APPLIED AND ENVIRONMENTAL MICROBIOLOGY, Feb. 1977, p. 345-350 Vol. 33, No. 2
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Effect of Temperature, Aeration, and Moisture on CO_2 Formation in Bench-Scale, Continuously Thermophilic Composting of Solid Waste[1]

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Received for publication 21 June 1976

A compost production system was employed to supply uniform material for controlled experiments of factorial design. Over a 96-h composting period, the cumulative amount of CO_2 evolved was maximal at 56 to 60°C, an aeration rate that left an O_2 residual of 10 or 18% in the exhaust gas and a moisture content of 60% wet weight. Carbon dioxide evolution was submaximal at 64°C and higher.

Masses of organic material newly assembled for batch-type composting can self-heat from mesophilic to thermophilic temperatures within a few days. In contrast, composting processes of the intermittently charged type, employing well-designed digestor structures, eliminate the initial mesophilic stage and operate continuously in the thermophilic range. Continuously thermophilic composting is possible because the fresh incoming material is boosted immediately into this temperature range by the heat of the resident compost. The new material displaces a like volume of the oldest compost from the digestor. Compared with batch composting the continuous type is more amenable to process control, which is especially advantageous in the treatment of solid wastes of an obnoxious nature. The literature on the microbiology and process control of batch and continuously thermophilic composting was reviewed previously (5).

In continuously thermophilic composting, the operational temperature can be controlled within selected bounds by adjustment of the air supply (7, 8). There is little information, however, on the optimal temperature for the various composting objectives. Disinfection is presumably fastest at the highest temperature attainable, but this may not be favorable for the destruction of putrescible materials, bulk reduction, narrowing of the C/N ratio, and other objectives.

In the present work, certain simplifying departures from usual composting practices were made to examine the effect of temperature, aeration, and moisture on composting activity. Activity was judged mainly as CO_2 evolved. The departures were the provision of externally supplied heat for selected composting temperatures and the separation of compost production from the actual experiments. To the extent that it was feasible, the experimental approach was modeled after continuously thermophilic composting systems in use for the treatment of solid waste.

[1] Paper of the Journal Series, New Jersey Agricultural Experiment Station, Cook College, Rutgers—The State University of New Jersey, New Brunswick, NJ 08903.

MATERIALS AND METHODS

Waste. Table residue from 1 day of operation at a student dining facility was collected after particle size reduction in a commercial wet pulper. The residue consisted of food scraps, paper napkins, and plastic tableware. Sufficient material for the entire project was preserved by drying in forced hot air. Before use, the residue was combined with an equal weight of shredded newspaper. This mixture is called waste. Ninety-two percent of the waste consisted of volatile matter (weight loss upon ignition over a burner flame).

Production of compost. Experimental material was produced in a 12-liter glass cylinder fitted with a perforated false floor, cover, and gasket (Fig. 1). The floor and cover were made of stainless steel. Air from a compressed-air reservoir was humidified by passage over water and then forced through the composting mass at a rate of about 0.06 m^3/min. The production unit was housed in an incubator maintained at 55 ± 0.5°C.

Every 7 days the cylinder was emptied. Approximately 0.8 kg (dry weight) of the compost was retained, and the remainder was discarded. The retained compost was combined with 0.5 kg of waste followed by tap water to bring the moisture content to 60% (wet weight). The waste-compost mixture was then put into the cylinder, except that when an experiment was scheduled a portion was transferred to the experimental chambers. This routine for producing compost was initiated approximately 6 months before the first experiment and was maintained throughout the project period.

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Experimental apparatus. The trials were performed with the apparatus diagramed in Fig. 2. Carbon dioxide-free air exiting from an alkali scrubber was split into three streams for separate flow rate control by means of needle valves and flow meters. To prevent changes in the compost moisture content, the air was prehumidified. At the high flow rate, humidification was accomplished by injecting the air into water through a sparger. At the intermediate rate, injection was through a glass tube. At the low rate, the air was passed over the water surface.

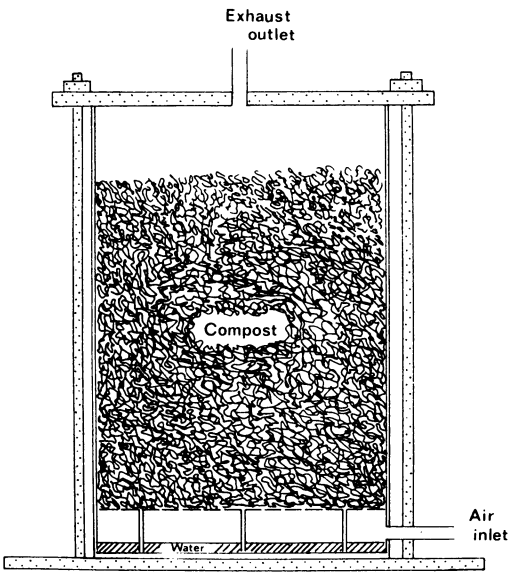

FIG. 1. *Compost production unit.*

The experimental chambers consisted of glass tubes (5.7-cm ID) fitted with rubber stoppers at both ends, and screens held in place 0.5 cm in from the stoppers. Compost occupied the space (approximately 1 liter) between the screens. The chambers were held in a water bath controlled to ±0.3°C. The temperature of the experimental material was that of the bath water, as observed during one trial.

The exhaust stream from the experimental chambers was passed through a condensation trap and then sparged sequentially through 2 N H_2SO_4 to remove NH_3 (which interferes with the oxygen determination) and through 6 N NaOH to trap the CO_2. It was established that no CO_2 escaped from the trap. When an O_2 determination was required, the exhaust was diverted briefly, before CO_2 removal, to a chamber fitted with a Beckman model 777 polarographic O_2 analyzer probe.

Experiments. An average of 79 g (dry weight) of newly combined waste-compost mixture was placed into each experimental chamber. When a moisture content other than the 60% supplied by the produc-

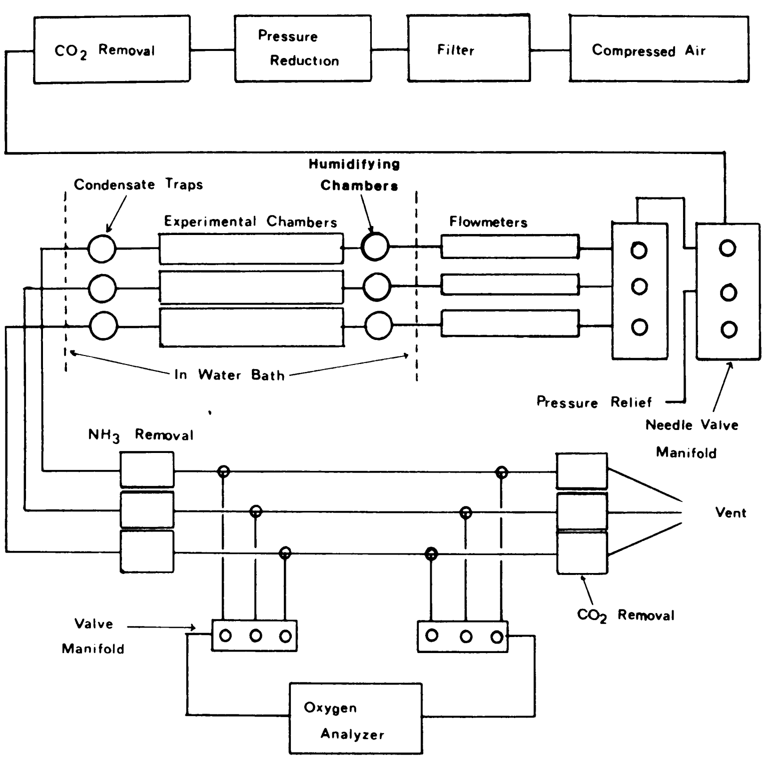

FIG. 2. *Experimental apparatus.*

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tion unit was required, the mixture was so adjusted before placement into the chambers.

The air flow rate to each chamber was adjusted to provide the design-level O_2 residual in the exhaust (see Table 1). Frequently throughout the experimental period, which was 96 h, the O_2 residual was determined and, where necessary, corrected to the design level by adjusting the flow rate. For a special experiment, bottled gases were used (N_2-O_2, 60:40 and 70:30 by volume).

Determinations. The traps in the exhaust path were replenished daily with fresh acid and alkali. The spent alkali containing trapped CO_2 was titrated to the phenolphthalein end point with 1 N HCl after the addition of excess 3 N $BaCl_2$. The results are expressed as grams of CO_2 evolved per 100 g (dry weight) of starting experimental material.

At the termination of some of the trials, CO_2 remaining in the compost was flushed into the alkali traps in a stream of N_2. When this procedure was omitted, a correction factor was calculated based on the amount of CO_2 flushed from compost subjected to comparable experimental conditions.

The pH was determined in a slurry made from an equal volume of experimental material and distilled water. Dry weight was determined after oven-drying the sample at 104°C for 24 h.

RESULTS

Production of compost. The production unit was housed in an incubator maintained at 55°C, but self-heating raised the compost temperature to 61°C during the first day after charging with fresh waste. Thereafter, the temperature gradually declined to about 57°C. At the time of peak temperatures, O_2 in the exhaust gas was at its low point of about 5% of the total gas. Toward the end of the 1-week charging cycle, this recovered to 18 to 20%. The production system can be characterized as a continuously thermophilic, intermittently charged (weekly), completely mixed, composting process. Operating installations of the Fairfield and Dano types are continuously thermophilic, intermittently charged (usually daily), piston-flow processes.

Experimental results. Each experiment was carried out at one temperature, one moisture content, and three aeration levels adjusted to provide the design O_2 residuals in the exhaust (Table 1). The 96-h test period approximates the retention time at a full-scale, continuously thermophilic solid-waste composting installation (8). Comparability among the trials, which were carried out over 8 months, was assured by the system of producing uniform compost as described above.

During the first day of the test period, O_2 consumption was intensive and highly variable, necessitating frequent correction of the air flow rate to approximately achieve the design O_2 residual. After the first day, the O_2 residual from the A series of chambers was usually between 1 and 3%, that from B was between 7 and 12%, and that from C was between 17 and 19%.

Starting moisture contents were within a few percent of the design values. Moisture tended to increase slightly during the experimental period.

TABLE 1. *Experimental design and characteristics of test compost*

Temp (°C)	Design exhaust O_2 residual[a] (%)			Moisture content (%)					pH			
					Realized							
						End				End		
	A	B	C	Design	Start	A	B	C	Start	A	B	C
48	2	10	18	60	60	64	64	65	8.4	8.3	8.5	8.5
52	2	10	18	60	58	60		64	8.4	6.4		8.2
52	2	10	18	60	56	60	62	62	8.4	6.1	8.7	8.6
56	2	10	18	60	58	61	64	68	8.1	8.1	8.4	8.0
56	2	10	18	60	59	63	66	66	8.2	6.4	8.7	8.3
56	2	10	18	50	49	52	54	53	7.5	6.3	8.4	8.2
56	2	10	18	70	72	77	77		8.2			
60	2	10	18	60	59			63	7.6			8.3
60	2	10	18	60	57	62	65	64	7.5	7.7	8.7	8.6
64	2	10	18	60	60	60	63	64	8.0	8.3	6.5	8.3
64	2	10	18	60	59	65	65	65	7.3	8.8	8.5	8.7
68	2	10	18	60	57	58	59	57	7.4	8.1	8.5	8.0
72	2	10	18	60	57	57	58	56	8.2	6.0	6.0	6.0
56[b]	18	25	35	60	61	65	64	65	7.3	8.4	8.4	8.3

[a] See text for conformance to design.
[b] Special study employing 30% O_2-70% N_2 for the 25% residual and 40% O_2-60% N_2 for the 35% residual.

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Starting pH values ranged from 7.3 to 8.4. At termination, in the two more strongly aerated series the pH was usually 8 or higher. Lower final values were associated with weak aeration. The pH response at 72°C was unusual in two respects: at this temperature, relatively acidic conditions (pH 6.0) developed, and the final values were identical in all three experimental portions.

The importance of the N_2 flush at termination depended upon aeration. This procedure accounted for an average of 15% (7.7 to 25%) of the total cumulative CO_2 in the A series, 2% (2 to 3%) in B, and 0.8% (0.4 to 1.7%) in C.

The daily rate of CO_2 evolution in the A series showed no trend throughout the 96-h test period. The rate in the B and C series was in decline on the terminal day.

The effect of temperature and aeration on the cumulative amount of CO_2 formed at a moisture content of 60% is summarized in Fig. 3. Two sets of data were available over most of the range from 52 to 64°C (Table 1), and these were averaged for graphic presentation. (The results of all three trials at 56°C, 18% O_2 residual were averaged.) In the more strongly aerated series (B and C), there was good agreement between pairs of CO_2 values derived at common temperatures, with the individual cumulative values deviating from the means by 1.3 to 8.5%. The comparable range with weak aeration (A) was 10.4 to 41%.

Relatively small amounts of CO_2 were formed when the O_2 residual was 2%, regardless of temperature. Foul odors sometimes developed in these portions. Substantially more CO_2 was produced with residuals of 10 and 18%, and the CO_2 yield increased with each temperature increment until a plateau was reached between 56 and 60°C. A decline was observed with succeeding temperature increments, and at 72°C little CO_2 was formed. Except at 68°C, the 18% O_2 residual was slightly more productive than the 10% residual.

In a special experiment, the effect of aeration with O_2-enriched atmospheres (N_2-O_2 mixtures) was examined at 56°C (Fig. 3). An O_2 residual of 25% yielded slightly more CO_2 than 18%, but a residual of 35% was relatively less productive.

Composts adjusted to moisture contents of 50 and 70% were tested at 56°C (Fig. 4). The results at 56°C, 60% moisture are presented again here for completeness. Carbon dioxide formation was maximal at the intermediate moisture content, although the drier compost was nearly as active. The high moisture level was clearly inferior. At both favorable moisture contents, the 18% O_2 residual yielded slightly more CO_2 than the 10% residual.

Determination of dry weights before and after the trials provided a cruder measurement of composting activity than CO_2 evolution, but

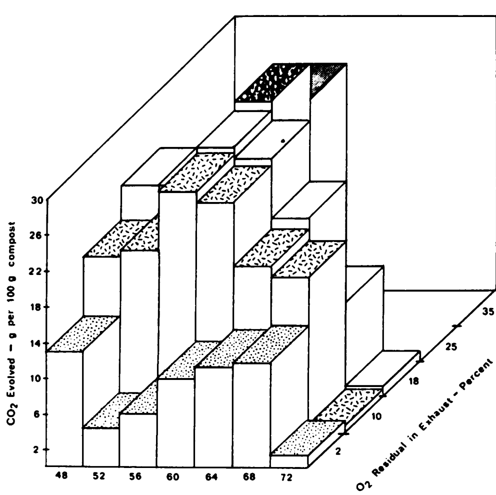

FIG. 3. *Effect of temperature and aeration on CO_2 evolution per 100 g of compost (dry weight) during 96-h trial periods. The moisture content was 60% (wet weight). The top of the 52°C, 18% O_2 column is almost hidden.*

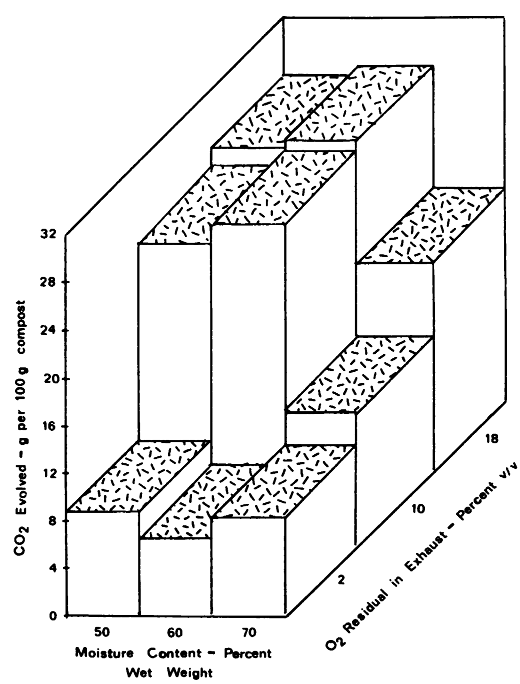

FIG. 4. *Effect of moisture content and aeration on CO_2 evolution per 100 g of compost (dry weight) during 96-h trial periods. The experimental temperature was 56°C.*

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the response was similar (Fig. 5). Weight loss was usually depressed at the 2% O_2 residual, and also at the higher temperatures regardless of aeration rate. The coefficient of determination relating dry weight loss and CO_2 evolved was $R^2 = 0.55$ (O_2 enrichment data deleted). Using the data from the 18% O_2 residual treatment only, $R^2 = 0.71$.

DISCUSSION

A more stringent investigative procedure than the one employed herein would require compost production conditions to match test conditions in all trials. This being beyond our resources, we produced compost at a temperature and moisture content corresponding to the middle of the test range. It could be argued that such a procedure carries an element of self-fulfilling prophesy, partially accounting for the fact that compost produced at 57 to 61°C and 60% moisture performed best at similar conditions. Although this possibility cannot entirely be excluded, it seems likely that the 4-day experimental period employed would have been sufficient for any response to more favorable test conditions.

Moisture content is a convenient and useful process control parameter in composting, but it is a poor means of comparing the water status of dissimilar organic materials as this relates to microbial activity (2). Nevertheless, it is often found that for the composting of solid wastes a moisture content of 50 to 60% is suitable, whereas 70% is too high (6, 10). The present

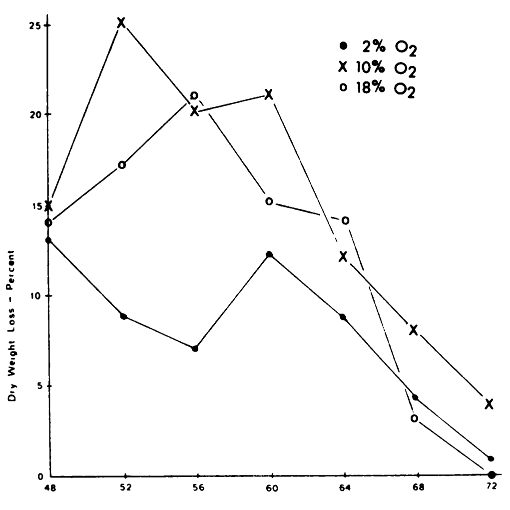

FIG. 5. *Effect of temperature and aeration on weight loss in compost during 96-h trial periods. The moisture content was 60% (wet weight).*

results based on CO_2 formation are in agreement with such findings.

Oxygen-rich gas that left a 25% O_2 residual in the exhaust supported only slightly more CO_2 formation than air. This limited testing does not indicate any significant benefit from the use of special O_2 sources in composting.

The air flow rate that left 2% O_2 in the exhaust severely restricted CO_2 formation. Generally, at the 10% O_2 residual, CO_2 formation was only marginally less than at 18%. Apart from other considerations, these findings suggest that the intermediate aeration rate is adequate for metabolism and preferable for operating economy. However, in some continuously thermophilic field installations, aeration serves both to provide O_2 and to remove excess heat (8). Any economizing on aeration costs must be consistent with the requirement to remove excess heat.

Undesirably high temperatures can be prevented by a different strategy also; that of limiting aeration and, thus, metabolic heat generation. However, imposition of an O_2 restriction is not an acceptable process control measure, as this would retard waste decomposition.

It would be acceptable to separate the cooling function from aeration by means of heat exchangers. The technical feasibility of this approach has been demonstrated on a bench scale (11) and as part of a leaf composting operation in which there was an attempt to usefully employ the excess heat (K. Schwindt, personal communication). The heat was transferred, by circulating water through tubes placed in the windrow, to an adjacent greenhouse for use in space heating. Although the windrow reached 60°C, only 32°C was consistently attained in the water at the point of use. It is considered that 45°C is needed for practicality. Improved performance is being sought by repositioning the heat collector tubes.

The finding from the present bench-scale system (that 10 and 18% O_2 residuals favored CO_2 formation) may be considered in relation to Schulze's report in which he demonstrated on a laboratory scale the feasibility of continuously thermophilic self-heated composting (7), and his experience at a full-scale continuously thermophilic plant at Altoona, Pa. (8). Aeration to Schulze's experimental unit was adjusted so that at various waste loading rates the O_2 residual in the exhaust was usually 5 to 10%. At the treatment plant, O_2 was usually 3 to 12% in the compost interstitial atmosphere. A direct measurement of the effect of aeration on composting activity was not part of these studies.

More recently, aeration control at the Altoona plant has been improved (J. S. Coulson,

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personal communication). The operational goal is now to maintain interstitial O_2 at 16%. Occasionally, this falls to 12% for unknown reasons. A larger version of the Altoona plant is under construction in Toronto, Canada, for the combined treatment of municipal refuse and sewage sludge.

With respect to the optimum temperature for composting, in the present investigation CO_2 formation was maximal at 56 to 60°C and submaximal at 64°C and higher. This contrasts with Shulze's bench-scale results (7) in that he found the rate of O_2 uptake directly related to temperature throughout the test range, which extended to 70°C. At the full-scale plant (8), the digestor contents were usually maintained between 55 and 65°C, but the relative activity within this range is unknown. In batch trials, Wiley (11) found that 55 to 63°C was a more favorable peak temperature range than 67 to 73°C. Wiley's results, like ours, contradict the widely held impression that in composting "hotter is necessarily better."

The timeliness of resolving the question of temperature optimum is emphasized by a recent report, stressing disinfection, on the composting of sewage sludge in combination with wood chips (4). In this batch process, composting is for 21 days during which the temperature is usually well above 60°C and often in excess of 70°C. It is possible that disinfection could be accomplished at lower temperatures and, if our results are applicable, this would favor other objectives. Significantly, the "finished" product continues to self-heat with some vigor. This process has a number of innovative features that result in low capital costs. It is presently used in several locations and has attracted widespread interest. At least one additional city plans to adopt this process in response to a general ban on ocean dumping of sludge (M. Sadat, personal communication).

In connection with the question of temperature optimum, the course of self-heating in freshly assembled batches is of interest. Perhaps the best data are those of Walker and Harrison (9) for heat output from self-heating wet wool. During the course of the temperature ascent, the greatest rate of heat output (calories/time) in the thermophilic range was usually at 60°C. The rate declined sharply as the temperature climbed higher. Similarly, the rate of temperature increase (Δtemperature/time) in wool (9) and straw (3) was greatest at 60°C. This type of observation, however, cannot be extrapolated directly to composting processes. There may have been a delay between the attainment of a temperature unfavorable for growth and the expression of this condition during which previously formed microbial enzymes continued to function.

Whatever the optimum temperature for waste decomposition in composting is, and this may vary somewhat with different wastes and process conditions, it is certainly lower than the maximum that can be attained. Although peak temperatures in the vicinity of 70°C are more common, large composting masses sometimes reach 80°C. The theoretical limit to self-heating may be set by the maximum temperature tolerance of heterotrophic extreme thermophiles, which is at least 90°C (1). The management of a composting process to exceed 60°C presumably aims to favor extreme thermophiles. The presence of such organisms in compost is yet to be demonstrated. Regardless, any benefit so derived may be more than offset by a loss of population diversity.

ACKNOWLEDGMENTS

One of us (D.J.S.) received financial support from Air Resources Management Training Program AP-80 and Water Supply and Pollution Control Training Grant DI-WP-163-04.

We thank Richard Habrukowich for statistical analysis of the data, and Merry L. Morris and Peter F. Strom for helpful discussions.

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