption (mg/g OS) (according to Becker)	Material status
I	> 60	> 40	> 80	Raw material
II	60–50.1	40–8.1	80–50	Fresh compost
III	50–40.1	28–16.1	50–30	Fresh compost
IV	40–30.1	16–6.1	30–20	Matured compost
V	≤ 30	≤ 6	≤ 20	Matured compost

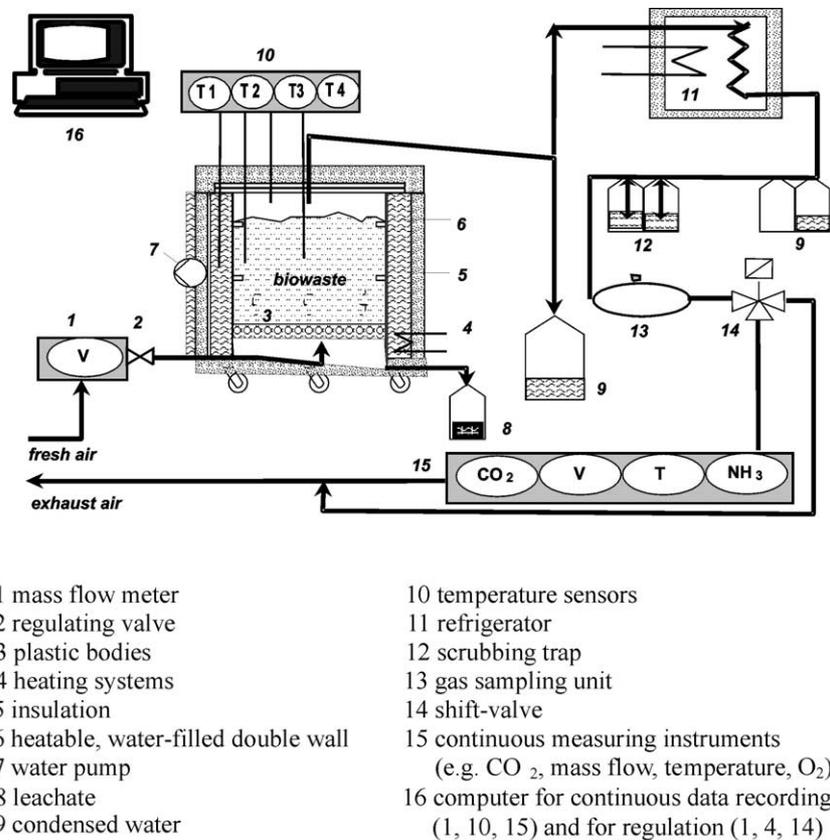


Fig. 7. Set-up of composting unit: Bioreactor with periphery equipment.

reactor wall, in the air above the substrate) as well as water temperature in the double wall or other important temperatures (e.g. inlet air, exhaust air) were measured continuously (10). Compressed air was used for forced aeration or alternatively, vacuum-induced aeration could be simulated by using a pump in the exhaust air stream. The gas flow could be manually adjusted (2) and was continuously measured by a mass flow meter (1). If necessary, the mass flow meter could be replaced by a mass flow regulator. In this way, the aeration rates could be adjusted automatically—e.g. as a function of the temperature of the substance or on the O₂-content of the exhaust air. The inlet air was distributed to the reactor bottom by sieves and, if necessary, was filled with plastic bodies (3) to improve air distribution. Air inlet could also take place at the top of the reactor. All reactors are closed in an airtight way to allow balancing of all mass flows. The reactors were provided with outlets for leachate (8), exhaust air, and for other purposes. The exhaust air was drawn off and led into tubes. It was cooled by ambient temperature and, in the event that well defined cooling was required, by a refrigerator (11). The condensed water was collected or automatically returned. The air stream could be conducted through bottles with scrubbing solutions (12) to remove special

components possibly contained in exhaust air. For instance, 0.5 n H₂SO₄ was used to remove and measure ammonia. The sampling unit (13) allowed gas samples to be taken manually to determine CO₂, N₂, CH₄, O₄, H₂, N₂O content of the exhaust air. The composition of the exhaust air could also be controlled semi-continuously with respect to CO₂- or O₂-content (15). Only one continuous measurement unit was available for the entire composting unit. Shift valves (14), automatically regulated by a computer (16), allowed a semi-continuous recording of the measurement values of all reactors. All exhaust air streams were led to the central exhaust air system in the laboratory hall. If required, exhaust air could be led back (completely or in parts) into the reactors to simulate re-circulating air systems.

Samples of the composting substrate could be taken as necessary. For this purpose and for a turning simulation, the reactor could be emptied by means of a toppling unit and refilled with the substrate previously mixed. Absolute mass losses could be determined by a conducting a mass balance for the whole reactor. Moistening may be simulated (e.g. by water addition during turning) by distribution on the substrate surface in the reactor and/or by aeration with air led through tempered water.

5. Examples for practical application of technical-scale experiments

Some selected examples for the practical application of technical-scale experiments are presented to demonstrate the potential applications in the field of composting.

5.1. Investigation into the behavior of odor-reducing additives during waste collection and composting

To investigate the influence of the odor-reducing additives A and B (Section 3.2) added to biowaste bins during collection, two test series (*Bin Period I and II*) were carried out in the composting unit shown in Fig. 7 (Leikam et al., 1996).

For *Bin Period I*, a well-defined model biowaste was used. The components were shredded to a fine particle size and the additives were added in a way to promote homogeneity of the material. The reactors were completely filled.

In *Bin Period II*, a larger particle size of the same model waste was used. Non-treated biowaste was fed into the reactor step by step every second day. After placing each layer, the surface of the biowaste was sprayed with the additives.

For comparison, one biowaste variant remained untreated in each series. To simulate biowaste collection in a bin, the reactors were kept gas-tight and temperatures simulating ambient conditions (20 or 30 °C) were employed. Gas and odor samples were taken via valves installed in the top of the reactor. Odors were measured by an olfactometer.

During *Bin Period I*, a difference between odor concentrations in the biowaste with **additive A** and the biowaste without it could not be determined (Fig. 8). During *Bin Period II*, the difference amounted to approximately 4 dB_{Odor}. Humans are able to perceive changes in odor concentrations only when they are larger than 3 dB_{Odor}. For this reason, the testers noticed a slight change, however it was not distinctive since the threshold was only exceeded by 1 dB_{Odor}.

With the application of additive B, odors were avoided to a larger extent (Fig. 8). In *Bin Period I* the difference between biowaste without and with **additive B** (high concentration) ranged between approximately 5 and 10 dB_{Odor}. A reduction of odor was clearly distinguishable, with an approximate 50% reduction of the odor impression. However, when *Bin Period II* was simulated in the variant with additive B (high concentration), the odor was only reduced by approx. 4 dB_{Odor}, which is not considered distinct.

The testers were also asked about their odor impressions with regard to quality. Odor of biowaste without additive and of biowaste containing additive A was classified as “unpleasant”, “rotten” or “smells like old waste”. The addition of additive B led to an odor classification of “more pleasant”, “fresh” or “fruity”.

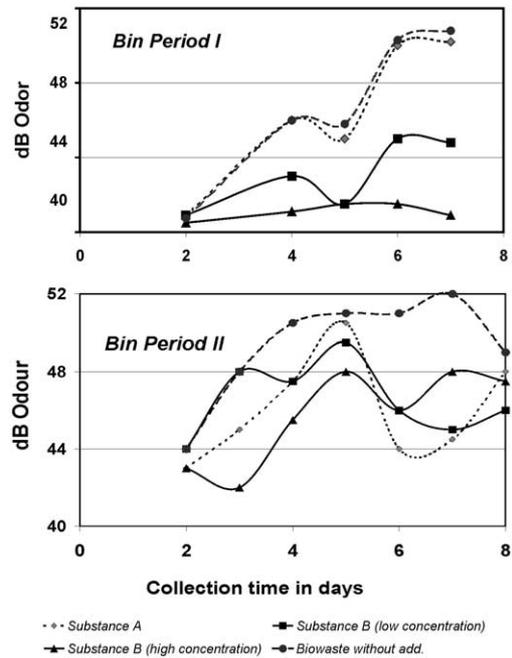


Fig. 8. Odor units during *Bin Periods I and II* and for model waste with and without additives A and B.

Overall, it was concluded that both substances led to odor reduction, but not always to a high degree. Substance B was more effective than substance A. The change of the type of odor was considered more significant than the degree of odor reduction.

After the *Bin Periods*, the waste was treated in the laboratory composting unit (Fig. 7). The aim of these experiments was to verify the results of the small-scale experiments (Section 3.2) regarding the behavior of additives during composting. Two test series (*Composting Period I and II*) were carried out with the following parameters:

In *Composting Period I*, the waste of *Bin Period I* was mixed with bark (33 wt.%) to improve the structure. Test reactors were continuously aerated at a rate of 50–150 l/h. Air flowed through the biowaste. This set-up simulated an in-vessel composting system with pressure-forced aeration.

In *Composting Period II*, the waste of *Bin Period II* was mixed with bark (50 wt.%) to improve the structure and was inoculated with compost of *Composting Period I* (10 wt.%) to add microorganisms adapted to the odor-reducing additives. The test reactors were continuously aerated at a rate of 10–20 l/h. The air only flowed over the top and bottom of the biowaste. This set-up simulated an open windrow system with natural ventilation.

Additive A decreased the rate of waste degradation, proved by the reduced CO₂-production in Fig. 9. Limitations were especially high in *Composting Period I*, the

system that simulated in-vessel composting. In the other system, simulated open windrow composting, degradation was generally limited in the *Composting Period II* due to an O_2 -deficit.

Experiments with **additive B** in *Composting Period I* showed that CO_2 -production, along with substrate degradation, was inhibited by the additive at the beginning of the composting process (Fig. 9). Degradation of organic materials started after about 20 days, when additive B had been fully degraded. The degree of degradation after the inhibition period was nearly the same as the biowaste without additive. This is proved by the CO_2 -production, proceeding parallel to the non-treated variant. By inoculation with adapted microorganisms in *Composting Period II*, inhibition of the microbial activity could be avoided. The degree of degradation of variants, with and without additive B were comparable (Fig. 9).

The technical-scale experiments verified the results of the small-scale experiments with respect to the potential adaptation of microorganisms and the influences of additives A and B on substrate degradation. However, additive A resulted in a larger delay of substrate degradation in the technical-scale experiments than in the small-scale experiments.

It was concluded that since substance B had better odor-reducing properties and better and more stable behavior during composting, its application should be preferred to that of additive A. An inoculation with adapted microorganisms was also suggested to avoid composting delay at the beginning of the process.

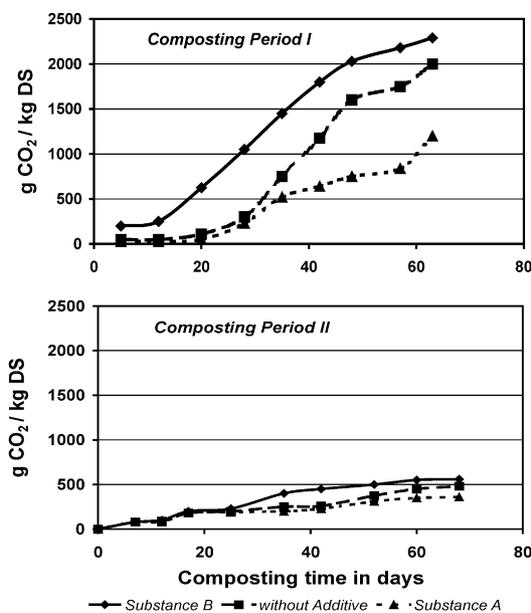


Fig. 9. Cumulative CO_2 -production during *Composting Period I* and *II* for model waste treated with and without additives A and B.

5.2. Investigation into the possibility to produce tailor-made compost with respect to Nitrogen

These experiments were carried out to investigate the possibility of the production of tailor-made composts with respect to N-content and N-composition by regulating measures during the composting process. For that purpose, a *two-step regulation method* was developed. Practical feasibility of that method was tested by comparison of a regulated and a non-regulated variant in the experimental unit (Fig. 7) with a modified set-up (Körner et al., 1999).

Step 1 of the **regulated variant** was characterized by increased ammonia releases via exhaust air during the thermophilic phase. For high releases, aeration was regulated based on different process parameters (temperature, CO_2 -content, pH). To remove total ammonia from the exhaust air, a bubbling column was installed. The set-up for *step 1* of the **non-regulated variation** was similar to Fig. 7 and reflected a normal composting process in an enclosed reactor system with pressure-forced aeration. The increased aeration of the regulated variant allowed increased ammonia releases (Fig. 10).

In *step 2* of the **regulated variant**, the bubbling column was filled with a solution rich in ammonia and installed in the aeration stream. This set-up was simulating a re-circulation of the previously stripped ammonia so that ammonia could be re-introduced into

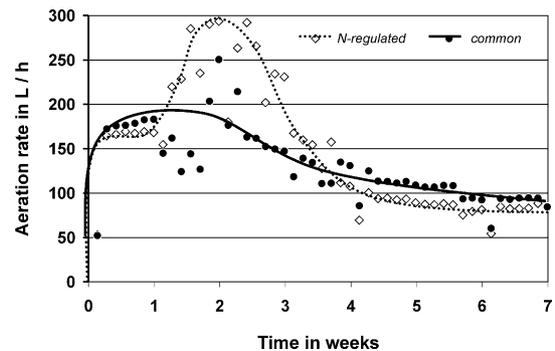


Fig. 10. Aeration rates during *step 1* of experiments simulating a normal composting process and an N-regulated process.

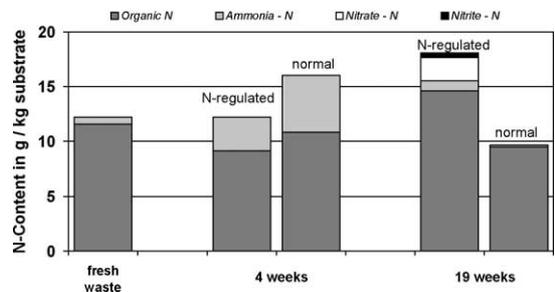


Fig. 11. N-Contents and composition of composts after a certain time of N-regulated and of normal composting.

the compost. *Step 2* of the **non-regulated variation** reflects the curing in a standard composting process. The compost was occasionally aerated.

As a result of both steps, in the regulated variant compost with a total N-content almost twice as high as in the non-regulated variant (Fig. 11) was produced. The inorganic N-content was increased to about 20% of the total N compared to only 2% in the non-regulated variant.

It was shown that it is possible to influence the total N content and the form of N during the composting process to a significant extent. Optimizations and processing modifications carried out with the experimental unit could lead to further improvements.

5.3. Investigation into the suitability of O₂-enriched air for acceleration of composting

Experiments carried out by a company in an open windrow system showed that the first phase of composting could be enhanced when substrate was aerated with O₂-enriched air. In order to make sure that this method could also be used in other composting systems, our department was instructed to carry out laboratory-scale experiments.

Six experimental series were carried out to study different operating conditions. In each set, identical model biowaste and composting parameters were used with the exception of aeration and bulk density. The corresponding conditions of experiments 1–6 are listed later. Aeration with normal air was compared with the application of O₂-enriched air in each experiment. If not mentioned explicitly, the oxygen concentration in the O₂-enriched air was adjusted to 25% (Braukmeier and Stegmann, 1997).

Exp. 1: 25% lower aeration rate in the O₂-enriched reactor (70–130 l/h/reactor) than in the normally aerated reactor (80–150 l/h/reactor), resulting in same oxygen inlet per unit time.

Exp. 2: 25% lower aeration rate in the O₂-enriched reactor (240 l/h/reactor) than in the normally aerated reactor (280 l/h/reactor), resulting in same oxygen inlet per unit time; higher oxygen concentrations in exhaust air in comparison with series 1 resulting from higher aeration rates.

Exp. 3: Same aeration rates (150 l/h/reactor).

Exp. 4: Same aeration rates (290 l/h/reactor—but two reactors in line connected by aeration system to simulate a high compost pile; material in the first reactor was compressed).

Exp. 5: Same aeration rates (240 l/h/reactor); higher oxygen concentrations in exhaust air in comparison with series 3 resulting from higher aeration rates; compressed material to study the bottom of a high pile in detail.

Exp. 6: Same aeration rates (200–240 l/h/reactor); 30% oxygen in the inlet air to investigate the highest realizable oxygen level (higher oxygen levels would result in security problems associated with the potential for an explosion).

Degradation in the normal and the O₂-enriched variants was very similar in all experiments (Fig. 12). In the experiments with identical oxygen inlet per unit time and, therefore, different aeration rates (first and second experiment), slightly less degradation (less C-loss) was observed in the variants with the O₂-enriched air than in the normally aerated reactors. This indicated that a good distribution of air (due to higher aeration rates) in the bulky substrate had a higher impact than the actual O₂-content of the air. The theoretical advantages of a reduced flow rate could be reduced drying effects and enhanced degradation. But, in order for these benefits to be achieved good air distribution would be necessary. In the third, fourth, and fifth experiment, slightly higher degradation could be observed in the O₂-enriched variant. Only the differences of the fourth experiment after 7 days could be considered to be significant. In this case, the O₂-enriched air, especially, had the potential to enhance degradation in the reactor second in line simulating the upper layers of a high compost pile. A large quantity of the O₂ initially fed into the system with the inlet air was already consumed so that higher O₂-contents were useful. The calculated gain of time would be about 25% after 1 week. In the sixth experiment, the maximum feasible oxygen concentration showed the same results as for normal aeration, since aeration rates were high and no O₂-limitation was encountered.

In conclusion, it can be said that when the right operation modus is selected, O₂-enriched air could have some positive effects—especially in the first phase of composting with high O₂-consumption and on layers at

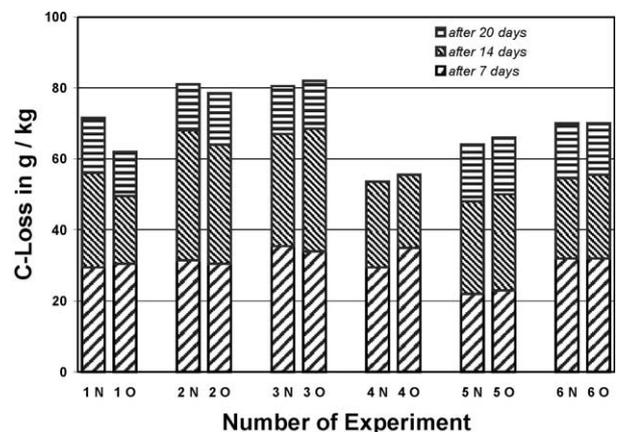


Fig. 12. Comparison of the cumulative C-loss of the waste in a normally aerated reactor (N) with a reactor aerated with O₂-enriched air (O) after different time periods for six experimental sets differing in operation modes.

the opposite end of the inlet air inlet. As far as reactor systems are concerned, O₂-enriched aeration could probably be most helpful in tower composting. However, the adjustment of other composting parameters such as aeration rate and substrate structure is much more important than O₂-concentration in the inlet air.

6. Conclusions

The course of a composting process depends on the system used and on several other factors. Before composting, the substrate properties are usually adjusted (e.g. by shredding, mixing, homogenizing, moistening) to achieve acceptable conditions with respect to substrate structure, water and nutrient content, as well as pH. The substrate properties change during the process due to degradation so that measures are necessary to re-adjust suitable conditions. Control operations normally used in a composting facility during the composting process are: aeration, moistening, and turning. The utilized variants and combinations are miscellaneous and with it the possible results for the course of composting. It is difficult to define the optimal course of composting as it depends on composting aims and boundary conditions. In some cases, it might be necessary to treat waste in a very short time—e.g. when there is not enough space or when the compost is urgently needed. In other cases, space and time may be available but finances for an improved processing are the limiting factor. In other examples, only certain kinds of waste shall be treated, e.g. because a certain compost quality is to be produced. To determine the optimal course of composting for each specific case, the facility may have to carry out experiments. The selection of the right experimental set-up depends on that question. Each set-up is useful for a particular application and has its limits. The previously discussed experiments did depict some potential applications for small-scale (Sections 5.1–5.3) and laboratory-scale experiments.

Advantages of small-scale experiments in comparison to laboratory-scale composting experiments are, for example, that low amounts of samples are necessary, that a high amount of different variants can be investigated, and that the experiments can be carried out easily guaranteeing results within a short period of time. Working with a laboratory composting unit is more cost-intensive but is less expensive than experiments in a real-scale facility. For both small- and technical-scale experiments, skilled workers are needed to run and interpret the experiment. Each experimental unit should only be applied for certain tasks so that they can be used effectively.

Respiration experiments are not valuable in cases, for example, where the complex interaction of the different factors of a composting process is important. Investiga-

tion can only be carried out with regard to the influence of substrate-specific parameters on biodegradability under aerobic conditions as well as O₂-consumption in general. Respiration experiments are useful to optimize all factors that can be adjusted during substrate pretreatment with the exception of particle size. For composting, they can give helpful hints for useful aeration rates and, since substrate properties strongly change during composting, the conditions for degradation during composting can be optimized. The exceptions are the particle size and temperatures over 35 °C. Furthermore, respiration experiments can be used to determine the progress of composting and the maturity of compost. The following list gives some examples for the successful application of respiration experiments:

- investigations into the general degradability of a substrate or an additive;
- investigations to find out whether a substrate is polluted or treated with degradability limiting substances;
- investigations into the effect of additives on degradation;
- investigations into the formation of certain intermediate products of aerobic metabolism;
- investigations into the degradability for temperature ranges between 15 and 35 °C;
- investigations into the effect of special microorganisms on degradation;
- determination of the amount of O₂ needed for degradation;
- optimization of moisture, pH, nutrient contents, and concentration of additives; and
- determination of the degree of maturity of compost.

With respiration experiments, the number of variants which must be investigated using more detailed large-scale experiments can be reduced. In most cases, larger scale investigations follow a respiration series for verification—and take into consideration the complex cooperation of all influencing factors simultaneously. No larger scale experiments are necessary, when the respiration experiments ends with negative results—e.g. when a substrate or additive showed degradation limiting properties. The suitability of a substrate should be ascertained in small-scale experiments before running experiments in the laboratory composting unit as investigations would be too ineffective and expensive otherwise. As all regulation possibilities such as aeration, moistening, and turning can be simulated with the laboratory composting unit, their complex cooperation can be taken into consideration. Furthermore, encouraging composting variants can be tested, compared, and optimized—e.g. gained by use of models. By that, the best variants for industrial-scale can be determined. The results can also be used to improve models. With the

composting unit, most composting systems and their potential regulation can be simulated. But modifications have to be carried out in most cases to fulfill the special requirements. The set-up shown in Fig. 7 should simulate processes such as pressure-forced windrow and pile composting as well as tunnel, box, container, and channel systems. To simulate tower composting, more reactors should be coupled in series and the bulk density of the reactor contents should be varied to simulate the special height of a tower. For simulating drum composting, the reactor should be replaced by a rotating drum reactor. Vacuum-induced and exhaust air recirculation systems could be simulated by integration of a pump. A naturally ventilated system could be simulated by very low aeration of the substrate bottom and top. The set-up of an industrial-scale facility is not directly transferable to laboratory-scale. Simplifications, specifications, and modifications have to be carried out, but the general properties of the system can still be ensured. The results gained on laboratory-scale are not transferable 1:1 on industrial-scale, but the tendencies can be recognized. Final optimizations have to be adjusted in the facility.

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