

Thermal balance of invessel composting of tomato plant residues

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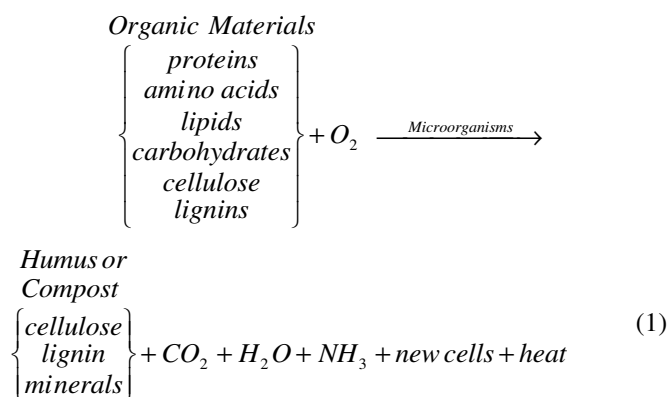
Ghaly, A.E., Alkoaik, F. and Snow, A. 2006. **Thermal balance of invessel composting of tomato plant residues.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 6.1 - 6.11. Heat and mass balances were performed on an insulated laboratory composting bioreactor operating on tomato plant residues. Wood shavings and municipal solid compost were used as a bulking agent and an inoculum, respectively. The moisture content and C:N ratio were maintained at 60% and 30:1, respectively. The temperature peaked after 31 h of operation reaching 63.3°C and lasted for 9 h. The result of the thermal analysis indicated that the average heat production value was 14.6 MJ/kg DM degraded. The conductive heat losses through the cylindrical body and the sidewalls of the bioreactor accounted for 30.0% of the total cumulative heat produced, whereas the heat loss due to aeration accounted for 61.0% and the heat gained by the compost and bioreactor materials accounted for the remaining 9.0%. **Keywords:** compost, bioavailable carbon, tomato residues, wood shavings, nitrogen, carbohydrate, protein, fat, temperature.

Des bilans de masse et de chaleur ont été réalisés sur un bioréacteur isolé pour le compostage en laboratoire de résidus de plants de tomate. Des copeaux de bois ont été utilisés comme substrat et du compost de solides municipaux a servi d'inoculant pour le procédé. La teneur en eau et le ratio C:N ont été maintenus respectivement à 60% et 30:1. Une température maximale de 63.3°C a été observée après 31 heures d'opération et cette température a pu être maintenue durant neuf heures. Les résultats de l'analyse thermique ont indiqué que la valeur moyenne de production de chaleur durant le processus de compostage a atteint 14,6 MJ par kilogramme de matière sèche dégradée. Les pertes de chaleur par conduction au travers des parois du bioréacteur se sont élevées à 30,0% de la chaleur totale produite tandis que les pertes de chaleur liées à l'aération ont atteint 61,0% alors que la chaleur accumulée par le compost et le bioréacteur lui-même représentaient les 9,0% restant. **Mots clés:** compost, carbone biologiquement disponible, résidus de tomates, copeaux de bois, azote, hydrate de carbone, protéine, gras, température.

INTRODUCTION

Greenhouse tomato production represented 58% of the greenhouse total vegetable production in Canada in 2000 with a production area of 1550 hectares yielding 182,736 tonnes (AAFC 2001). There is a considerable amount of plant residue, as a result of trimming and after harvesting the crop, that must be disposed of properly. Typical vegetable greenhouse operations produce 40-60 tonnes of organic residues per hectare per year (OMAFRA 2004). Since tomato plants are subjected to intensive pesticide application to control insects and diseases, the disposal of their residues causes several undesirable agronomic and environmental problems, especially recycling plant pathogens (Conway 1996).

Composting of greenhouse wastes is considered to be the preferred organic waste management method (NSDAFF 2004; OMAFRA 2004). Composting is the aerobic biological decomposition of organic matter which is enhanced and accelerated by mixing organic waste with other ingredients in a prescribed manner for optimum microbial growth (Tchobanoglous et al. 1993; USEPA 1993). During the composting process, microorganisms break down the organic matter and produce humus, carbon dioxide, water, ammonia, new cells, and heat, as shown in Eq. 1.



The end product is safer to use than the raw organic material and one that improves soil fertility, tilth, and water holding capacity (Murphy 1991). In addition, composting reduces the bulk of organic material to be spread, improves its handling properties, reduces odor, flies, and other vector problems, and can destroy weed seeds and pathogens (Holden 1990).

Under optimal conditions, composting proceeds from the initial or psychrophilic state through three phases: (a) the mesophilic or moderate-temperature phase, which lasts for a few days, (b) the thermophilic or high-temperature phase, which can last from a few days to several months, and (c) the cooling and maturation phase which lasts for several months as shown in Fig. 1. The first, second and third phases are referred to as the active stage in which heat is produced. This active stage is governed by the basic principals of heat and mass transfer and by the biological constrains of living microorganisms (Keener et al. 1993). The published data on the rate of heat production by organic material decomposition (Wiley 1955; Walker and Harrison 1960; Miller 1984; Iwabuchi et al. 1995) suggest that there are wide variations in the rate of heat released by compost. This is because the rate of heat production is a function of

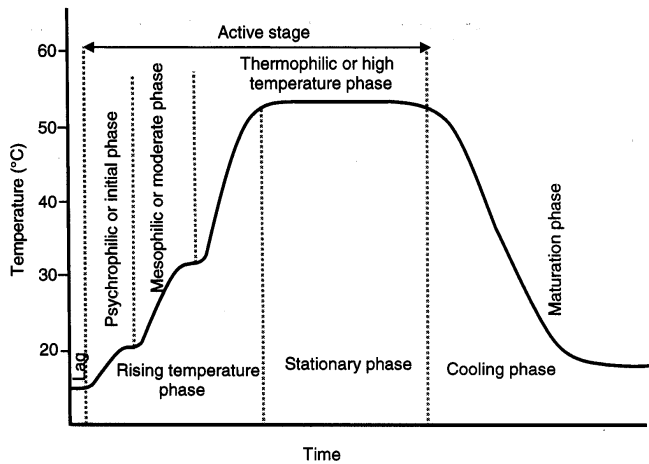


Fig. 1. Composting phases.

chemical, physical, and biological properties of the composted material.

The aim of this study was to perform a heat balance on a laboratory scale batch bioreactor operating on greenhouse tomato plant residue to determine: (a) the metabolic energy and the heat produced by mixing during the composting process and (b) the heat losses from the bioreactor walls and with the exhaust gas.

EXPERIMENTAL APPARATUS

The experimental set up shown in Fig. 2 consisted of a frame, three bioreactors, mixing unit, air supply unit, and data acquisition system. The frame was made of aluminum sheets

(3.2 mm thick) and angles (3.2 mm thick) and was used to hold the mixing motors, flow meters, air and exhaust gas manifolds, tubing, and thermocouple wires.

Each bioreactor (Fig. 3) was constructed of 203 mm (ID) polyvinyl chloride (PVC) tube having a length of 520 mm and a wall thickness of 5 mm. One end of the tube was covered with a removable circular plexiglas plate of 203-mm diameter and 6-mm thickness which was recessed and secured into the cylinder by means of six stainless steel screws (6 mm). A rubber gasket lining (O-ring, 2.5-mm thick) was added to the inner side of the circular plate to keep it tight. A circular PVC plate of 203-mm diameter and 6-mm thickness was glued into the other side of the tube and secured by means of six stainless steel screws (6 mm) and fitted into an aluminum ring, which was fastened into the frame by means of four bolts (6 mm) and nuts. There were three holes at the bottom and one at the top of the bioreactor, which were drilled and threaded to take a 12-mm nylon hose barb. The holes at the bottom were connected to a manifold by 6.4 mm diameter Tygon tubing and used for aeration, whereas the one at the top was used for the exhaust gas. Both circular plates were insulated with a 38.1-mm thick styrofoam layer, while the tube was insulated with 38.1-mm thick fiberglass and covered with an aluminum cylinder.

A removable 10.5-mm diameter solid stainless steel mixing shaft (having 5 stainless steel collars in which five bolts of 69-mm length and 6-mm diameter each were mounted) was mounted on two bearings inside each bioreactor. The shaft was rotated (5.76 rpm) by a thermally protected electric motor (Model No. 127P1486/B; D. C., Sigma Instruments Inc., Braintree, MA).

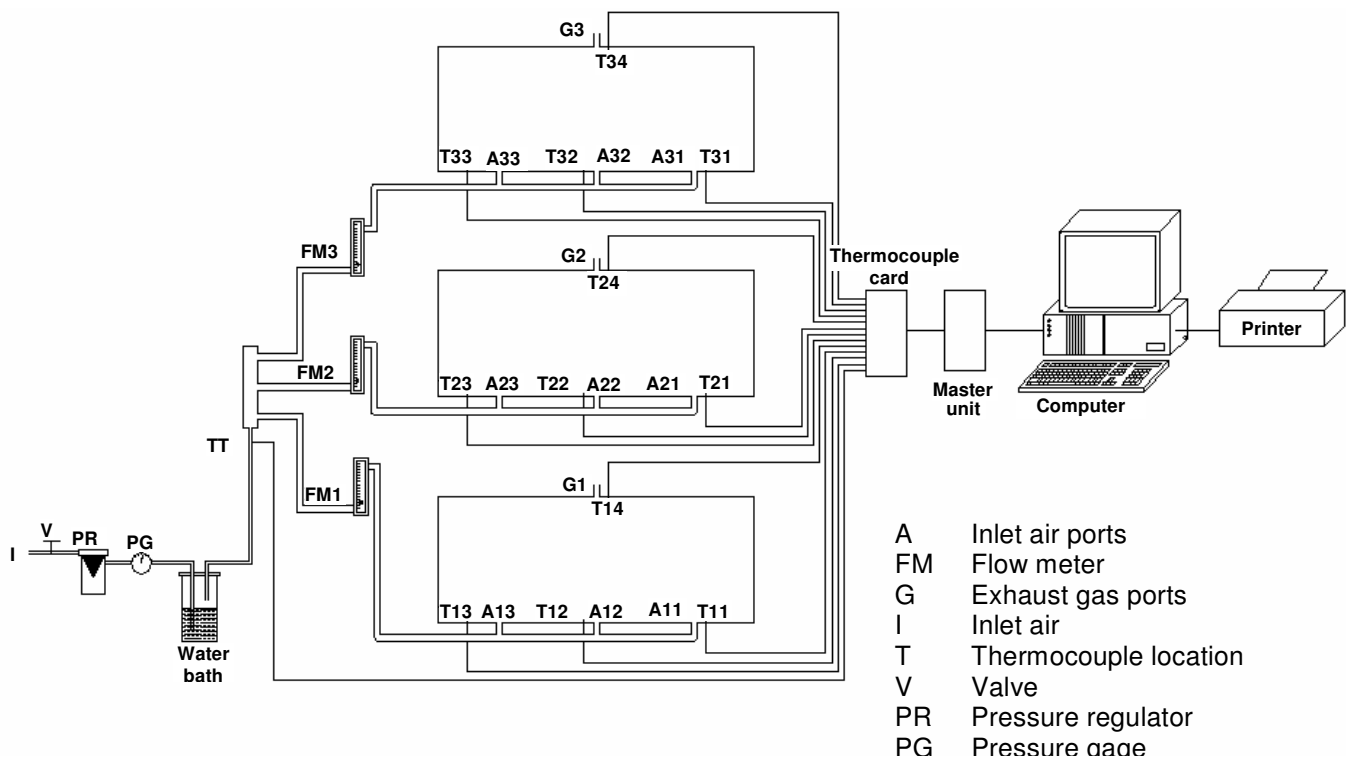


Fig. 2. Experimental setup.

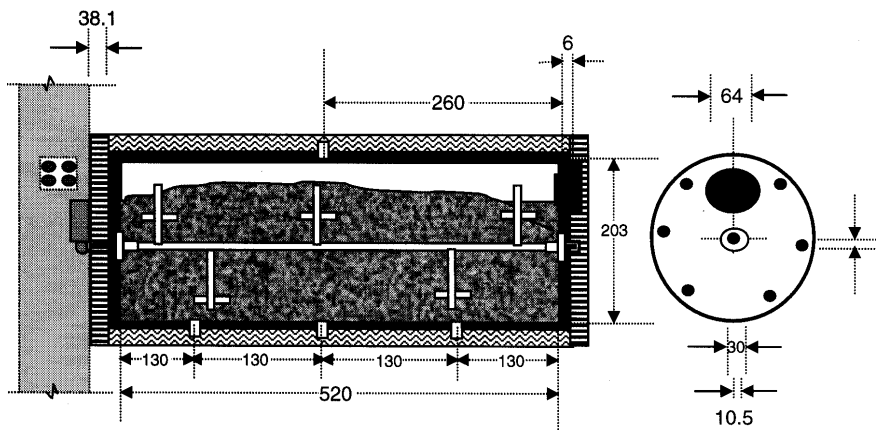


Fig. 3. Detailed schematic of the bioreactor (dimensions in millimeters).

Table 1. Some characteristics of tomato residues, wood shavings, and municipal solid waste.

Characteristics	Tomato remains	Wood shavings	Municipal compost	Mixture
Moisture content (% dry basis)	76.0	8.0	58.6	60.0
Total solids (TS) (g/kg DM)				
Volatile solids (VS) ⁺	693.0	997.4	854.6	873.5
Ash	307.0	2.6	145.4	126.5
Nitrogen (g/kg DM)				
Total Kjeldahl nitrogen	27.0	1.0	18.0	12.1
Ammonium nitrogen	2.2	0.2	5.2	1.4
Carbon (g/kg DM)				
Total	327.0	499.0	440.0	431.2
Organic	260.0	390.0	350.0	339.2
Elemental composition (g/kg DM)				
Ca	51.0	0.8	20.0	21.2
Na	0.7	0.0	6.2	0.9
Fe	0.4	0.0	2.8	0.4
Mg	4.7	0.1	1.8	1.9
Zn	0.0	0.0	0.1	0.0
K	57.6	0.6	7.8	21.8
Cl	0.7	0.0	0.3	0.3
P	10.5	0.0	2.7	4.1
S	7.9	0.9	2.3	3.9
Others [‡]	174.1	0.2	101.4	72.0
C:N	12:11	499:1	24.4:1	30:1*

Values are the average of 3 replicates (CV = 1.9-6.1%).

⁺ Volatile solids are the organic matter (largely carbon, oxygen, and nitrogen) which are lost at 550°C, leaving only the ash.

[‡] Others include mostly silica and other elements.

* After the addition of urea.

The air was supplied continuously to the bottom of the bioreactor from the laboratory air supply. It passed through a pressure regulator and a pressure gage (to maintain the pressure near 5 kPa) and then through a water bath (to be humidified to nearly 100% saturation) and finally through a flow meter (Model 32461-14, Cole-Parmer Instrument Company, Vernon

Hills, IL) capable of measuring a flow in the range of 0.0566-0.566 m³/h.

The data acquisition unit consisted of a master unit, a thermocouple scanning card, software, temperature sensors, a personal computer, and a printer. The master unit (Multiscan 1200, Omega, Stamford, CT) was connected to a computer via an RS232 interface. The thermocouple/volt scanning card (MTC/24, Omega, Stamford, CT) contained 24 isolated differential input channels. A window-based software (Tempview, Image Therm Engineering, Waltham, MA) allowed easy configuration of hardware and the acquisition and displays parameters.

Four type T (copper-constantan) thermocouples (Cole Parmer, Chicago, IL) were used for temperature measurements on each bioreactor. Three thermocouples were located at the bottom of the bioreactor and were used to measure the temperature of the compost mass whereas the fourth was located at the top of the bioreactor, near the outlet air exit (21 mm away), and was used to measure the temperature of the exhaust gas. Thermocouple locations, on the bottom of all bioreactors, were chosen to be far enough from the inlet air (65 mm away). An IBM personal computer (Pentium IV) and an hp (Hewlett Packard) laser jet 4 printer were used.

EXPERIMENTAL PROCEDURE

Compost mixture preparation

The materials used in this study included tomato plant residues, wood shavings, municipal solid compost, and urea. Some characteristics of these materials are shown in Table 1. The tomato plant remains (leaves, stems, and some fruits) were collected from a greenhouse at an average moisture content of approximately 90% and left over night at room temperature ($\approx 25^{\circ}\text{C}$) to partially dry (MC 76%). They were then chopped into small pieces using a shredder (Model 242A645-515, SHP, Briggs and Stratton, Plainfield, NJ), mixed with wood shavings (1: 1.5 by weight dry basis) and then ground in a hammer mill (Model C-H, Horvick Manufacturing, INC., Moorhead, MN) to an average size of 6.0 mm. A mixture of tomato remains: wood shavings: municipal compost at a ratio of 1: 1.5: 0.28

was prepared.. The 15-day old municipal solid compost was added to the tomato trimmings mixture to introduce a wide range of active composting microorganisms. Urea [$\text{CO}(\text{NH}_2)_2$] was used as a nitrogen source (46% nitrogen) to adjust the C: N ratio to 30:1. The moisture content of the final mixture was adjusted to approximately 60% (dry basis).

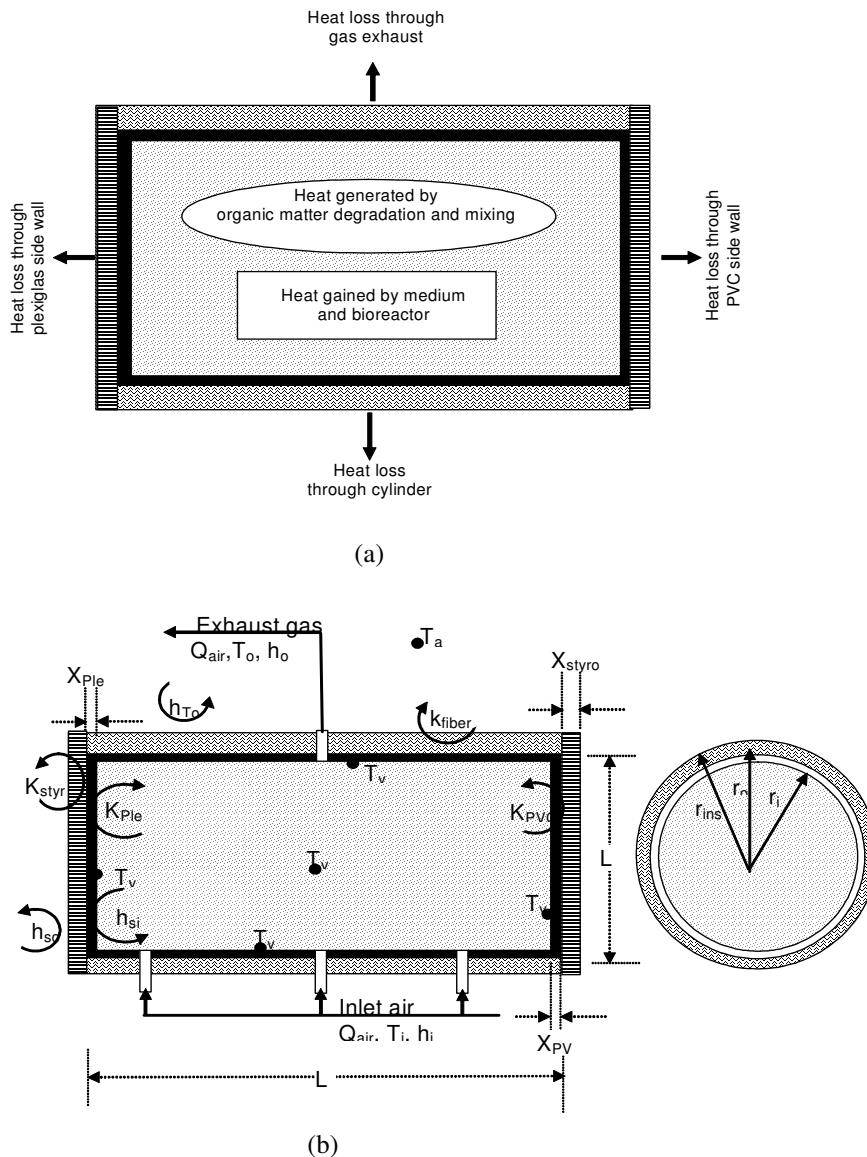


Fig. 4. Heat balance: (a) heat generation and losses; (b) heat transfer.

The heat of mixing experiment

The mixture, bioreactor, and mixing unit were completely sterilized to insure that the composting experiment was free of microorganisms. The mixture was placed in several 1-L Griffin beakers, covered with double sheets of aluminum foil and then autoclaved (Sterilizer Model STM-E, Market Forge Industries Inc., Everett, MA) at a temperature of 121°C and a pressure of 98.1 kPa for one hour. The beakers were then left to cool down for 24 hours. The sterilization process was repeated three times to insure all microorganisms and spores were inactivated. A solution was made from the sterilized mixture (4 grams of the sterilized mixture was added to 400 mL of sterilized distilled water) and plated on a standard plate agar in replicates according to the procedure described by Benson (1998). The plates were then incubated at 35°C for 48 hours to determine the effectiveness of the sterilization.

All air inlet and outlet ports in the bioreactor were sealed and the bioreactor and the mixing shaft were chemically

sterilized using 2% potassium metabisulfite solution. As a precaution, the laboratory exhaust fan was turned off, and laboratory doors were closed to prevent any air current in the working area. The same chemical was sprayed around the bioreactor to minimize any contamination during material loading.

The sterilized bioreactor was filled with the sterilized mixture of the composted material (3.5 kg). The plexiglas side wall was screwed in place and the mixing unit was turned on at 5 rpm. The air flow rate was maintained at 0.15 m³/h. The temperature was recorded continuously. The power consumption was also recorded using a sensitive power meter (EXTECH True RMS Power Multimeter, Model 382860, EXTECH Instruments, Waltham, MA). The power consumption of the mixing shaft was also measured without the compost mixture. The bioreactor mixing shaft was left to run in the empty bioreactor while collecting the measurements for 13 hours.

The heat of metabolism experiment

Sterilization did not take place. The final mixture (3.5 kg) was mixed well and then placed in the bioreactor which occupied 75% of the total bioreactor volume (0.012 m³). The plexiglass side wall was screwed in place and the mixing unit was run continuously at 5 rpm. The air flow rate was maintained at 0.15 m³/h. Temperatures were continuously monitored.

HEAT BALANCE

In a bioreactor with continuous mixing, heat energy is produced as a result of the microbial conversion of chemical energy into thermal energy as well as by friction between the composted material and the mixing shaft (Nakasaki et. al. 1985; Kubota and Nakasaki 1991). However, when composting a sterilized material, microbial heat generation is eliminated and heat input by the mixing shaft can be measured by conducting an energy balance on the bioreactor. To perform a heat balance on a bioreactor with a mixing unit, the heat produced in the unit, the heat lost from the unit (sensible and latent), and the heat accumulated in the unit must be considered (Haug 1993). The heat produced (evolved) during the process can be removed via a combination of several different thermal energy transfer mechanisms, radiation, conduction, evaporative cooling, and sensible heating of the air (Miller 1993).

A heat (energy) balance was performed on the composting system as shown in Fig. 4. The heat balance includes: (a) the heat generated as a result of microbial metabolism of organic substrate, (b) the heat generated by mixing, (c) the heat required to raise the temperature of the medium, (d) the heat losses through the system horizontal body (cylinder), (e) the heat

losses through the system PVC side wall, (f) the heat losses through the system plexiglas side wall, (g) the heat losses with the exhaust gas, and (h) the heat losses by radiation. Mathematically, the energy balance equation can be written in a simple form as:

$$q_p + q_m = q_s + q_c + q_{pvc} + q_{plexi} + q_e + q_r \quad (2)$$

where:

- q_p = heat generated by organic substrate metabolism (kJ/h)
- q_m = heat added by mixing unit (kJ/h),
- q_s = total heat required to raise temperature of medium and components (kJ/h),
- q_c = heat loss through main body of cylinder (kJ/h),
- q_{pvc} = heat loss through the PVC side wall (kJ/h),
- q_{plexi} = heat loss through plexiglas side wall (kJ/h),
- q_e = heat loss with exhaust gas (kJ/h), and
- q_r = heat loss by radiation (kJ/h).

The heat loss in the form of radiation from a laboratory scale bioreactor is usually negligible (Finstein et al. 1980) and Eq. 2 can be rewritten as:

$$q_p = -q_m + q_s + q_c + q_{pvc} + q_{plexi} + q_e \quad (3)$$

The total heat required for raising the temperature of the medium and the bioreactor components can be calculated as:

$$q_s = q_{compost} + q_{pvc-c} + q_{fiber-c} + q_{alumi-c} + q_{pvc-w} + 2 q_{styro-w} + q_{plexi-w} + q_{mixing} \quad (4)$$

where:

- $q_{compost}$ = heat required to raise temperature of medium (kJ/h),
- q_{pvc-c} = heat required to raise temperature of horizontal PVC cylinder (kJ/h),
- $q_{fiber-c}$ = heat required to raise temperature of horizontal fiberglass around cylinder (kJ/h),
- $q_{alumi-c}$ = heat required to raise temperature of aluminum cover of cylinder (kJ/h),
- q_{pvc-w} = heat required to raise temperature of PVC side wall (kJ/h),
- $q_{styro-w}$ = heat required to raise temperature of styrofoam insulation of side wall (kJ/h),
- $q_{plexi-w}$ = heat required to raise temperature of plexiglas side wall (kJ/h), and
- q_{mixing} = heat required to raise temperature of mixing shaft (kJ/h).

The values of $q_{compost}$, q_{pvc-c} , $q_{fiber-c}$, $q_{alumi-c}$, q_{pvc-w} , $q_{styro-w}$, $q_{plexi-w}$, q_{mixing} , q_c , q_{pvc} , q_{plexi} and q_e can be calculated from Eqs. 5 - 16 (Holman 1997):

$$q_{compost} = M_{compost} C_{p,compost} (T_f - T_i) / \Delta t \quad (5)$$

$$q_{pvc-c} = M_{cylinder} C_{p,pvc} \Delta T_1 / \Delta t \quad (6)$$

$$q_{fiber-c} = M_{fiber} C_{p,fiber} \Delta T_2 / \Delta t \quad (7)$$

$$q_{alumi-c} = M_{alumi} C_{p,alumi} \Delta T_3 / \Delta t \quad (8)$$

$$q_{pvc-w} = M_{pvc} C_{p,pvc} \Delta T_4 / \Delta t \quad (9)$$

$$q_{styro-w} = M_{styro} C_{p,styro} \Delta T_5 / \Delta t \quad (10)$$

$$q_{plexi-w} = M_{plexi} C_{p,plexi} \Delta T_6 / \Delta t \quad (11)$$

$$q_{mixing} = M_{ss} C_{p,ss} \Delta T_7 / \Delta t \quad (12)$$

$$q_c = U_c A_c (T_v - T_s) \quad (13)$$

$$q_{pvc} = U_{pvc} A_{pvc} (T_v - T_s) \quad (14)$$

$$q_{plexi} = U_{plexi} A_{plexi} (T_v - T_s) \quad (15)$$

$$q_e = Q_{air} \rho (h_o - h_i) \quad (16)$$

where:

- A_{plexi} = surface area of plexiglas side wall (m²),
- A_{pvc} = surface area of PVC side wall (m²),
- A_c = surface area of the cylinder (m²),
- $C_{p,compost}$ = specific heat of the compost (kJ kg⁻¹K⁻¹),
- $C_{p,pvc}$ = specific heat of cylinder material (PVC) (kJ kg⁻¹K⁻¹),
- $C_{p,fiber}$ = specific heat of fiberglass (kJ kg⁻¹K⁻¹),
- $C_{p,alumi}$ = specific heat of cover (aluminum) (kJ kg⁻¹K⁻¹),
- $C_{p,styro}$ = specific heat of styrofoam (kJ kg⁻¹K⁻¹),
- $C_{p,plexi}$ = specific heat of plexiglas side wall (kJ kg⁻¹K⁻¹),
- $C_{p,ss}$ = specific heat of stainless steel mixing shaft (kJ kg⁻¹K⁻¹),
- h_o = enthalpy of air at T_o (kJ/kg dry air),
- h_i = enthalpy of air at T_{in} (kJ/kg dry air),
- $M_{compost}$ = mass of compost (kg),
- $M_{cylinder}$ = mass of cylinder (kg),
- M_{fiber} = mass of fiberglass (kg),
- M_{alumi} = mass of aluminum sheet (kg),
- M_{styro} = mass of styrofoam (kg),
- M_{plexi} = mass of plexiglas side wall (kg),
- M_{ss} = mass of stainless steel mixing shaft (kg),
- M_{pvc} = mass of PVC side wall (kg),
- Q_{air} = inlet airflow rate (m³/h),
- T_f = temperature of compost at end of time interval (K),
- T_i = temperature of compost at beginning of time interval (K),
- T_{in} = air inlet temperature (K),
- ΔT_{1-7} = temperature changes in material of cylinder, fiberglass, aluminum, PVC side wall, styrofoam, plexiglas side wall, and mixing shaft, respectively, within time interval (K),
- T_v = average temperature of compost within time interval (K),
- T_a = laboratory ambient temperature (K),
- T_s = temperature of outside surface of bioreactor within time interval (K),
- T_o = exhaust gas temperature within time interval (K),
- Δt = time interval (h),
- U_c = overall heat loss coefficient of cylinder (kJ m⁻² h⁻¹ K⁻¹),
- U_{pvc} = overall heat loss coefficient of PVC side wall (kJ m⁻² h⁻¹ K⁻¹),
- U_{plexi} = overall heat loss coefficient of plexiglas side wall (kJ m⁻² h⁻¹ K⁻¹), and
- ρ = air density (kg/m³).

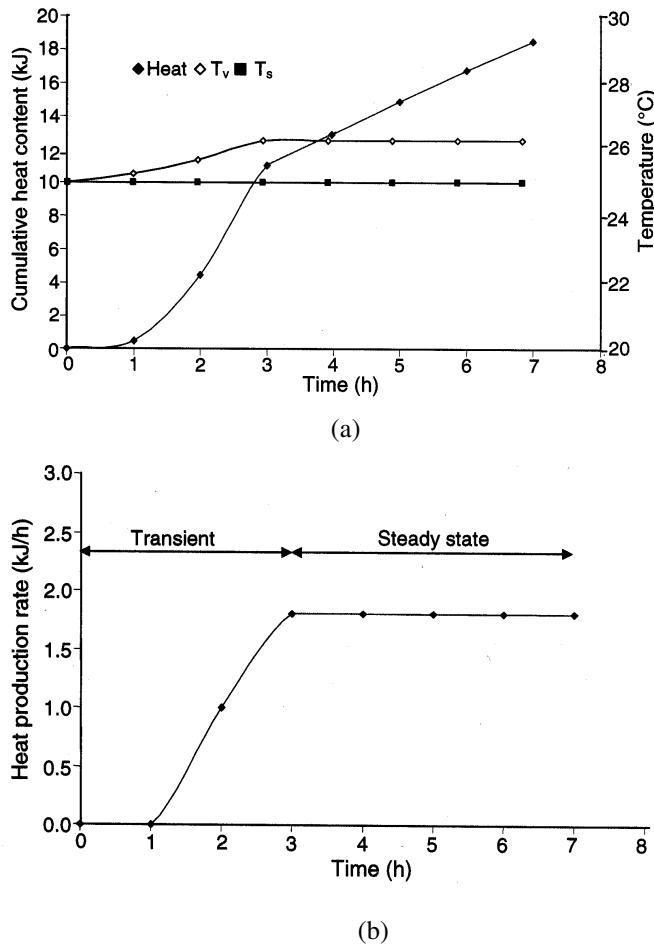


Fig. 5. Temperature and heat production by mixing of sterilized composting materials: (a) temperatures and cumulative heat production; (b) heat production rate.

RESULTS

Heat of mixing

The plate count test performed on the sterile compost mixture samples indicated that the mixture was free of microorganisms. Therefore, it was safe to assume that the heat generated in the bioreactor was completely due to the friction force created by the mixing process.

The average power consumption while the mixing shaft operated in an empty bioreactor was 36 kJ/h (10 W) whereas the average power consumption while the mixing shaft operated in a filled bioreactor with the sterilized material was 38.16 kJ/h (10.6 W). Therefore, the energy required for mixing was 2.16 kJ/h (0.6 W). The values were the average of 10 readings each with a coefficient of variation (CV) of 0% for the empty reactor and 2.6% for the filled reactor.

The profiles of the average temperatures inside (T_v) and on the outside surface (T_s) of the bioreactor are presented in Fig. 5. The average bioreactors temperatures (T_v) of the sterilized compost increased with time due to heat generated by particle friction reaching the steady state (constant temperature) after 3 h, at which time the heat generated by mixing was equivalent to the heat losses from the bioreactor. Since the experiment was run without aeration and sterilized material was used, the heat

lost with the exhaust gas (q_e) and the metabolic heat production (q_p) can be set to zero. At steady state, heat accumulation within the material and the bioreactor body (q_s) is zero; therefore, Eq. 2 can be rewritten as:

$$q_m = q_c + q_{pvc} + q_{plexi} \quad (17)$$

The overall heat transfer coefficients of the sidewalls of the composting system (U_{pvc} and U_{plexi}) were calculated as (Çengel 2003; Holman 1997):

$$U_{pvc} = \frac{1}{\frac{1}{h_{si}} + \frac{X_{pvc}}{k_{pvc}} + \frac{X_{styro}}{k_{styro}} + \frac{1}{h_{so}}} \quad (18)$$

$$U_{plexi} = \frac{1}{\frac{1}{h_{si}} + \frac{X_{plexi}}{k_{plexi}} + \frac{X_{styro}}{k_{styro}} + \frac{1}{h_{so}}} \quad (19)$$

where:

- X_{pvc} = thickness of PVC sidewall (m),
- X_{plexi} = thickness of plexiglas sidewall (m),
- X_{styro} = the thickness of styrofoam insulation (m),
- h_{si} = convective heat transfer coefficient between compost and surface of inside wall of system ($\text{kJ m}^{-2} \text{h}^{-1} \text{K}^{-1}$),
- h_{so} = convective heat transfer coefficient between outside surface of system and room ($\text{kJ m}^{-2} \text{h}^{-1} \text{K}^{-1}$),
- k_{pvc} = thermal conductivity of PVC material ($\text{kJ m}^{-1} \text{h}^{-1} \text{K}^{-1}$),
- k_{plexi} = thermal conductivity of plexiglas material ($\text{kJ m}^{-1} \text{h}^{-1} \text{K}^{-1}$), and
- k_{styro} = thermal conductivity of styrofoam material ($\text{kJ m}^{-1} \text{h}^{-1} \text{K}^{-1}$).

The overall heat transfer coefficient of the cylinder (U_c), based on its outside area (A_{co}) is calculated as (Çengel 2003; Holman 1997):

$$U_c = \frac{1}{\frac{A_{co}}{A_{ci}} \frac{1}{h_{ci}} + \frac{A_{co} \ln(r_o / r_i)}{2\pi k_{pvc} L_c} + \frac{A_{cins} \ln(r_{ins} / r_o)}{2\pi k_{fiber} L_c} + \frac{1}{h_{so}}} \quad (20)$$

where:

- A_{co} = outside surface area of cylinder (m^2),
- A_{ci} = inside surface area of cylinder (m^2),
- A_{cins} = outside surface area of insulation (m^2),
- h_{ci} = convective heat transfer coefficient between compost and inside surface of cylinder ($\text{kJ m}^{-2} \text{h}^{-1} \text{K}^{-1}$),
- r_i = inner radius of cylinder (m),
- r_o = outer radius of cylinder (m),
- r_{ins} = radius of insulation material (m), and
- L_c = characteristic length of cylinder (m).

Since mixing produced a homogenous temperature distribution, the bioreactor inside surface temperature was assumed to be equal to the average temperature inside the bioreactor. Therefore, Eqs. 18, 19, and 20 can be rewritten as:

$$U_{pvc} = \frac{1}{\frac{X_{pvc}}{k_{pvc}} + \frac{X_{styro}}{k_{styro}} + \frac{1}{h_{so}}} \quad (21)$$

Table 2. Values of various parameters.

Parameter	Value
PVC cylinder	
r_i (m)	0.1015
r_o (m)	0.1065
k_{pvc} † (kJ h ⁻¹ m ⁻¹ K ⁻¹)	0.3240
L_c (m)	0.5200
A_{ti} (m ²)	0.3320
A_{to} (m ²)	0.3480
Fiberglass insulation	
k_{fiber} † (kJ h ⁻¹ m ⁻¹ K ⁻¹)	0.1368
r_{ins} (m)	0.1446
A_{iin} (m ²)	0.4720
PVC side wall	
r_i (m)	0.1015
thickness (m)	0.0060
Plexiglas side wall	
k_{plexi} † (kJ h ⁻¹ m ⁻¹ K ⁻¹)	1.9440
$A_{pvc} = A_{plexi}$ (m ²)	0.0324
Styrofoam insulation	
k_{styro} † (kJ h ⁻¹ m ⁻¹ K ⁻¹)	0.1188
thickness (m)	0.0380
Aluminum	
M_{alumi} (kg)	0.4950
Cp_{alumi} † (kJ kg ⁻¹ K ⁻¹)	0.8960
Mixing shaft	
M_{ss} (kg)	1.1240
Cp_{ss} † (kJ kg ⁻¹ K ⁻¹)	0.4800
Compost	
$M_{compost}$ (kg)	3.5000
$Cp_{compost}$ † (kJ kg ⁻¹ K ⁻¹)	0.8700
System volume (m ³)	0.017

† Holman (1997)

$$U_{plexi} = \frac{1}{\frac{X_{plexi}}{k_{plexi}} + \frac{X_{styro}}{k_{styro}} + \frac{1}{h_{so}}} \quad (22)$$

$$U_c = \frac{1}{\frac{A_{co} \ln(r_o / r_i)}{2\pi k_{pvc} L_c} + \frac{A_{cins} \ln(r_{ins} / r_o)}{2\pi k_{fiber} L_c} + \frac{1}{h_o}} \quad (23)$$

Equations 21, 22, and 23 were used to determine the overall heat transfer coefficients of the PVC side wall, the plexiglas side wall, and the cylindrical body of the bioreactor, respectively. Then, the conductive heat losses were calculated using Eqs. 13, 14, and 15. Finally, the sum of all heat losses was set equal to the heat generated by the mixing shaft and was calculated using Eq. 17. The values of the constants used in these calculations are summarized in Table 2.

The heat production rate and the cumulative heat content of the sterilized tomato remains-wood shavings-municipal compost

Table 3. Calculated heat losses and production by mixing of sterilized composting materials.

	Heat (kJ/h)	Percentage (%)
Heat loss		
q_c	1.574	87.7
q_{pvc}	0.108	6.0
q_{plexi}	0.113	6.3
Heat produced		
q_m	1.495	100

Calculations were performed on the average temperatures of 3 replicates (CV = 3.1-7.4%)

q_c = heat loss through main body of cylinder

q_{pvc} = heat loss through PVC side wall

q_{plexi} = heat loss through plexiglas side wall

q_m = heat added by mixing unit

mixture are presented in Fig. 5. The values of the various heat losses are shown in Table 3. The measured energy input for mixing was 2.16 kJ/h. The calculated total heat loss through the bioreactor body was found to be 1.795 kJ/h or 83.1% of the energy required for mixing.

Metabolic heat

The amount of thermal energy in the exhaust gas leaving the system is equal to the latent and sensible heat gained as the air passes through the composting mass. The exhaust gas is considered to be a mixture of two independent perfect gases (dry air and water vapor), each is assumed to obey the perfect gas law (ASAE 1999):

$$P_a V = m_a R_a T \quad (24)$$

$$P_v V = m_v R_w T \quad (25)$$

where:

P_a = partial pressure of dry air (Pa),

P_v = partial pressure of water vapor (Pa),

V = total volume of gas mixture (m³),

m_a = mass of dry air (kg),

m_v = mass of water vapor (kg),

R_a = gas constant (J kg⁻¹ K⁻¹),

R_w = water constant (J kg⁻¹ K⁻¹), and

T = air temperature (K).

The enthalpy of the exhaust gas equals the sum of the individual partial enthalpies of the mixture of dry air and water vapor and can be calculated from (ASAE 1999):

$$h_m = h_a + wh_g \quad (26)$$

where:

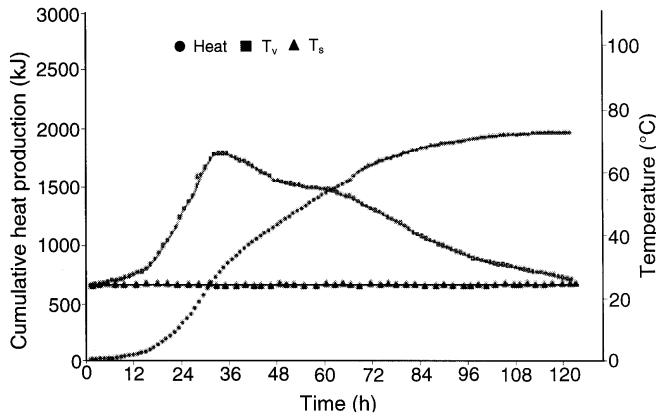
h_m = specific enthalpy of mixture (kJ/kg dry air),

h_a = specific enthalpy of dry air (kJ/kg dry air),

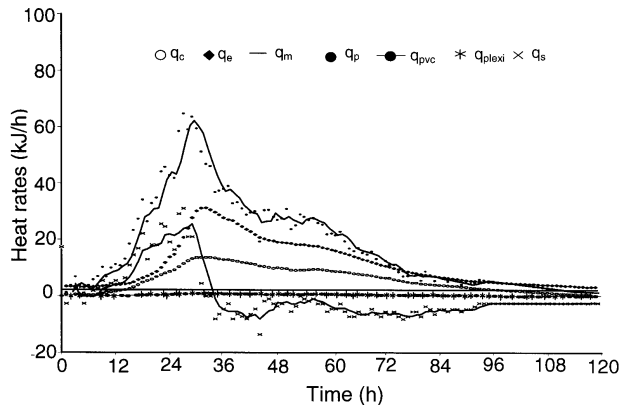
w = humidity ratio (kg water/kg dry air), and

h_g = specific enthalpy for water vapor (kJ/kg water).

The humidity ratio (w) of the exhaust gas is defined as the ratio of the mass of water vapor to the mass of the dry air containing the water vapor, and can be determined by (ASAE 1999):



(a)



(b)

Fig. 6. Temperature and heat production/losses:
(a) temperature and cumulative heat production;
(b) rates of production/losses.

$$w = 0.622 \frac{P_v}{P_{atm} - P_v} \quad (27)$$

where: P_{atm} = atmospheric pressure (Pa).

The partial pressure of the water vapor can be defined by the relative humidity and the saturation vapor pressure from (ASAE 1999):

$$RH = P_v / P_s \quad (28)$$

$$\ln\left(\frac{P_s}{R}\right) = \frac{a + bT + cT^2 + dT^3 + eT^4}{fT - gT^2} \quad (29)$$

where:

P_s = saturation vapor pressure (Pa) and
 RH = relative humidity (dimensionless)

and the constants are:

$$R = 22105649.25$$

$$a = -27405.526$$

$$b = 97.5413$$

$$c = -0.146244$$

$$d = 0.12558 \times 10^{-3}$$

$$e = -0.48502 \times 10^{-7}$$

$$f = 4.34903$$

$$g = 0.39381 \times 10^{-2}$$

In the temperature range of 263.16 to 323.16 K, the specific enthalpies of the dry air and the saturated water vapor can be approximated with negligible error from (Çengel and Boles 1989):

$$h_a \approx T_c \quad (30)$$

$$h_g \approx 2501 + 1.80T_c \quad (31)$$

where: T_c = dry bulb temperature of mixture (°C).

The enthalpy for the exhaust gas can, therefore, be calculated by substituting Eqs. 30 and 31 into Eq. 26 to obtain:

$$h_m = T_c + w(2501 + 1.80T_c) \quad (32)$$

Due to the high rate of evaporative cooling during the composting process, the exhaust air was 100% saturated. Therefore, the saturation pressure (P_s) equalled the partial pressure of the water vapor (P_v) and the relative humidity (RH) was 1.0. Also, the saturation pressure (P_s) of the exhaust air was calculated based on the temperature directly inside the system, while the humidity ratio (w) of the inlet air calculation was based on the partial pressure of the water vapor and the relative humidity of the incoming air.

Equations 21, 22, and 23 were used to determine the overall heat transfer coefficients of the PVC-side wall, the plexiglas-side wall, and the main body of the bioreactor (cylinder), respectively. The conductive heat losses were calculated using Eqs. 13, 14, and 15. The energy stored within the composted material, which is responsible for raising the average temperature, was calculated using Eq. 5. The heat loss due to aeration (latent and sensible) was calculated using Eq. 16. Finally, the sum of all heat losses minus the heat produced by mixing shaft was set equal to the heat produced due to microbial metabolic activities and was calculated using Eq. 3. The temperatures, cumulative heat production, and heat rates are shown in Fig. 6. The result showed that the individual rate of heat produced/lost varied significantly during the composting process. The accumulative heat production/losses are shown in Table 4. The rates of heat produced/lost at the peak temperature are shown in Table 5.

DISCUSSION

Heat evolution during the composting process is due to the microbial degradation of bioavailable substrate (Nell and Wiechers 1978). The calculated average heat production value in this study was 14.6 MJ/kg decomposed material. Miller (1984) reported heat of production in the range of 15.2 - 21.8 MJ/kg decomposed dry matter of sewage sludge and wood chips mixtures. Hogan et al. (1989) reported heat of production in the range of 14.2 - 16.7 MJ/kg decomposed dry matter of rice hulls and rice flour. Harper et al. (1992) reported heat of production in the range of 15.4 - 22.0 MJ/kg for mushroom compost production. The wide range in these studies may be due to the effect of heat lost during pre-composting or the wide variability in the compost mixtures as reported by Harper et al. (1992).

The heat production rate during the composting process increased with time reaching its peak value after 31 hours from

Table 4. Cumulative heat produced or lost during the 114 hours of active composting.

	Heat (kJ)	Heat (%)	Average rate (kJ/h)
Heat produced			
q_m	205.2	9.62	1.80
q_p	1927.1	90.38	16.90
Total	2132.3	100	18.70
Heat losses			
q_c	683.6	32.05	5.99
q_{pvc}	46.7	2.18	0.41
q_{plexi}	48.9	2.28	0.43
q_e	1334.0	62.59	11.70
Total	2113.2	99.10	18.53
Net heat gain, q_s	19.1	0.90	0.17

Calculations were performed on the average temperatures of 3 replicates (CV = 3.1-7.4%)

q_c = heat loss through main body of cylinder

q_{pvc} = heat loss through PVC side wall

q_{plexi} = heat loss through plexiglas side wall

q_e = heat loss through exhaust gas

q_s = heat gained by compost and system materials

q_m = heat added by mixing unit

q_p = metabolic heat produced

the start of the composting process. As the heat was generated, the temperature of the compost material increased reaching 63.3°C at the peak time. The peak of heat production rate was calculated to be 51.14 kJ/h. The rate of heat production decreased dramatically after the temperature of the material reached 60°C. This temperature may have exceeded the optimum condition for the thermophilic microorganisms and, as a result, microbial growth and possibly microbial activity declined resulting in decreased bioreactor temperature. Another reason would be the consumption of bioavailable nutrients by the microorganisms.

In this experiment, 30.0% of the total heat produced was lost by conduction through the cylindrical body and sidewalls of the bioreactor. According to Clark et al. (1977) and Miller (1993), the conductive heat losses in laboratory-scale bioreactors are expected to be high due to the higher surface area to volume ratio. Bach et al. (1987) reported that the conductive heat losses from a well-insulated composting experimental chamber accounted for as high as 61.6% of the overall heat losses. Hogan et al. (1989) reported conductive heat losses of about 90% of the total heat losses. Therefore, when simulating the actual composting system, it is usual practice to totally reduce the conductive heat losses in laboratory scale bioreactors by using a controlled water bath with an average temperature as close as possible to the one inside the bioreactor (Sikora et al. 1983; Hogan et al. 1989; Iwabuchi et al. 1995; Huang et al. 2000), controlled air bath as an insulative medium (Strom 1985; Atkinson et al. 1996; Larsen and McCartney 2000), or electrical coil around the system (Huang et al. 2000). In this study, the total conductive heat losses were very small due to the good insulation of the bioreactor. Heat loss due to aeration (as

Table 5. Rates of heat produced or lost at the peak temperature.

	Rate (kJ/h)
Heat produced	
q_m	1.78
q_p	49.36
Total	51.14
Heat losses	
q_c	13.67
q_{pvc}	0.93
q_{plexi}	0.98
q_e	31.02
Total	46.60
Net heat gain, q_s	4.54

Calculations were performed on the average temperatures of 3 replicates (CV = 3.1-7.4%)

q_c = heat loss through main body of cylinder

q_{pvc} = heat loss through PVC side wall

q_{plexi} = heat loss through plexiglas side wall

q_e = heat loss through exhaust gas

q_s = heat gained by compost and system materials

q_m = heat added by mixing unit

q_p = metabolic heat produced

sensible and latent heat) in this study accounted for 62.6% of the total heat produced. According to MacGregor et al. (1981), the latent portion can be as high as 90% of the total heat losses due to aeration. To minimize the heat losses with exhaust gas, a heat exchanger should be used to heat the incoming air or a portion of the exhaust air (which still has a high oxygen concentration) should be recycled.

CONCLUSIONS

The energy required for mixing (1.80 kJ/h) was only 83.1% of the energy input into the bioreactor (2.16 kJ/h). The heat losses in the motor assembly accounted for 16.9%. The three main phases encountered in the composting process (lag, active, and maturation phase) were clearly identified in the experiments. The heat generated from the degradation of the organic matter raised the temperature through the three thermal stages of the active phase (psychrophilic, mesophilic, and thermophilic). The rate of heat production decreased dramatically after the temperature had reached 60°C due to the decline in microbial growth and activity. The peak heat production rate (at 63°C) was 62.5 kJ/h. Approximately 30.0% of the total heat produced was lost by conduction through the cylindrical body and side walls of the bioreactor whereas the heat losses with the exhaust gas accounted for 61.0%. The heat gained by the system accounted for only 9.0 %.

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LIST of SYMBOLS

A_c	surface area of the cylinder (m^2)	Q_{air}	inlet airflow rate (m^3/h)
A_{ci}	inside surface area of cylinder (m^2)	$q_{alumi-c}$	heat required to raise temperature of aluminum cover of cylinder (kJ/h)
A_{cins}	outside surface area of insulation (m^2)	q_c	heat loss through main body of cylinder (kJ/h)
A_{co}	outside surface area of cylinder (m^2)	$q_{compost}$	heat required to raise temperature of medium (kJ/h)
A_{plexi}	surface area of plexiglas side wall (m^2)	q_e	heat loss with exhaust gas (kJ/h)
A_{pvc}	surface area of PVC side wall (m^2)	$q_{fiber-c}$	heat required to raise temperature of horizontal fiberglass around cylinder (kJ/h)
a	-27405.526	q_m	heat added by mixing unit (kJ/h)
b	97.5413	q_{mixing}	heat required to raise temperature of mixing shaft (kJ/h)
c	-0.146244	q_p	heat generated by organic substrate metabolism (kJ/h)
Cp_{alumi}	specific heat of cover (aluminum) ($kJ\ kg^{-1}K^{-1}$)	q_{plexl}	heat loss through plexiglas side wall (kJ/h)
$Cp_{compost}$	specific heat of the compost ($kJ\ kg^{-1}K^{-1}$)	$q_{plexi-w}$	heat required to raise temperature of plexiglas side wall (kJ/h)
Cp_{fiber}	specific heat of fiberglass ($kJ\ kg^{-1}K^{-1}$)	q_{pvc}	heat loss through the PVC side wall (kJ/h)
Cp_{plexi}	specific heat of plexiglas side wall ($kJ\ kg^{-1}K^{-1}$)	q_{pvc-c}	heat required to raise temperature of horizontal PVC cylinder (kJ/h)
Cp_{pvc}	specific heat of cylinder material (PVC) ($kJ\ kg^{-1}K^{-1}$)	q_{pvc-w}	heat required to raise temperature of PVC side wall (kJ/h)
Cp_{ss}	specific heat of stainless steel mixing shaft ($kJ\ kg^{-1}K^{-1}$)	q_r	heat loss by radiation (kJ/h)
Cp_{styro}	specific heat of styrofoam ($kJ\ kg^{-1}K^{-1}$)	q_s	total heat required to raise temperature of medium and components (kJ/h)
d	0.12558×10^{-3}	$q_{styro-w}$	heat required to raise temperature of styrofoam insulation of side wall (kJ/h)
e	-0.48502×10^{-7}	R	22105649.25
f	4.34903	R_a	gas constant ($J\ kg^{-1}K^{-1}$)
g	0.39381×10^{-2}	R_w	water constant ($J\ kg^{-1}K^{-1}$)
h_a	specific enthalpy of dry air (kJ/kg dry air)	RH	relative humidity (dimensionless)
h_g	specific enthalpy for water vapor (kJ/kg water)	r_i	inner radius of cylinder (m)
h_i	enthalpy of air at T_{in} (kJ/kg dry air)	r_{ins}	radius of insulation material (m)
h_m	specific enthalpy of mixture (kJ/kg dry air)	r_o	outer radius of cylinder (m)
h_{si}	convective heat transfer coefficient between compost and surface of inside wall of system ($kJ\ m^{-2}\ h^{-1}\ K^{-1}$)	T	air temperature (K)
h_{so}	convective heat transfer coefficient between outside surface of system and room ($kJ\ m^{-2}\ h^{-1}\ K^{-1}$)	T_a	laboratory ambient temperature (K)
h_o	enthalpy of air at T_o (kJ/kg dry air)	T_c	dry bulb temperature of mixture ($^{\circ}C$)
h_{Ti}	convective heat transfer coefficient between compost and inside surface of cylinder ($kJ\ m^{-2}\ h^{-1}\ K^{-1}$)	T_e	exhaust gas temperature within time interval (K)
k_{plexi}	thermal conductivity of plexiglas material ($kJ\ m^{-1}\ h^{-1}\ K^{-1}$)	T_f	temperature of compost at end of time interval (K)
k_{pvc}	thermal conductivity of PVC material ($kJ\ m^{-1}\ h^{-1}\ K^{-1}$)	T_i	temperature of compost at beginning of time interval (K)
k_{Styro}	thermal conductivity of styrofoam material ($kJ\ m^{-1}\ h^{-1}\ K^{-1}$)	T_{in}	air inlet temperature (K)
L_c	characteristic length of cylinder (m)	T_s	temperature of outside surface of bioreactor within time interval (K)
M_{alumi}	mass of aluminum sheet (kg)	T_v	average temperature of compost within time interval (K)
$M_{compost}$	mass of compost (kg)	ΔT_{1-7}	temperature changes in material of cylinder, fiberglass, aluminum, PVC side wall, styrofoam, plexiglas side wall, and mixing shaft, respectively, within time interval (K)
$M_{cylinder}$	mass of cylinder (kg)	Δt	time interval (h)
M_{fiber}	mass of fiberglass (kg)	U_c	overall heat loss coefficient of cylinder ($kJ\ m^{-2}\ h^{-1}\ K^{-1}$)
M_{plexi}	mass of plexiglas side wall (kg)	U_{plexi}	overall heat loss coefficient of plexiglas side wall ($kJ\ m^{-2}\ h^{-1}\ K^{-1}$)
M_{pvc}	mass of PVC side wall (kg)	U_{pvc}	overall heat loss coefficient of PVC side wall ($kJ\ m^{-2}\ h^{-1}\ K^{-1}$)
M_{ss}	mass of stainless steel mixing shaft (kg)	V	total volume of gas mixture (m^3)
M_{styro}	mass of styrofoam (kg)	w	humidity ratio (kg water/kg dry air)
m_a	mass of dry air (kg)	X_{plexi}	thickness of plexiglas sidewall (m)
m_v	mass of water vapor (kg)	X_{pvc}	thickness of PVC sidewall (m)
P_a	partial pressure of dry air (Pa)	X_{styro}	the thickness of styrofoam insulation (m)
P_{atm}	atmospheric pressure (Pa)	ρ	air density (kg/m^3)
P_s	saturation vapor pressure (Pa)		
P_v	partial pressure of water vapor (Pa)		