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Effect of Temperature on Composting of Sewage Sludge

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The effect of temperature on the composting reaction of sewage sludge was investigated at 50, 60, and 70°C. The total amount of CO_2 evolved and the final conversion of volatile matter were maximum at 60°C., suggesting that the optimal temperature for composting was around 60°C. The specific CO_2 evolution rate (moles of CO_2 evolved per hour per viable cell) was maximum at 70°C. The isolated thermophilic bacterium which was dominant at 60°C but did not grow at 70°C showed that the rate of O_2 consumption measured on the agar plate at 70°C was four times higher than that at 60°C. This showed that the energy yielded from catabolism is rather uncoupled with the anabolism at 70°C in the metabolism of microorganisms indigenous in the compost. A higher respiratory quotient was observed at 70°C than at any other temperature.

A high temperature during the composting of various materials is effective for the pasteurization of pathogenic microorganisms in the materials, for the promotion of water evaporation from the composting solid materials, and for the acceleration of the rate of degradation of organic matter in the composting materials. Because microbial activity is influenced by temperature, several researchers have tried to define the optimal temperature for composting (2, 5, 6, 10, 12, 13). Golueke (3) showed that the range of optimal temperature for the composting process as a whole is broad, from 35 to 55°C, because various microorganisms are involved in the decomposition of organic matter. Waksman et al. (13) stated that the amount of organic matter degraded per unit of time was maximum at 65°C in the composting of horse manure and wheat straw. Schultze (10) demonstrated that a linear relationship exists between the rate of O_2 consumption and temperature up to 70°C in municipal refuse composting. Recently, Bach et al. (2) found that the optimal temperature for sewage sludge composting was around 60°C as observed from the CO_2 evolution rate. McKinley and Vestal (6) stated that the microbial activity deduced from the chemical analysis of the solid component of compost was maximum at less than 55°C in the composting of sewage sludge. However, there have been only a few investigations concerning the optimal temperature under a controlled reaction environment.

In our previous papers (7, 9), we showed that the reaction rate of composting as measured by the CO_2 evolution rate is related to microbial succession, and we estimated the specific activity for thermophilic bacteria and actinomycetes. In this paper, the effect of temperature was investigated by the same procedure as in our previous papers, under controlled environmental conditions.

MATERIALS AND METHODS

Composting. The composting temperatures were kept at 50, 60, and 70°C as long as possible by controlling the rate of airflow. The operation of the reactor and the composting procedure were the same as those described in our previous paper (7). Two experimental series of runs were performed. In one series, raw sludge and the seed which was the compost product previously prepared in our laboratory were mixed at a ratio of 79 to 21% on a dry weight basis. These runs were denoted as Runs T1-50, T1-60, and T1-70, for the three different temperatures. In the other series, raw sludge and a compost product sterilized with gamma irradiation were mixed in the same ratio as in the Run T1 series. These runs were named T2-50, T2-60, and T2-70. The difference between the two series was in the initial number of thermophilic bacteria and actinomycetes.

Analytical method. The changes in CO_2 and O_2 concentrations in exhaust gas from the reactor during composting were measured with an infrared analyzer and a paramagnetic analyzer, respectively.

Isolation of microorganisms. Media and procedures for the isolation of the microorganisms which are responsible for the degradation of organic matter in compost were the same as described in our previous paper (7). Incubation temperatures were 30°C for mesophilic microorganisms and 60°C for thermophilic microorganisms.

Glucose uptake of thermophilic bacterium BH1. The glucose uptake rate of the isolated bacterium BH1, dominant in the thermophilic stage of composting, was measured in a Trypticase (BBL Microbiology Systems) medium containing Trypticase peptone (17 g), phyton peptone (3 g), glucose (2.5 g), K_2HPO_4 (2.5 g), and NaCl (5 g) in 1 liter. Preliminary characteristics of BH1 were given in our previous paper (8). Preculture was performed for 12 h at 60°C on a Trypticase medium. Precultured suspension (10 ml) was mixed with 90 ml of fresh Trypticase medium, and then the mixture was incubated at 60 and 70°C. Culture broth (5 ml) was sampled intermittently and centrifuged at 10,000 rpm for 10 min. The supernatant liquid was used for the analysis of glucose by the Glu-DH method (Merck & Co., Inc.). The viable cell numbers in the broth were determined on agar plates containing Trypticase medium.

O_2 consumption of thermophilic bacterium BH1. The oxygen uptake rate of the thermophilic bacterium, BH1, was measured by using a plastic box attached to an oxygen electrode, as described in our previous paper (8). The agar plate in which colonies of the BH1 cells were formed was placed in the box, and the change in O_2 concentration in the box was measured for 12 h at 60°C and for 4 h at 70°C. After the measurement, the viable cell number on the plate was determined.

RESULTS

Time course of composting at different temperature. The change in temperature, CO_2 evolution rate, conversion of volatile matter (VM), and microbial numbers are shown in

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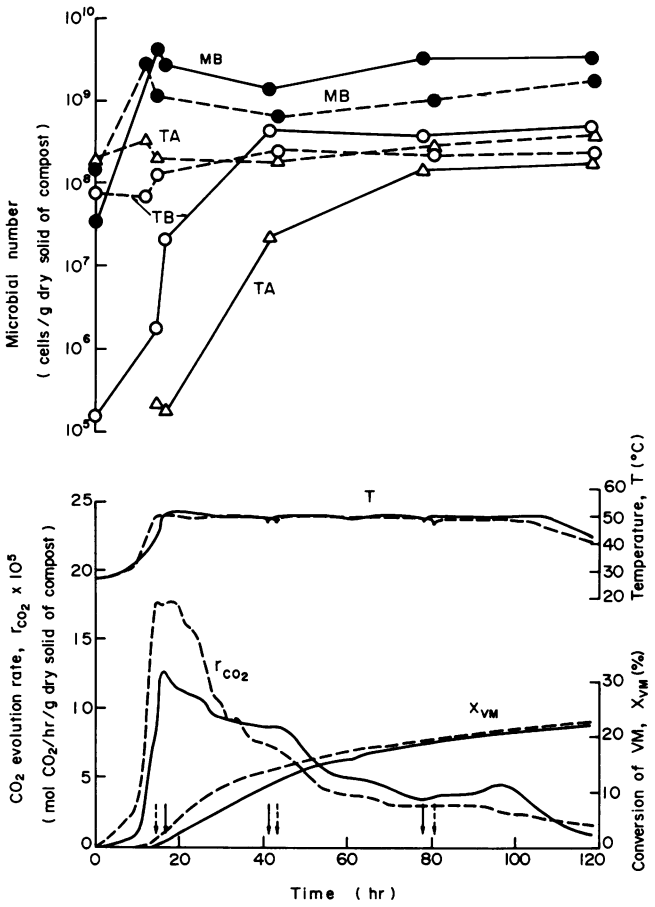

FIG. 1. Time courses of temperature (T), CO_2 evolution rate (r_{CO_2}), cell number of isolated microorganisms, and conversion of VM, X_{VM}, during composting at 50°C (Runs T1-50 and T2-50). Key for cell number: ●, mesophilic bacteria (MB); ○, thermophilic bacteria (TB); △, thermophilic actinomycetes (TA). The arrows on the abscissa in the lower panel indicate the points at which the compost was turned. Solid lines are for the composting containing 21% of sterilized compost product. Broken lines are for the composting containing 21% of compost product as a seed.

Fig. 1 to 3. The significant difference between Runs T1 and T2 was in the initial numbers of thermophilic bacteria and thermophilic actinomycetes. The CO_2 evolution rate and peak pattern were rather similar for the seeded T1 series composting and nonseeded T2 series composting at 60 and 70°C. At 50°C, the nonseeded composting had a lower rate of CO_2 evolution at the initial stage because of a lower rate of growth for thermophilic bacteria. The isolated dominant microorganisms were the same irrespective of operating temperature. In the nonseeded series, the rapid increase in the number of thermophilic bacteria was observed at the initial stage of composting, followed by an increase in the number of thermophilic actinomycetes at 50 and 60°C. At 70°C, the thermophilic bacteria at first increased up to 10^8 cells per g (dry solid) of compost and then decreased to 10^7. The thermophilic actinomycetes increased only when the temperature went below 70°C. In the seeded T1 series, the number of thermophilic bacteria and actinomycetes was constant at both 50 and 60°C, but there was a remarkable decrease on the order of 10^7 at 70°C. The change in the number of mesophilic bacteria showed the same tendency between the Run T1 and T2 series, i.e., the number increased to 10^9 in the period of rising temperature, and the decrease in number depended on the temperature. To reach the conversion of 15% of VM, 49 h were needed at 50°C, 40 h were needed at 60°C, and 53 h were needed at 70°C. This means that the average degradation rate of the organic matter in the compost material was highest at 60°C.

The total amount of CO_2 evolved, the final conversion of the VM of raw sludge, and the amount of time needed to maintain the setting temperature are shown in Table 1. The total CO_2 evolved and the final conversion of VM were maximum at 60°C. Although the change in microbial numbers showed different patterns between the seeded and nonseeded runs at each constant temperature, the data shown in Table 1 are almost the same. This result coincided with that obtained from the experiment on the effect of seeding in our previous paper (9).

The CO_2 evolution rates of the seeded T1 series were plotted against VM conversion of raw sludge (Fig. 4). The solid lines indicate CO_2 evolution rates in a range in which the setting temperatures of 50, 60, and 70°C were kept constant. At the region of low conversion, the difference in CO_2 evolution rates was slight, but as conversion increased, the CO_2 evolution rate was remarkably high at 60°C and lowest at 70°C. This trend was also observed in the nonseeded T2 series experiment. Based on these results, 60°C is an optimal temperature for the composting of sewage sludge.

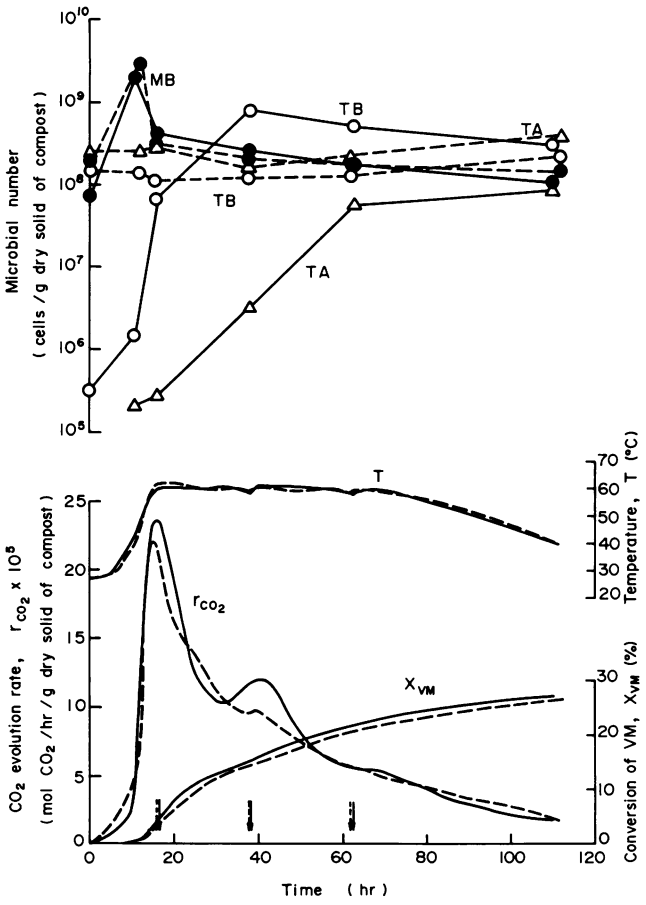

FIG. 2. Time courses of composting at 60°C (Runs T1-60 and T2-60). For the key to cell numbers and remarks, see the legend to Fig. 1.

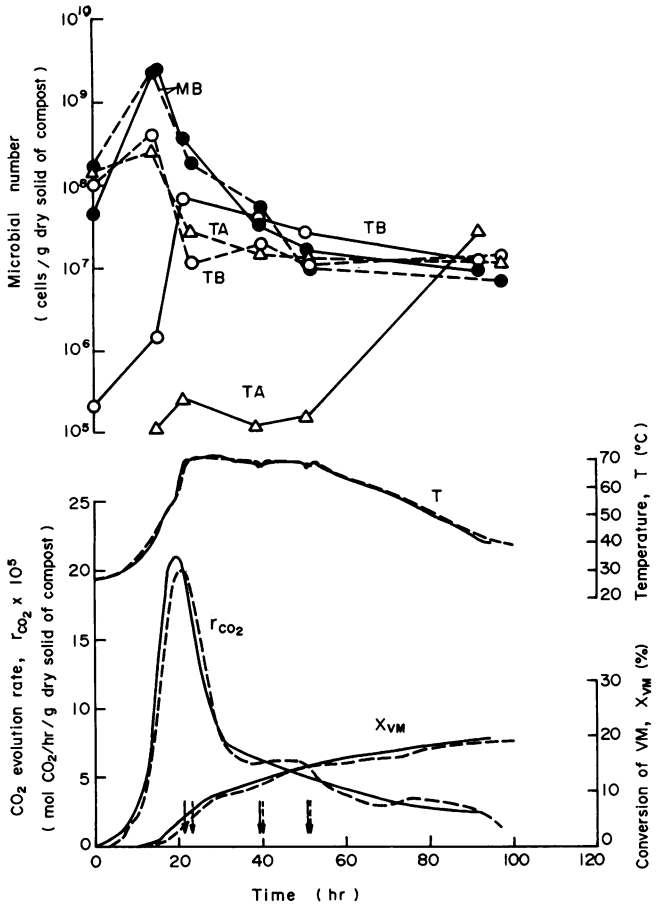

FIG. 3. Time courses of composting at 70°C (Runs T1-70 and T2-70). For the key to cell numbers and remarks, see the legend to Fig. 1.

Characteristics of thermophilic bacterium BH1. The experimental results of growth and glucose consumption of the thermophilic bacterium, BH1, in the Trypticase medium at 60 and 70°C are shown in Fig. 5. At 60°C, the cell number increased for 8 h and then declined. At 70°C, the viable cell number rapidly decreased. Glucose consumption lasted for 2 h, but no glucose consumption was detected after that. The initial rate of glucose consumption was the same at 60 and 70°C.

When the cells grown on the agar plate were placed in the plastic box to detect O_2 concentration, a linear decrease in O_2 concentration was observed at 60°C, and the specific

TABLE 1. Experimental results for composting at three different temperatures

Run	% Final conversion of VM (dry wt)	Amt (mol) of CO_2 evolved	Amt of time (h) required to maintain setting temperatures
T1-50	22.5	7.90	88
T2-50	21.6	7.35	91
T1-60	25.7	9.21	53
T2-60	27.2	9.82	56
T1-70	19.5	6.12	29
T2-70	19.2	6.43	28

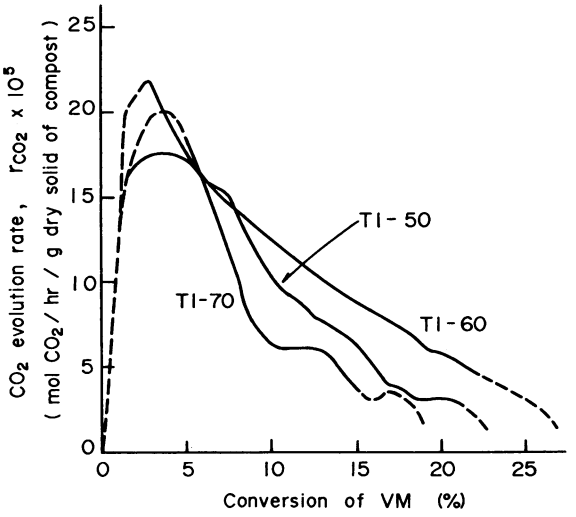

FIG. 4. CO_2 evolution rate versus conversion of VM at three different temperatures. The broken lines show the region where this temperature was below the setting temperature.

oxygen consumption rate was measured as 4.5×10^{-13} (mol of O_2 per h per cell). At 70°C, the decrease in oxygen concentration was observed for 4 h, but later no O_2 consumption was detected. The average value of the specific O_2 consumption rate for 4 h was 1.7×10^{-12} (mol of O_2 per h per cell).

DISCUSSION

Several reports on the optimal temperature for the composting of various materials have already been published (2, 5, 6, 10, 12, 13). However, the results were not necessarily obtained from well-defined and controlled reactor systems. Bach et al. (2) showed that the optimal temperature for the composting of a mixture of sewage sludge and rice husk that was used as a bulking agent was around 60°C in a laboratory-scale reactor, that is, a continuously mixed isothermal reactor. However, this reactor system is not applicable on a larger scale. The autothermal packed-bed reactor

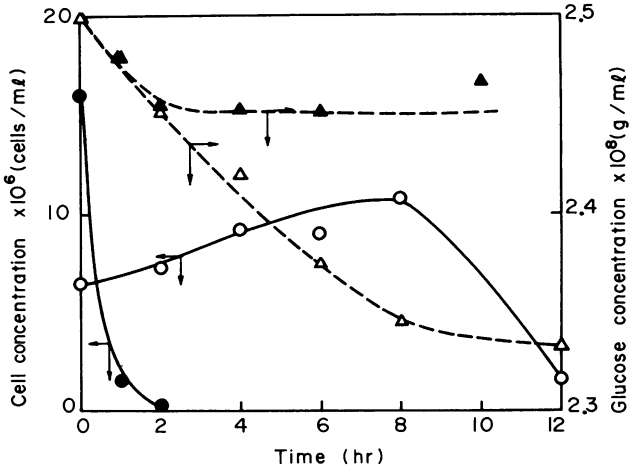

FIG. 5. Change in glucose concentration and viable cell number of the thermophilic bacterium , BH1, in the liquid medium at 60 and 70°C. Symbols: ○, viable cell number at 60°C; △, glucose concentration at 60°C, ●, viable cell number at 70°C; ▲, glucose concentration at 70°C.

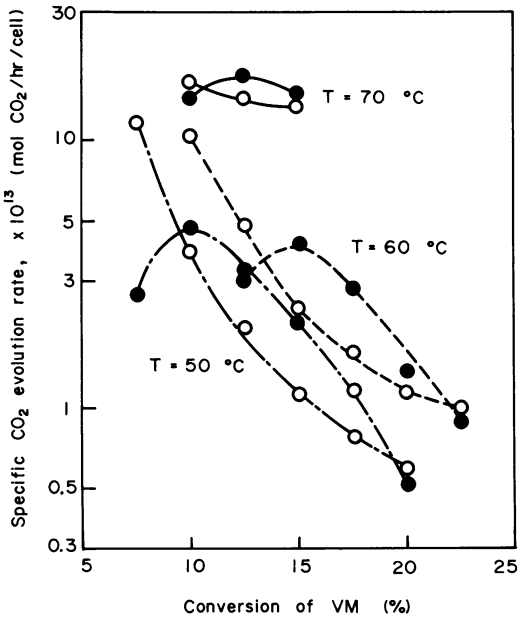

FIG. 6. The estimated specific CO_2 evolution rate at three different temperatures. Symbols: ○, thermophilic bacteria; ●, thermophilic actinomycetes; –·–, 50°C; -----, 60°C; ——, 70°C.

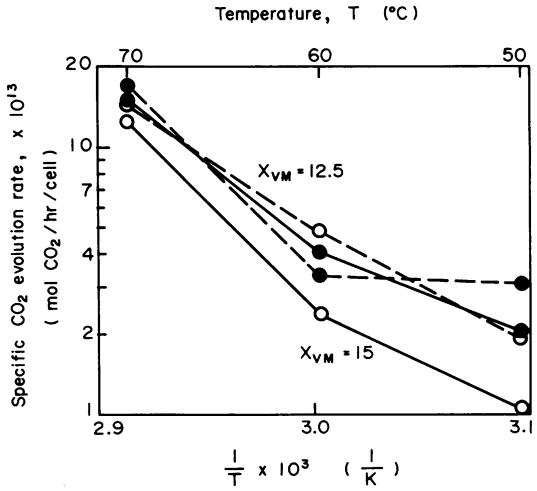

FIG. 7. Arrhenius plot of specific CO_2 evolution rate for thermophilic bacteria (○) and thermophilic actinomycetes (●). The ordinate was obtained from the data shown in Fig. 6 for each conversion of VM. Symbols, ——, 15%; -----, 12.5%.

we used in this work, the temperature of which is controlled by the rate of airflow, is practically applicable. In our experiment, the raw sewage sludge used was collected at the same wastewater treatment plant as that used by Bach et al. (2), but to simplify the reaction environment no bulking agent was added. As a result, the optimal temperature was 60°C. This means that the degradation of organic matter in the raw sludge, measured as the rate of CO_2 evolution, is most efficient at 60°C irrespective of the addition of a bulking agent or of the reactor systems used.

The specific CO_2 evolution rate for thermophilic bacteria and actinomycetes at three different temperatures estimated by the procedure described in our previous paper (7) is shown in Fig. 6. Of particular interest is that the rate of specific CO_2 evolution of the thermophiles was highest at 70°C, although the average number of viable cells at 70°C was smaller than those at 50 or 60°C. To elucidate this point, we investigated the activity of the isolated thermophilic bacterium, BH1. The rate of specific O_2 consumption of the bacterium at 70°C was four times higher than that at 60°C. This corresponds to the higher rate of CO_2 evolution at 70°C in the compost. Glucose was consumed by BH1 in the liquid medium even under conditions in which the cell number decreased remarkably at 70°C (Fig. 5). The initial rate of glucose consumption, however, was almost the same at 60°C. This was mainly because the reaction rate was limited by oxygen diffusion into the liquid phase. Therefore, the specific activity of glucose consumption between 60 and 70°C cannot be compared. The Arrhenius plot of the specific CO_2 evolution rate shown in Fig. 6 is presented in Fig. 7. Although the average slope in the range from 50 to 70°C gave an activation energy of 22 kcal (ca. 92,048 J), and similar values for the activation energy of thermophilic bacteria (4), thermophilic communities (6), and mesophilic bacteria (1, 11) were reported, the activation energy in Fig. 7 appears to be higher in the range of 60 to 70°C than in the range of 50 to 60°C. This suggests that CO_2 is evolved during composting from two parallel reactions, i.e., catabolism and anabolism with different activation energies. The one having a higher activation energy becomes dominant at the higher temperature. If the fraction between anabolism and catabolism is variable at different temperatures, the respiration quotient (RQ) will depend on the temperature. Because the elementary analysis of raw sewage sludge gave the formula $CH_{2.12}N_{0.09}O_{0.52}$, the following equation will be obtained when raw sludge is degraded only by catabolism.

$$[CH_{2.12}N_{0.09}O_{0.52} + 1.2\ O_2 \rightarrow CO_2 + 0.93\ H_2O + 0.09\ NH_3]$$

Consequently, the value of RQ is 0.83. The change in RQ calculated from the measured rates of CO_2 evolution and O_2 consumption during composting is shown in Fig. 8. It is obvious that the RQ value is higher at 70°C as compared with 50 or 60°C. This may be interpreted as indicating that catabolism is dominant at higher temperatures.

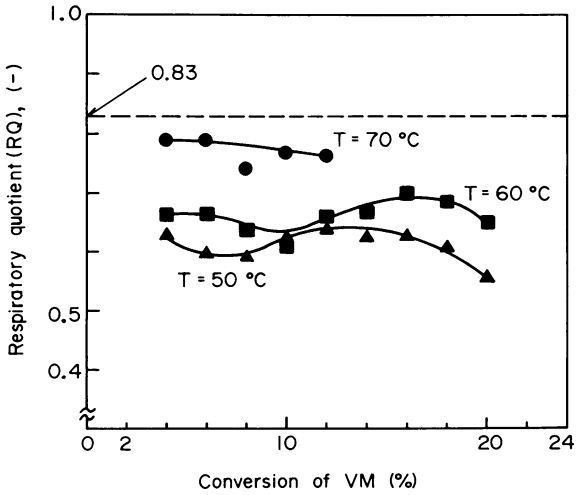

FIG. 8. RQ for each conversion of VM at three different temperatures. Symbols: ▲, 50°C; ■, 60°C; ●, 70°C.

Senez (11) showed a similar result for mesophilic bacteria. He measured the rate of O_2 uptake of the mesophilic bacterium *Aerobacter aerogenes*, showing that the respiratory activity of the bacterium was 175.6 (microliters of O_2 consumed per hour per milligram of cells) at the optimal temperature of 37.6°C, but that the activity still increased to 199.2 at 41.8°C and finally became 146.3 at 47°C, at which point no growth was observed. This result was interpreted as indicating an energy uncoupling between energy-yielding metabolism and cell synthesis. Our results reflect the case of thermophilic bacteria. So far, no data are available concerning energy uncoupling of thermophilic microorganisms.

It must be emphasized that the measured CO_2 evolution rate during the composting process as shown in Fig. 1 to 4 was the product of the specific CO_2 evolution rate and the cell number. Therefore, even though the specific CO_2 evolution rate was higher at 70°C, the optimal temperature should be the temperature that gives the maximum CO_2 evolution rate value.

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