Methods for Laboratory Studies on Composting of Standard Substrate in Static and Rotated Bioreactors

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Abstract

Novel methods of rapid composting in the laboratory, using bioreactors insulated against loss of heat and reproducible standard substrate, were developed. Influence of insulation, aeration, additives such as meat meal, shredded paper, shredded milk cartons, grass clippings, chicken residues, and poultry manure as well as various mixtures of bulking material was studied.

In the less well insulated bioreactors the temperature in the substrate started to decrease already after some hours when peak of 40-45°C was achieved. In the well insulated ones the temperature continued to raise up to above 60°C and lasted some days above 40°C before it declined. The pH decreased during the first one to four days, depending on additive, by one half or two pH units, after which it increased to between pH 8 and 9 over a period of two to five days. The content of readily available plant nutrients in product was influenced by the additives. Fresh weight losses during the two weeks processing were between 20 and 30%.

The evolved methods can be used for all kinds of studies concerning bioconversion of various organic materials and organic or inorganic compounds. They great flexibility makes it possible to study processes and products of both aerobic and anaerobic microbial transformation.

Keywords: composting in bioreactors, standard substrate, additives, insulation, aeration, agitation, temperature, pH, mass balance.

Abbreviations: cs - centrally sorted, LWI- less well insulated, MSW - municipal solid waste, OM - organic material, OW - organic waste, RB - rotated bioreactors, SB - static bioreactors, SS - standard substrate, ss -source separated.

Introduction

Composting is an aerobic bioconversion or microbial transformation of substrates made of mixtures containing different organic materials. Organic compounds in wastes, residues and in fuel crops are the raw material which is transformed by microorganisms to various products. Unfortunately, current composts are mostly produced using old composting methods working with low precision. Using higher precision can be manufactured products, which will be classified as biofertilizers of desired quality.

Microbial transformation is used in many industrial processes, mainly in production of food and feed. Several products created through microbial activity are also used in pharmacology, mining, the food industry, and in households. Microorganisms since ancient times catalyse the chemical reactions in production of wine, cheese and other foods, and can also be put to work in the manufacture of biofertilizers from various organic materials.

For an optimal environment for bioconversion of organic materials both internal and external requirements for proper composting were listed. Internal requirements can be called 'substrate characteristics'. Stentiford and Zane (1995) pointed out three internal requirements for successful aerobic bioconversion: nutrient balance, structure and water content. Changing one of these process factors affects the other factors, process, and the quality of the final product. External requirements, also called 'equipment aspects', refer to the insulation, aeration and agitation of the substrate during processing.

At the Division of Root and Substrate Research in Alnarp, studies were carried out concerning the crop response to compost in mixtures with peat or different soils (Gajdos, 1987; Gajdos, 1989; Gajdos, 1997). The quality of the composts did not consistently correspond to the requirements of the cultivated crops. Hence trials were started 1988 with composting plant wastes in different backyard composters (in Sweden called composting containers). The results from backyard composting showed the potential for improving the quality of the compost with the aid of insulated containers and proper handling (Gajdos, 1992a,b). The satisfactory insulation was obtained in thermoses which were used as bioreactors for composting in laboratory. To create a substrate, which could be reproducible, various vegetable residues were collected, shredded, and mixed with sawdust and straw. One of these mixtures became "standard substrate" for laboratory studies on composting.

The aim of the work was to answer following questions: How to manage composting and achieve efficient recycling of plant nutrients? How to at the same time save or utilise energy bound in organic material, inactivate pathogens and weed seeds, and avoid a negative impact on the environment? What kind of equipment and methods are needed for studies on product-oriented composting?

Materials and Methods

Substrate

A well defined reproducible standard substrate (SS) was composed of fresh (not processed) organic constituents adjusted to a mixture suitable for the experimental process (Tab. 1). Eleven weight parts out of fourteen contained fresh, shredded, water-rich and relatively nitrogen-rich constituents. Because of high water content and for the microorganisms readily available nutrients, these constituents were processed immediately, or as soon as possible. Preservation was achieved by cooling for a short time (1 - 4°C), or freezing (-18°C) for a long period of time. The last three parts of SS were "bulking materials" which contained dry constituents. These are usually suitable for long term storage, often carbon-rich and mostly nitrogen-poor. Water in the SS originated from the wet constituents (biologically bound water). All constituents were shredded on a large shredder with changeable sieves at KAMAS factory in Vellinge (southern Sweden). In early experiments sieves with openings of 3 mm were used, while sieves with 1.5 mm in diameter were used later. Analysis of the total amount of most of the elements of the SS and its constituents are shown in Tab. 2.

TABLE 1. Constituents of standard substrate are presented as a parts of the fresh weight and in percent of total, fresh, and dry weight.

Material	Parts of substrate	% of weight total	% of weight fresh	% of weight dry	C/N ratio
Fresh, water-rich and relatively nitrogen-rich constituents:					
potato	5		35.7	22	23
carrot	3		21.4	7	21
cabbage	3		21.4	7	24
Dry carbon-rich constituents:					
pine sawdust	2		14.3	42	248
barley straw	1		7.2	22	69
Dry matter		32			
Water		68			
Standard substrate	14	100	100.0	100	63

TABLE 2. Content of elements in raw constituents of the standard substrate (SS) and in SS at the start and when processed (% or ppm of dry matter).

Elements	Constituents of the SS					SS			
	Potato	Carrot	Cabbage	Sawdust	Straw	start[1)]	start[2)]	Start[3)]	treated[1)]
	%								
C	44.90	45.45	46.82	52.08	47.58	49.60	47.26	44.47	48.86
N	1.97	1.89	2.28	0.21	0.69	0.79	0.60	0.97	0.95
P	0.23	0.32	0.32	0.01	0.07	0.12	0.13	0.15	0.22
K	2.25	2.82	3.11	0.06	1.49	1.31	1.28	1.24	1.99
Ca	0.04	0.40	0.53	0.06	0.43	0.20	0.22	0.24	0.33
Mg	0.10	0.19	0.18	0.01	0.67	0.07	0.06	0.06	0.10
S	0.18	0.22	0.84	0.01	0.13	0.15	0.11	0.14	0.17
	ppm								
Na	60	6927	717	13	2708	1101	522	858	807
Si	104	234	22	15	1337	403	811	376	1193
Fe	87	284	25	6	62	65	219	65	340
Al	67	213	3	8	11	38	113	49	164
Mn	9	97	11	107	8	58	38	41	59
Zn	15	61	14	12	12	16	13	18	23
Ba	3	61	4	4	13	9	10	9	14
Rb	19	41	13	2	6	10	6	7	8
Sr	4	35	22	2	20	10	9	13	11
B	5	27	17	1	6	6	6	9	7
Cu	1	13	6	1	4	5	3	6	6
Cr	1	1	1	1	2	1	nd[4)]	nd[4)]	nd[4)]

[1)] SS - first mixture, [2)] SS - second mixture (sample 1), [3)] SS - second mixture (sample 2)
[4)] not detected

The SS was processed with and without additives or modified in the content of some constituents. Part of the SS was then replaced by various additives as: chicken residues containing skin and bones (10%), composting agent (0,25%), sludge from paper industry (50%), grass clippings (10%), ground paper (5%), shredded milk cartons (10%), meat meal (4 or 5%), poultry manure (50 or 67%) and shredded intestines from slaughter house inclusive of their content (75 or 83%). All amendments were made in weight % of the fresh weight of the substrate.

The SS was modified in several runs by using 1.5 parts pine sawdust and 1.5 parts barley straw, in the three parts of the bulking material, instead of 2:1 ratio. In one run the wet constituents were mixed with only pine sawdust and barley straw, respectively. In experiment with shredded intestines only barley straw was used.

Equipment

A battery of seven vertical, static bioreactors (SB) was in operation at the time of the start of the investigation. Bioreactors were made with different degrees of insulation against loss of heat. Five well insulated (WI) bioreactors were actually 3 litres thermoses for laboratory use (ISOTHERM, Germany). As two less well insulated (LWI) bioreactors were used Plexiglas cylinders of 3 L volume with plastic bags inside. The cylinders were covered with 1.5 cm thick paper cylinders. Stoppers made of plastic-covered rubber foam were placed in the top of all bioreactors. One bioreactor of each type is shown in Fig. 1.

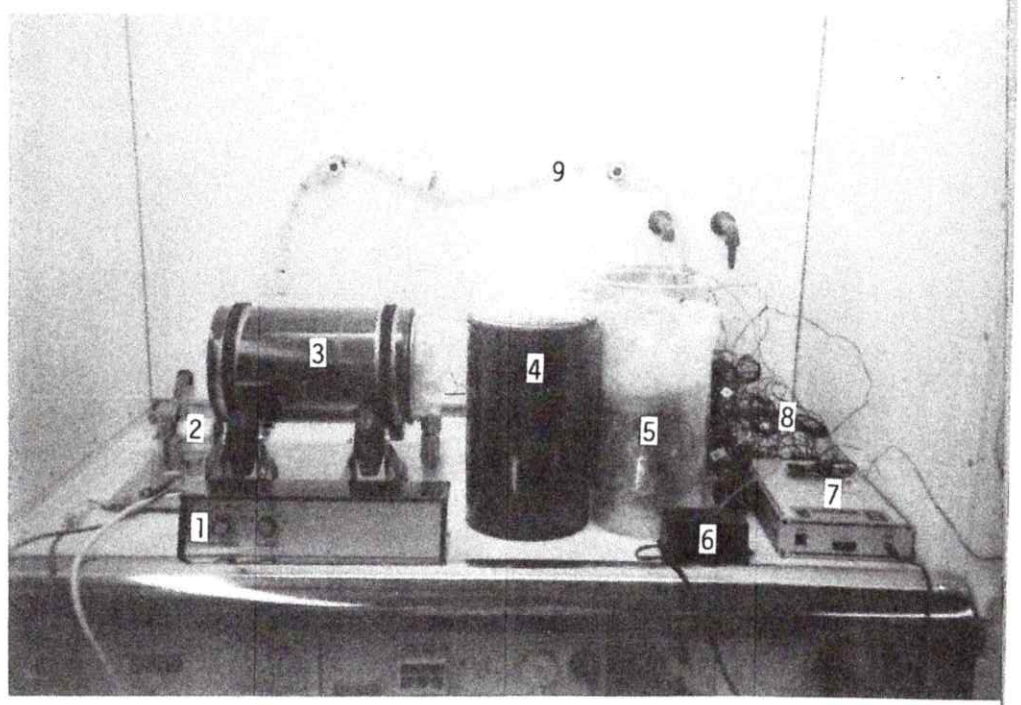

FIGURE 1. Laboratory composting equipment at the time the rotated bioreactor was tested. 1 - control unit for the rotated bioreactor, 2 - engine, 3 - well insulated rotated bioreactor, 4 - well insulated static bioreactor, 5 - less well insulated static bioreactor (plastic tube and behind it paper tube, which serves as insulation), 6 - air pump, 7 - logger, 8 - thermo-sensors, and 9 - plastic tube connected to air pump and branched to small tubes entering the bioreactors.

The capacity of insulation was tested using 1 L of warm water. A comparison between the temperature changes in WI and LWI bioreactor is shown in Fig. 2.

Aeration of all seven bioreactors was provided by an air blower (for water tanks). Air was blown through a plastic tube with 10 mm in diameter, which was then branched

into small plastic tubes with 1 mm in diameter. Two of the small tubes were placed at the bottom of each bioreactor under a double bottom. The air flow into each bioreactor was controlled by an air-flow meter and adjusted to a flow of 10 L/h for each bioreactor (i.e. 40 L per kg of dry matter and hour). A net placed on plastic sticks was used as a double bottom in the early experiments, but was later replaced with corrugated plastic foam.

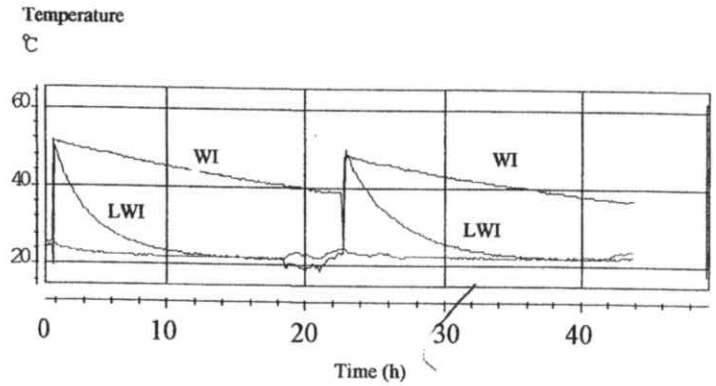

FIGURE 2. Temperature changes in one litre warm water placed in two vertical static bioreactors. WI - well insulated bioreactor, LWI - less well insulated bioreactor. Bottom curve - air temperature in the laboratory.

Agitation during experiment was achieved when horizontal, rotated bioreactors (RB) were constructed and the possibilities to control the process were improved. The agitator operated in both directions in each cycle. Two parallel-working systems were built with three bioreactors in each.

In the first system, the bioreactors (S1, S2, S3) were made of 3 litres thermoses (Fig. 3a,b). They were mounted horizontally on four wheels, two of which had grooved rims and were in contact with corresponding belts on the bioreactors, causing them to rotate. Each bioreactor was equipped with an engine for sequential or continuous steering. The plastic-covered rubber foam stoppers were used in the early runs. They were later replaced by stoppers made of hard plastic, insulated with rubber discs. Four openings were made in each stopper (Fig. 3b). Two was for air inlet and outlet (5 mm in diameter), one for the temperature sensor (10 mm), and one for taking samples during processing (20 mm). Each bioreactor had a separate air-blower (for fish aquarium) for aeration. Inside the bioreactors plastic tubes with 5 mm of diameter were placed for aeration and for outlet air. In this tubes 1 mm holes were bored. During some runs the outlet was connected to plastic bags for collecting the exhaust air. Contents of oxygen and carbon dioxide were measured.

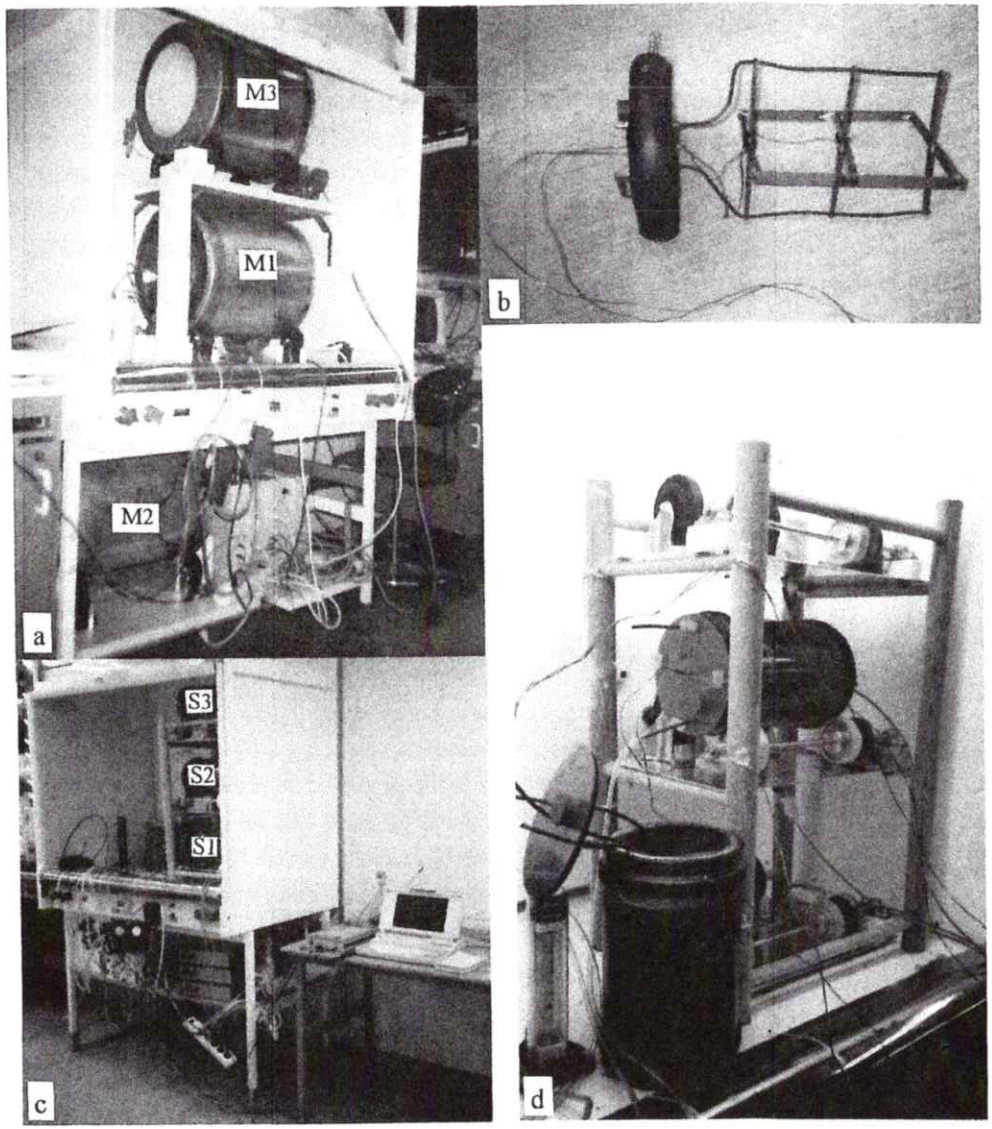

FIGURE 3. Well insulated, continuously aerated and sequentially rotated bioreactors in laboratory. a - bioreactors (18 L), control units, and air pumps. M3 bioreactor is empty. b - The lid with equipment keeping plastic tubes for aeration and exhaust in desired positions. Two thermo-sensors are mounted on the construction. c - bioreactors (3 L), control units, air pumps, temperature logger, and computer. d - In the front bioreactor S1 and a lid with plastic tubes for aeration, thermo-sensors, and a rubber stopper. To the left is an air flow meter.

In the second system, bioreactors (M1, M2, M3) of the 18 L volume were build (Fig. 3c). The bioreactors were constructed of plastic acid-proof inner-containers, covered by foam insulation and metallic outer-container. A plastic tube, 1 cm of diameter, were wound directly on each plastic container. It could be used for cooling or warming the substrate in the bioreactor by circulating cold or warm water. Steering of the bioreactors was based on position sensors. They were used to stop the rotation after one cycle followed by a reverse cycle. Aeration apparatus was the same as for the bioreactors in the first system. Stoppers consisted of two plastic discs with insulation between them. Rubber wheels from small bicycles were used for airtight closing of bioreactors. They fixed stoppers in the upper part of the inner-containers (Fig. 3c,d). Four openings were in each stopper, as described above for the smaller bioreactors. To keep the aeration tubes in the same position during processing, and to improve remixing of the substrate at the same time a special equipment was built (Fig. 3d). During some runs the outlet tube from bioreactors was provided with a cooling spiral for condensation and collection of the liquid compounds from the outlet air. Each bioreactor was connected to a control unit to modify the steering intervals.

Measurements and sampling

Temperature was measured each 30 seconds and recorded at the rate of 10 registrations per hour with an INTAB AAC-2 logger. Temperature sensors were thermocouple of type T. The sensor-end of thermocouple was constructed of two wires which were wound round each other and covered with shrink-cap by using a blowtorch. In the SB the sensors were placed at various positions in the processed substrate. In the RB two temperature sensors were placed in the middle of each rotated bioreactor, but at different distances from the lid. In the 3 litres bioreactors 10 and 18 cm, respectively, and in the 18 litres bioreactors 20 and 30 cm, respectively. After transferring collected data to the computer, temperature curves were printed out.

pH was measured in some runs once a day during the first week of processing and at the termination of each run. Samples (5 g of substrate) were taken from each bioreactor and immediately diluted in 45 ml distilled water. After shaking for 30 minutes, pH was measured with a MESSKOFFER pH 10 LCD-pH meter.

Material balance estimations in terms of fresh weight were based on the initial weight of the SS and the final weight at the termination of each run. The product, called raw compost, was stored in freezer for later use. Cultivation tests which were carried out are not published except for one report (Svedelius and Gajdos, 1994).

Analyses on elements were made by BIOSPECTRON, Sirekõpinge and readily available plant nutrients were analysed by LMI, Helsingborg.

Performance

Wet and dry constituents of the SS were shredded separately and then mixed. Well disintegrated and homogenised SS was analysed on total amount of 19 elements and stored in a freezer at minus 18°C. Before start of each run the SS was defrosted at room temperature. Then, with or without additives, it was placed in bioreactors. In the small bioreactors 800 g and in the large 5.6 kg substrate was used for each batch. To investigate temperature differences between various positions in WI and LWI SB, two to six temperature sensors were placed in various positions in the composting matrix. Here presented results are from following runs running for two weeks, except run four.

In the first run two WI and two LWI SB were used. One bioreactor of each kind was filled with SS while in the second SS was amended with chicken residues. Six temperature sensors were placed in three bioreactors and five in one because there was a total of 24 sensors available. One sensor was always used for registration of the temperature in the laboratory. Effects of chicken residue and insulation on temperature were registered.

In the second run three WI SB were used. Effects of 10 % of the added grass clippings to SS and increased aeration in SS were investigated. Four temperature sensors were placed in each bioreactor.

Three WI SB were used in the third run. Differences in the temperature development were registered in the SS substrate, in the SS amended with 5% meat meal, and in the SS amended with 5 % shredded paper. Two temperature sensors were used in each SB.

In the fourth run three RB from the first system were used (S1, S2, and S3). Shredded intestines were mixed with 25, 17, and 12.5 weight % barley straw, respectively. Two temperature sensors in each bioreactor registered the temperature development. These substrates were processed during four weeks.

In the fifth run also three S bioreactors were used. One bioreactor was filled with modified SS. This was composed of the 11 weight parts of wet constituents as SS, but the bulking agent in the modified SS contained 1.5 part barley straw and 1.5 part pine sawdust instead of the ratio 2:1 as in the SS. Two bioreactors were filled with modified SS containing 50 and 67 weight % poultry manure, respectively. The differences in temperature development was registered with two thermo sensors in each bioreactor.

In the sixth run three RB bioreactors from the second system were used (M1, M2, and M3). One bioreactor was filled with SS. In two bioreactors the 11 weight parts of wet constituents were mixed with 3 parts of barley and pine sawdust, respectively. Effects on temperature development caused by changes in bulking agent were registered with two temperature sensors in each bioreactor.

In the seventh run both systems with RB were used (i.e. S1, S2, S3, M1, M2, and M3). All bioreactors were filled with SS containing 4 weight % meat meal. The temperature development was registered with two temperature sensors in each bioreactor.

Simultaneously with studies on composting process, microorganisms in SS were studied in one run (Robertsson, 1994) and survival of weed seeds in SS placed in well and less well insulated bioreactors, respectively, were studied in three runs (Ekenroth, 1994).

Results

Insulation of bioreactors and various temperature sensor positions in the substrate

Differences between the temperature development in LWI and the WI SB are shown in curves from run one in Figures 4 and 6. When substrate was processed in the LWI bioreactors the temperature peaked at 42 and 45°C, respectively, or in few experiments some degrees less, lasted only a few hours, then declined over a period of a few days to a level some degrees above the room temperature. In the parallel-working WI bioreactors the temperature reached peaks above 62°C, and the temperature stayed above 40°C for three to six days. The temperature curves then declined and followed the daily temperature fluctuation of the air blowing in from the laboratory, being only some degrees higher as recognised for the LWI bioreactors.

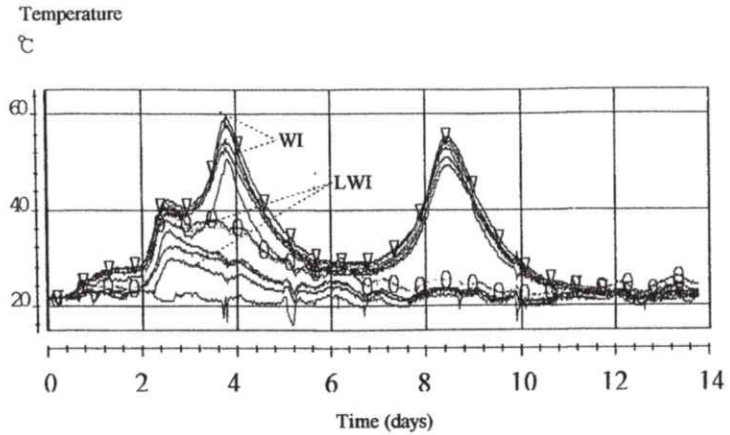

FIGURE 4. The temperature development during aerobic bioconversion of the standard substrate with 10 % of chicken residues (skin and bones) in two parallel-working static bioreactors (3 L) with 800 g of substrate. WI - well insulated bioreactor, LWI - less well insulated bioreactor. The WI bioreactor contains six thermo-sensors and the LWI bioreactor contains five thermo-sensors were placed in various positions in the substrate. Bottom curve - air temperature in the laboratory.

The temperature gradient between temperature sensors placed in the SS without additive, and the same amended with well ground residues from a chicken (bone and skin) is also shown in Fig. 4. In the substrate within the same bioreactor the temperature differences between five or six positions were registered. The highest temperatures were recorded in the middle of the composting matrix. The temperature sensor placed in the middle but only one cm under the surface of substrate showed almost the same temperature development as the first one. The third, fourth and fifth temperature curves from above were given from sensors which were placed by the wall; under the surface, in the middle of the substrate, and at the bottom, respectively. The lowest temperature was achieved when the sensor was placed at the bottom and in the middle of the processed substrate. The difference between the lowest and the highest temperature value in LWI bioreactors can be more than 10°C. In the WI is the difference smaller and lasted shorter time.

Aeration

In Fig. 5 there temperature curves from processed substrate in two WI bioreactors with two aeration regimes in run two are presented. Using standard air-flow (40 L air per kg dry matter per hour) gave the highest peak at 58°C, while in bioreactor receiving the four times elevated air-flow the temperature reached highest point at 49°C. The temperature stayed above 40°C for four and two-and-a-half days for the normal and the four times higher air-flow, respectively.

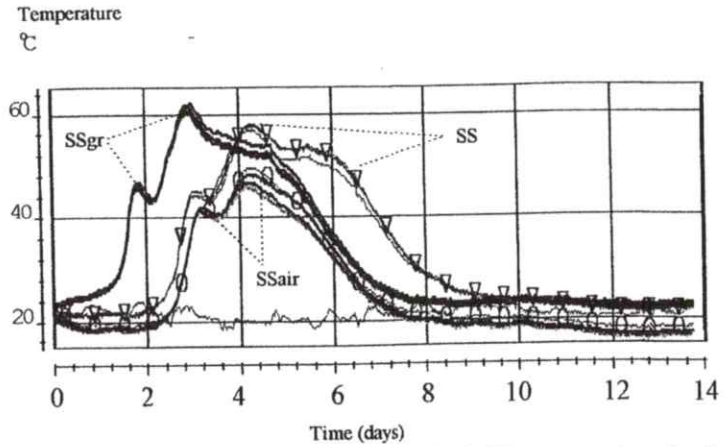

FIGURE 5. Effect of aeration and additive, respectively. The temperature development at various positions in the substrate during aerobic bioconversion in three parallel-working well insulated static bioreactors (3 L) with 800 g substrate. Four thermo-sensors were placed in each bioreactor. SS - standard substrate with air flow 40L/min and kg dry matter, SSair - standard substrate with air flow 160L/min, SSgr - standard substrate with 10 weight % of grass clippings. Bottom curve - air temperature in the laboratory.

Additives

Various additives influence content of nutrients in substrates and thus can affect microbial activity. This can be seen when temperature development is registered. Compared with SS an earlier temperature increase was achieved by addition of 10% grass clippings in run three (Fig. 5), and 5% shredded paper and 5% meat meal in run four (Fig. 6).

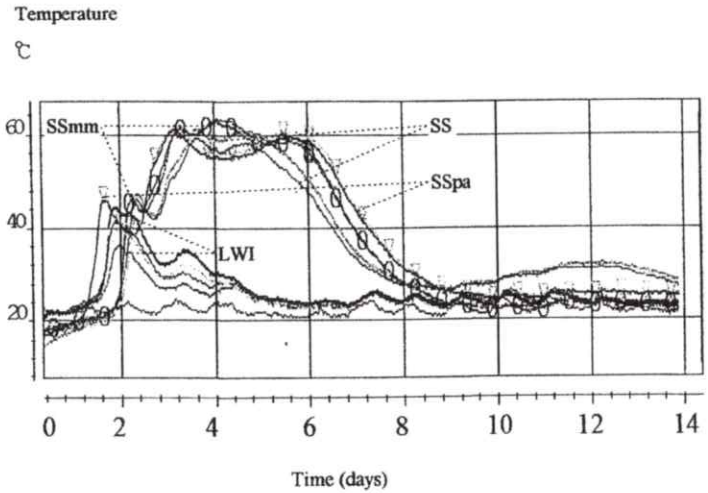

FIGURE 6. Effect of additives and insulation of bioreactor. The temperature development during aerobic bioconversion in four bioreactors (3 L) with 800 g substrate. Three well insulated bioreactors: SS - standard substrate, SSmm - standard substrate with 5 weight % meat meal, SSpa - standard substrate with shredded paper. LWI - less well insulated bioreactor. Bottom curve - air temperature in the laboratory.

Amendment of substrate with some additives caused faster increase of the temperature, higher temperature peak, and also held the temperature at a higher level compared with SS. This appeared when 5% shredded paper and 5% meat meal in run four (Fig. 6) were used.

In some experiments additives could cause two high temperature peaks with deep fall between the peaks, as in SS with 10% of chicken residues (Fig. 4). The peaks were repeated several times when shredded intestines from slaughter-house were mixed with only barley straw in run five (Fig. 7). This run was carried out for four weeks.

The increase of the temperature or the period during which the temperature remained at a higher level was affected by addition of 10% well ground residues (bone and skin) from a chicken (Fig. 4), 5% shredded paper (Fig. 6), 5% meat meal (Fig. 6), and 50 and 67% poultry manure (Fig. 8) when compared with SS.

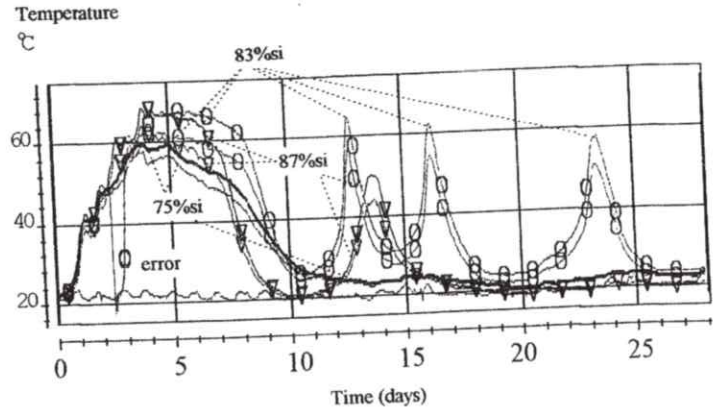

FIGURE 7. The temperature development during aerobic bioconversion in two well insulated rotated bioreactors (3 L) and 800 g of substrate. 75%si - shredded intestines (si) with 25% barley straw, 83%si - si with 17% barley straw, 87%si - si with 13% barley straw. Bottom curve - air temperature in the laboratory. "error" - the deep temperature fall was caused by an accident when the substrate fell out and became dry. After rewetting the temperature increased rapidly.

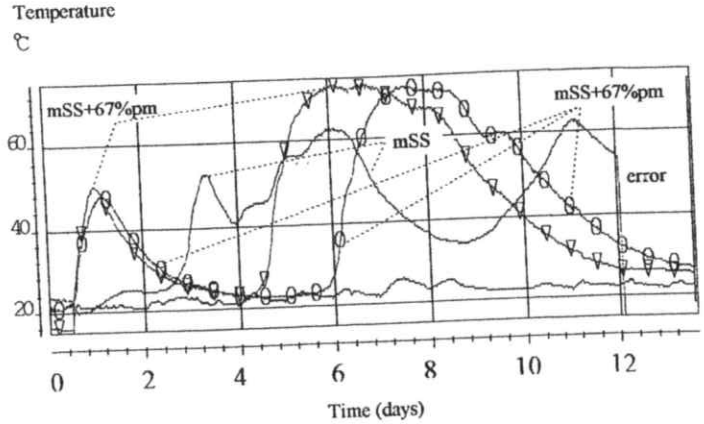

FIGURE 8. The temperature development during aerobic bioconversion in three well insulated rotated bioreactors (18 L) containing 5.6 kg of substrate. mSS - modified standard substrate (bulking materials i.e. sawdust and straw 1:1), pm - poultry manure. "error" - interrupted temperature curve due to damage on thermo-sensor. Bottom curve - air temperature in the laboratory.

Bulking material

The temperature increased faster when substrate contained only barley straw that in substrate containing only pine sawdust. The temperature increase was even faster when

the SS, which contained barley straw and pine sawdust in the ratio 2:1, was processed in run seven (Fig. 9).

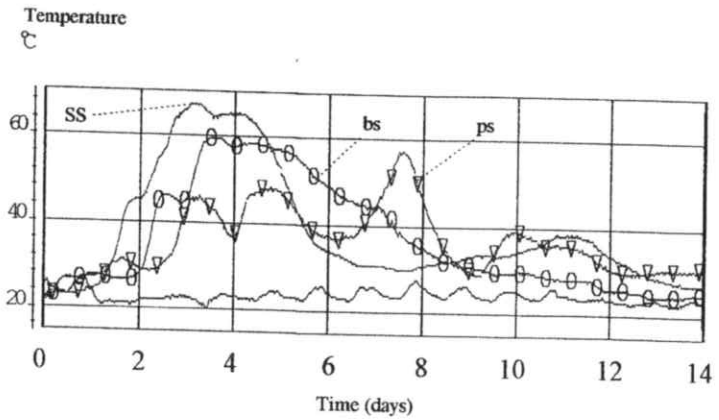

FIGURE 9. Effect of different bulking agents mixed with the wet part of the standard substrates containing shredded potatoes, carrots and cabbage. The temperature development during aerobic bioconversion in three rotated and well insulated bioreactors (18 L) with 5.6 kg of substrate. SS - standard substrate with three parts of bulking agent (two parts of barley straw and one part of pine sawdust), bs - only barley straw, ps - only pine sawdust. Bottom curve - air temperature in the laboratory.

Similarity between temperature curves from parallel-working bioreactors

In Fig. 10 temperature curves are shown from all six parallel-working WI RB in run eight. At the start the temperature increased faster in the small bioreactors. Already on day one the difference in the temperature development between them could be seen. After day 4 and 5, when temperature begun to decrease, the difference became even more distinct.

The temperature in S bioreactors reached highest peak at 72°C on day 5, and stayed above 40°C for four to six days. The first temperature curve (S1) fell to 25°C on day 6, the second (S2) on day 7, and the third (S3) on day 10. In two of the large bioreactors (M2 and M3) the temperature development was identical during nearly the three first days, while in M1 bioreactor the temperature was delayed for about one half a day. In spite of that the decrease of temperature begun sooner in bioreactor M1 than in M3. The temperature reached highest peak at 70°C on day 5 and stayed above 40°C for three to four days.

The aeration in M2 bioreactor was interrupted, when the temperature reached 47°C, and warm water started to circulate in the plastic tube wound around the plastic container under the insulation. The temperature in this bioreactor declined gradually during seven days to 30°C, and then, when aeration was re-established, the temperature decreased during some hours to 25°C.

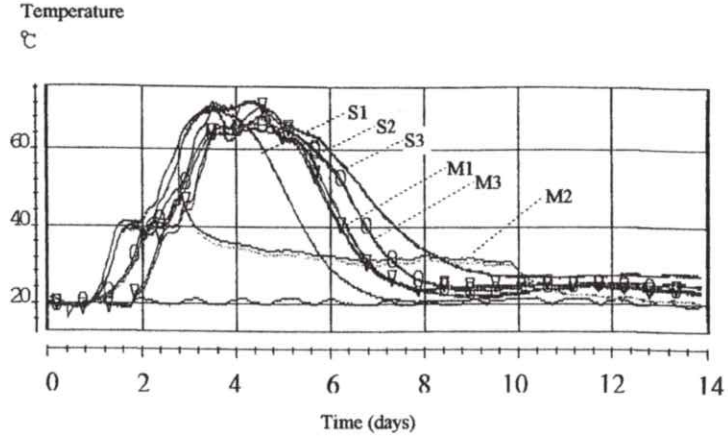

FIGURE 10. The temperature development during aerobic bioconversion of standard substrate containing 4 weight % meat meal in six parallel-working rotated well insulated bioreactors. S1-S3 - 3 litre bioreactors with 800 g of substrate, each bioreactor with two thermo-sensors. M1-M3 - 18 litre bioreactors with 5,6 kg of substrate, each bioreactor with two thermo-sensors. In the bioreactor M2 the aeration was stopped between day two and ten. Bottom curve - air temperature in the laboratory.

pH

The pH initially decreased during one up to three days after the start, then during two days increased to between pH 8 and 9. Effect of poor insulation on pH increase can be seen in Fig. 11. In this figure there are also shown pH changes during processing of SS without additives compared with changes in SS amended with ground paper (5%) or with meat meal (5%). The addition of ground paper lead to higher pH value in the substrate at the start (pH 6.8) compared to the SS with and without meat meal (pH 5.8). On the day one pH in SS with ground paper decreased only slightly, while already on the day three it was identical with pH in substrate amended with meat meal (pH 8.4). At that time in SS pH was only 4.4. From day four in all bioreactors pH was between 8 and 9.

Figure 12 shows pH changes in modified SS, containing barley straw and pine sawdust in ratio 1:1, amended with 50 or 70 weight % of poultry manure. The initial pH in substrates with poultry manure was 7.5, then decreased below pH 6 day one, to slightly above pH 5 day two, three, and four. Both in SS and the substrate with 70% poultry manure pH was above 8 on the day five, but in the substrate with 50% poultry manure only above pH 5. On the day eight all substrates reached pH 9.

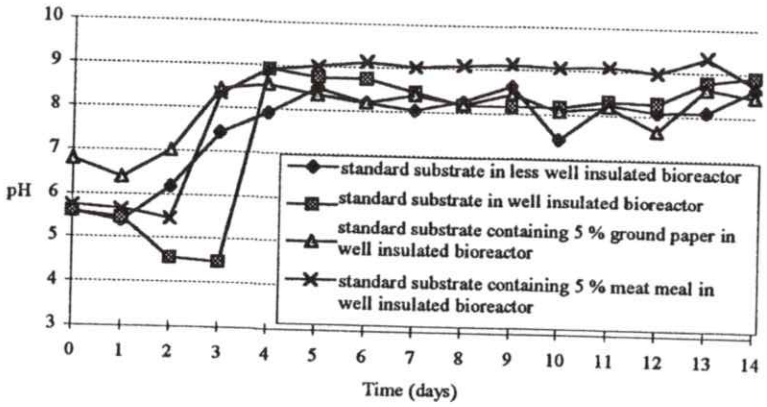

FIGURE 11. Effects of insulation of the bioreactors and of addives on pH changes during aerobic bioconversion in static bioreactors (3 L) containing 800 g substrate each.

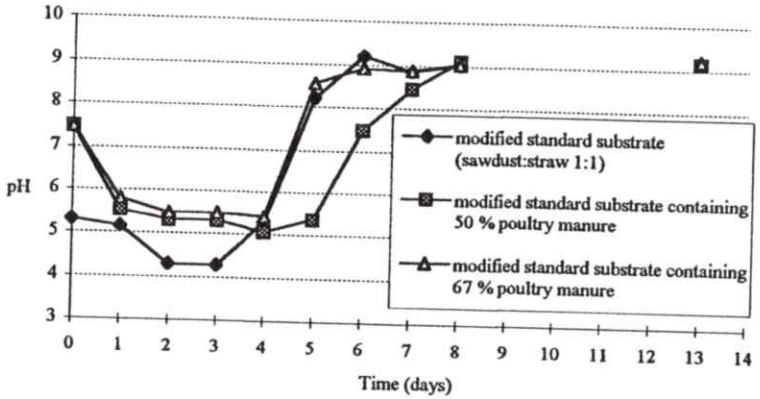

FIGURE 12. Effects of modified substrate with and without additives on pH changes during aerobic bioconversion in three rotated bioreactors (3 L). Two of them contained 800 g substrate. The third contained 850 g substrate made of 800 g modified standard substrate with 70 % poultry manure plus 25 g pine sawdust and 25 g barley straw.

Readily available plant nutrients

Results of analysis of the SS amended with 4% of meat meal were compared with those from SS. They showed effects on pH, conductivity and some plant nutrients (Tab. 3). Before processing, the SS with 4% meat meal had a higher content of P and Ca, and slightly higher pH, Mg, and Na than SS without additives. Following observations were made after processing: increase in pH, slight increase in K, S, Na, Cl, B, decrease in NH_4^+, and a slight decrease in Mg and Ca in all continuously aerated bioreactors i.e. all S and bioreactors M1 and M3. In the M2 bioreactor, which was without aeration during six days, the analysis was affected by anaerobic processes. It shows lower pH, slightly lower K, S, Na and Cl, while conductivity, NH_4^+, and Ca decreased, and P, Mg and Mn decreased only slightly.

TABLE 3. pH, conductivity and content of easily available plant nutrients in standard substrate (SS) with and without meat meal at the start and with meat meal at the termination of one composting run, when three small (S1-S3) and three medium (M1-M3) bioreactors were used simultaneously. Bioreactor M2 was without aeration between day 3 and 10. Temperature curves are shown in Fig. 10.

Para-meter	Standard substrate (SS)	Standard substrate with 4% meat meal						
		at the start	at the termination of the composting run					
			S1	S2	S3	M1	M2[1)]	M3
pH	5.7	6.5	9.7	10.1	9.9	10.0	**5.0**	10.0
Cond.	6.7	6.6	6.3	6.1	5.9	5.3	**10.8**	6.1
NO_3^-	8	1	0	1	1	0	1	1
NH_4^+	79	74	23	25	20	37	**176**	29
P	189	565	562	557	546	533	**762**	558
K	2225	2150	2608	2470	2527	2489	2239	2811
Mg	81	111	103	101	98	99	**137**	104
S	131	121	144	136	129	125	119	150
Ca	181	851	745	768	750	737	**1301**	721
Na	138	207	256	242	247	245	232	274
Cl	326	347	427	401	410	405	371	459
Mn	4.0	4.5	1.8	1.6	2.1	1.7	**2.9**	1.6
B	0.8	0.6	0.9	0.8	0.8	0.8	0.7	0.6

[1)] effects of anaerobic treatment on chemical composition on final product

Drying

In SB a dry part of the compost appeared always just 1-2 cm above the double bottom where air from the pump entered the substrate. In occasionally stirred bioreactors the air was spread evenly, so at the termination of the process the whole substrate had equal moisture content. In Fig. 12 it is demonstrated that drying of the substrate during processing does not always stabilise the product. The processed substrate dried out during one night when the stopper dropped down and the bioreactor, due to agitation, was emptied. The temperature of the substrate fell to air temperature in the laboratory, but after the substrate being moisturised to the same moisture level as it was at the start, temperature rose fast to the level above the temperature before the accident.

Material balance

About 30% of fresh weight was lost probably as gaseous compounds over the course of two weeks in small RB (3 L) when 800 g of the substrate was processed. Only about 20% of the fresh weight was lost during processing in the parallel-working larger RB (18 L) containing 5.6 kg of raw substrate.

Discussion

The development of the presented methods was done successively due to interest in getting answers to increasing number of general holistic questions with impact on the process such as insulation of the bioreactors, aeration, agitation, additives, and bulking material. These novel fairly simple methods increase the possibilities to carry out studies on bioconversion of various mixtures of organic materials in an inexpensive equipment. Numerous laboratory bioconversion methods (aerobic and anaerobic) are described in literature (Bågstam *et al.*, 1974; Citterio *et al.*, 1987; Cook *et al.*, 1994; Elwell *et al.*, 1994; Finstein et al., 1996; Michel *et al.*, 1993; Nakasaki *et al.*, 1994; Nelson *et al.*, 1994; Rivard, 1993; Sikora *et al.*, 1994; Switzenbaum *et al.*, 1994; Walker, 1994). Most of them were too expensive for our limited budget.

Temperature development

As the heat during composting is due to the excess energy released by the bacteria and the high temperature is maintained until the readily decomposable material has been broken down (Golueke, 1972), the temperature development in the processed substrate gives a picture of the progress in bioconversion. The temperature registered during the runs was influenced by changes in equipment aspects (insulation, aeration and agitation of bioreactors) and by substrate characteristics (composition and structure of the processed substrate).

There are still many questions concerning the most advantageous temperature levels and their development during the whole process. Microbial transformation processes are going through a lag, acceleration, exponential and the retardation phases where various microbial populations perform and operate, similarly to the closed (batch) culture growth cycle presented by Slater (1988). Regarding all figures on both temperature and pH changes (Fig. 5 to 12), can be assumed that the initial phase of microbial transformation seems to be the most sensitive for the whole process and probably also for the quality of final products. To make the process efficient and to achieve desired products need more research regarding control of all phases of the bioconversion, but especially the initial phase. The temperature curves, which were obtained by Wiley and Spillane (1962) during eight days composting of 4-6 tons refuse in bins, compared with thirty days composting of the same on windrows, show the same tendencies as shown in this study. In batch experiments by Michel et al. (1993) during forty days composting of fresh grass and fresh leaves, in a temperature controlled incubator in a laboratory, are shown similar results.

All here presented temperature curves differ from those obtained from composting piles, windrows, and bins where thermal insulation is poor or missing and substrate is more or less regularly turned. In those open systems the distribution of temperature can not be uniform throughout the whole substrate (Golueke, 1972) and thus final product are seldom of even and reproducible quality.

Insulation of bioreactors

Effect of insulation of bioreactors on the temperature development in the whole processed substrate is obvious (Fig. 4; Gajdos 1992b; Gajdos 1995a,b). The evolved temperature was higher and lasted in the WI bioreactors longer than in the LWI ones. In spite of using a uncomplicated laboratory equipment, the correlation obtained between the temperature curves was, for the purpose to point out necessity of insulation, satisfactory. To obtain accurate facts and manufacture high quality products, the increased precision of equipment to control the process is unquestioned.

Temperature development on various positions

When static bioreactors were used (Fig. 4; Gajdos, 1995a) the differences in the temperature development on various positions in the processed substrate indicate, that bioconversion of the substrate is not really equal in all places within the same bioreactor. The temperature gradient gave a picture of how heterogeneous and to a great

extend insufficiently transformed composts can be, when they are produced in static systems without frequent agitation, for example on piles, windrows or in bins. Thus the importance of agitation during microbial transformation was demonstrated. Observations on variation in the temperature at various sites in aerated piles made by Stentiford (1987) support this judgement.

Aeration and agitation of bioreactors

Effects of aeration and agitation of bioreactor are closely connected. The necessity of steering was more distinct when emptying the SB and near the air inlet the processed substrate was more dry compared with substrate from other parts of the static bioreactor. On the other hand pellets or small "balls" were formed of the processed substrate in the RB. This problem has to be solved by technicians who may improve the mixing implement within bioreactors. Changes in structure and moisture content of the raw substrate can help to avoid the "balls".

The amount of air required for keeping microorganisms in aerobic conditions in various substrates and during different stages of the bioconversion is not yet established. The effects of aeration shown in Fig. 5 indicate that aeration can be used to control composting.

Aeration in composting is similar to burning. Low air-flow causes slow rate of the oxidation processes. Too high air-flow cools down the substrate. Because of low oxygen levels in aerobic bioconversion, the low activity of aerobic microorganisms and low temperature will be obtained in the processed substrate. The number of anaerobic pockets can increase, and thus increase formation of bad smelling metabolites. The requirement of conditioned air have also to be deeply studied.

Particle size

Particle size reduction is one of the most important factors in yielding uniform substrate for the bioconversion and production of homogeneous biofertilizers. The effect of disintegration was tested earlier (Gajdos, 1992b). Various particle size of bulking material (sawdust and straw) were used in the standard mixture with well shredded wet constituents. The smaller the particles, the faster transformation to desired product can be achieved, under assumption that the substrate is treated properly. The finer bulking agent lead to steadier temperature development. The finer structure of substrate decreased the volume. It can also decrease retention time, increase the precision in process control, homogeneity of the product, and thus reproducibility of biofertilizers can be improved as well as their fitness for application in cultivation.

Nutrient balance affected by additives

The need of suitable nutrient balance for achieving desired process was demonstrated by using various additives in the SS (Figures 4 - 8). Some additives will hasten the metabolic activity of microorganisms at the start of processing, which corresponded to faster self-heating. That may be important for decreasing the retention time. An earlier temperature increase can be caused by addition of readily available compounds, as shown when grass clippings were added (Fig. 5). Similar effect can probably be reached by increased porosity of the substrate when 5 weight % ground paper (Fig. 6) or 10 weight % shredded milk cartons were added (Gajdos and Svedelius, 1994) or when well balanced bulking agent is used (Fig. 9). In the newsprint less than 5% of the organic carbon is water soluble or readily available for use by microorganisms (Lu, 1995), therefore the earlier temperature increase can probably not be explained by increasing the availability of the organic carbon in substrate amended with paper or milk cartons. Other additives, as the well ground residues from a chicken (Fig. 4), composting agent (Gajdos, 1995b), meat meal (Fig. 6), 50% sludge from the paper industry (unpublished), or poultry manure (Fig. 7), can affect the increase of the temperature level during the thermophilic phase or duration of temperature on a high level. This is important for hygienization of the substrate which means inactivation of pathogens and seeds. Supposedly, automatically regulated aeration could avoid appearance of several temperature peaks with deep fall between them, as in the case of some additives such as chicken residues (Fig. 4), composting agent (Gajdos, 1995b), or shredded intestines from slaughter-house (Fig. 8).

pH

Most of the used additives caused special effect on pH development. Some additives such as shredded paper and poultry manure affected increase of the initial pH. The development of pH during the runs could vary even if the initial pH was similar (Figures 11 and 12).

The pH changes during processing are always influenced by the transformation processes in the processed substrate which can be controlled by modifications of substrate and environmental conditions. The pH level dropped at the beginning sometimes to below 4 when substrate contained 2% of glucose (Gajdos, 1995b), due to the activity of acid forming bacteria. The subsequent pH rise is affected by protein degradation and liberation of ammonia from amino acids (Zucconi and de Bertoldi, 1987). The increased amount of barley straw in the substrate probably affected the longer period with low pH (Fig. 12).

The pH falls during the first days and then sharply increases indicating that processing

of "fresh" wet organic materials in batch systems is crucial for fast going natural bioconversion processes. Then homogenous products of required quality can be obtained. Similarly to other researchers (Wiley and Spillane, 1962) it was shown that final products with high pH can be produced during short retention time in closed systems. It is opposite to composting which is carried out during several weeks, months or sometimes up to some years in the open systems. In the closed systems cost efficiency can be increased. Besides other positive effects on soil fertility, the final products can cure soils with low pH caused by acid rain.

Readily available plant nutrients

Different quality of the final product was achieved by control of oxygen availability during processing of SS amended with meat meal. In the bioreactor with interrupted aeration main differences were obtained in decreased pH and increased conductivity and availability of nutrients. Effect of biofertilizers with low pH on soil properties have to be investigated. Under aerobic transformation in the soil the pH will probably increase. High conductivity can be balanced when such product is mixed with soil.

The anaerobic conversion caused also clearly higher amount of available NH_4^+, P, Ca, and slightly higher amount of Mg and Mn in the end product. This indicate that production of biofertilizer with properties sufficiently tailored for successful crop production can be promoted by bioconversion which use both aerobic and anaerobic co-processing processes.

Material balance

Results of processing in RB showed that from the raw material on a fresh weight basis 70 to 80 % final product will be obtained. Compared with composting in open systems, where losses of fresh weight are between 50 and 70%, the closed systems are to be preferred. By technical improvements of bioconversion systems the losses can be further reduced. Plant nutrients and energy bound in the substrate can be stored and then utilised more efficiently by soil microorganisms when added to cultivation media. Then the carbon dioxide, released by microbial transformation in the cultivation media receiving biofertilisers, can be faster incorporated into the growing crops, compared with carbon dioxide released from open composting systems. Increased amount of processed organic matter and increased microbial activity have also other positive effect on soil such as reduction or inactivation of pathogens, increased water and nutrient holding capacity, higher CEC, etc.

Bulking material

Various bulking materials can be used for different purposes such as for increasing available nutrients, the energy-rich compounds, or structure of the substrate. Thus they affect both process and final products. Well disintegrated bulking materials originating from natural residues or by-products (straw, sawdust, bark, wood) or previously manufactured waste products (paper, furniture) may be mixed to obtain optimal effects. This is shown in run seven (Fig. 9) when the mixture 2:1 of barley straw and pine sawdust gave the expected high temperature. More research on various bulking materials should be stimulated to prove their effects on high temperature levels which are needed for hygienisation (sanitation).

Similarity between temperature curves from parallel-working bioreactors

When the identical substrate was treated in three small and three large bioreactors in run eight, the temperature curves were not identically the same (Fig. 10). There are similarities in the shape of the curves. It can only be speculated about the influence of aeration and steering of bioreactors which could cause significant differences in the temperature development. The equipment should be improved to avoid discrepancy between bioreactors and to secure better agreement between results. New experiments with increased precision of the equipment are required.

Conclusions

To achieve biofertilizers with reproducible and proper quality in bioconversion of organic materials it is important to take into consideration all aspects concerning substrate characteristics as well as equipment function. Results in this work are only a small step towards the fundamental holistic knowledge which is necessary for successful processing of various organic materials. It is necessary to create systems where equipment is tailored in accordance with the requirements of microorganisms. To increase efficiency the microbial transformation processes have to be controlled with higher precision than it is done in present systems.

It seems technically possible, and for a faster development of the new systems advisable, to improve the herein presented laboratory systems where data needed as frame of reference can be obtained. Simultaneously can be build up desirable equipment for pilot use. The further investigations made in laboratory and pilot plant will form the basis for building up full scale facilities. Technicians need more information about factors affecting the biological processes for determination the best operational

conditions i.e. for improvement of "recipes" for practical use. To make relevant investigations concerning bioconversion processes and systems, there is a great need for flexible equipment. Thus cooperation between engineers building efficient facilities and researchers studying microbial transformation for plant nutrient recycling, where energy is saved or utilised, and simultaneously the environment protected, has to receive highest priority. All improvements made in the area of an efficient use of organic waste and fuel crops will also positively influence sustainable energy, water, and soil management.

Acknowledgements

I wish to thank my supervisor Paul Jensén and all colleagues at Department of Horticulture for their support. Especially my thanks goes to agronom Barbara Biegus and research student Martin Robertsson for their assistance with the performance of various experiments.

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