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Effect of Insulation on the Performance of a Rotary Bioreactor for Composting Agricultural Residues

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Abstract: Rotary drum composters are used to produce high-quality, pathogen-free compost without weed seeds. Insulation is usually applied to small-scale composters to warm up the composted materials and enhance metabolic reactions to produce stable and mature compost within a short time. However, the relationship between the composter size and the heat loss rate is still unclear. In this study, the relationship between the composter size (designated as the ratio of surface area to volume, A_s/V) and heat loss was analyzed and identified. To show the effect of insulation on the composting performance, two identical rotary drum bioreactors (each of $A_s/V = 9$) were used to compost tomato plant residues, one insulated and the other kept without insulation. Results showed that insulation increased the overall resistance against heat loss from the bioreactor from 0.37 (m^2 °C W^{-1}) to 1.12 (m^2 °C W^{-1}), quickly increasing the compost temperature, and a temperature of 55–67 °C could be achieved and remained for three days. Therefore, mature, stable, well-aged, and high-quality compost was obtained. In the non-insulated bioreactor, the compost temperature did not exceed 37 °C; this caused a decline of microbial activity and the composting process temperature was only in the mesophilic range, leading to a high risk of the existence of weed seeds and pathogens in the final immature compost. Insulation is necessary for laboratory-scale and small pilot-scale bioreactors ($A_s/V \geq 6$), because heat loss is high as A_s/V is high, whereas it is not necessary for commercial full-scale bioreactors ($A_s/V \leq 4$), because heat loss is minor as A_s/V is low. For larger pilot-scale bioreactors (A_s/V: 4–6), insulation cost must be considered when comparing the impact of energy saving on the composting process.

Keywords: Compost; tomato plant residues; energy generation; insulation; heat loss; rotary drum bioreactor

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1. Introduction

Typical vegetable greenhouses produce from forty to sixty tons of plant residues per hectare per year, and the greenhouse crops in Saudi Arabia produces more than 0.3 million tons of organic waste per year [1,2]. Trimming and after-harvesting of crops produce a considerable amount of plant residues that must be disposed of properly to eliminate environmental pollution [2,3]. Composting of plant residues is a bioconversion exothermic process, considered to be the most desirable and effective organic waste management method [3]. However, it is quite difficult to maintain a high operational temperature to ensure the production of high-quality compost that is free of pathogens and weed seeds [4]. Rotary bioreactors are an efficient and promising technology, as they are enclosed; provide agitation, uniform aeration, and compost mixing; and produce a consistent, quick, and uniform end product without any environmental-related problems [5]. They break down the materials into very fine compost, weed seeds and pathogens can be eliminated, and the composting time is drastically reduced [6]. Composting of organic wastes produces a considerable amount of heat, that is generated due to microbial metabolic activity. Consequently, an elevated temperature of compost (up to 90 °C) can be achieved during composting of municipal solid waste [7,8], and up to 70 °C can be achieved during composting of plant residues [9,10]. These elevated temperatures depend on the amount of heat generation during the composting process and contribute to the increased internal energy of compost. This depends on the chemical, physical, and biological properties of the composted material. Therefore, wide ranges of heat generation (0.5–20 MJ kg^{-1}) have been reported in the literature [9–12]. For laboratory- and pilot-scale bioreactors, the majority of the generated heat is lost to the surrounding air via convection and radiation mechanisms; these losses account for 30–94% of the total heat generation depending on the effectiveness of the bioreactor's insulation [9,13]. Therefore, during the thermophilic stage, it is important to optimize the operation conditions to reduce the composting time as much as possible [14]. Compost temperatures in the range from 52 to 60 °C are considered to maintain the highest thermophilic activity in composting systems; this range can reduce weed seed viability and suppress pathogen activity during composting [5,6]. In addition, holding the compost temperature above 55 °C for at least three days is necessary to ensure sanitation and demonstrate optimal biological activity [14]. Accordingly, reducing the rate of heat loss during the composting process by insulating the bioreactor surfaces is the main factor to manage and improve the bioreactor performance and compost quality. For better understanding, the energy balance equation to describe the composting process during a time interval of dt is given by:

$$Q_g - Q_{loss} = M_c Cp_c \frac{dT_c}{dt}, \tag{1}$$

where Q_{loss} is the rate of the total heat loss from the bioreactor (via convection, radiation and aeration in W), and Q_g is the heat generation rate (W); M_c is the mass (kg) and Cp_c is the specific heat of the composting materials (J kg^{-1} $°C^{-1}$); dT_c/dt is the rate of change of the compost temperature (°C s^{-1}). The right hand side term represents the rate of change of the internal energy of compost (Q_{in}, W) or the amount of heat used to raise the compost temperature. This is essential in the heating phases (i.e., psychrophilic and mesophilic), however, it can be neglected in the stationary phase, and the system undergoes the steady state condition. In Equation (1), enhancing the metabolic reaction would enhance the heat generation rate (Q_g) and in turn increase the internal energy of the compost, as well as the rate of compost temperature rise (dT_c/dt). The rate of temperature rise can be significantly enhanced by insulating the bioreactor surfaces.

According to Haug [8] and Mason [15], bioreactors have been classified based on: (i) Volume (V) as laboratory scale (V < 0.1 m^3), pilot scale (V = 0.1–2 m^3), and full or commercial scale (V > 2 m^3); and (ii) the ratio of surface area to volume (A_s/V, m^{-1}) as laboratory scale (10 < A_s/V < 88), pilot scale (A_s/V = 4–10), and full or commercial scale (A_s/V = 0.4–4). Since 1987, studies have reported that the heat loss from small-scale systems (i.e., pilot- and laboratory-scale bioreactors) is extremely high as the A_s/V is high [8,9,13,15–18]. In such small-scale systems, the surface heat loss can be significant, even with substantial insulation present [15]. Therefore, insulation is necessary to achieve metabolic reactions and the final product of compost [2,12–14,19,20]. However, in commercial bioreactors, heat removed by moisture evaporation and released to the outside via aeration is the greatest portion, while the portion of heat loss from the reactor surfaces is minor [21].

Previous heat energy studies have investigated the potential of energy content of compost; most of them focused on insulated laboratory-scale bioreactors to calculate the generated and lost heat energy terms during composting [9,11–13,16]. However, information on the relationship between heat loss and the size of the bioreactor is still missing. In other words, the size of laboratory- and pilot-scale bioreactors is in a wide range (A_s/V: 4–88 m^{-1}), and the questions are: For what size reactor do we have to apply insulation to get active metabolic reactions, high composting temperature, and good compost product? and What is the role of insulation in enhancing heat generation and raising compost temperature? The answers to these questions are still unclear and had never been discussed in previous studies. Highlighting such information is key factor to maintain the composting process at optimum conditions, to reduce composting time, and to enhance the duration and quality of compost.

Accordingly, the aims of this study were to (i) analyze the heat loss from a bioreactor with regard to the bioreactor size at different operating conditions to clarify the relationship between the heat loss rate and the bioreactor size, and (ii) investigate the effect of the bioreactor's insulation on the composting process, energy loss, and enhancement of the duration and quality of compost. Two identical pilot-scale rotary drum bioreactors were used, one insulated and the other kept without insulation. Both rotated at 3 rpm and were used to compost tomato plant residues. Such analysis and information will provide helpful knowledge for the proper design and optimal operation of compost bioreactors.

2. Materials and Methods

2.1. Analysis of Heat Loss from Bioreactors

In the pilot-scale bioreactors, heat loss due to aeration is minor (about 2% of the total heat loss) and can be neglected [13]. Convective and radiative heat losses (Q_{loss} in Equation (1)) are from the bioreactor surface to the ambient air (convection, Q_{con}) and to the sky dome (thermal radiation, Q_{rad}), respectively; they are given by [13] as:

$$Q_{\text{loss}} = Q_{\text{con}} + Q_{\text{rad}} = A_s(T_c - T_{\text{am}})/\Omega + \sigma\varepsilon_s\, A_s(T_s^4 - T_{sky}^4), \tag{2}$$

where Ω is the overall (equivalent for the bioreactor cylindrical part and side walls) heat transfer resistance (m^2 °C W^{-1}) between the compost material at a temperature of T_c and the ambient air at a temperature of T_{am} and A_s is the outside surface area of the bioreactor (m^2). In order to determine Q_{con} in Equation (2), the convective coefficients (h_{c3} and h_{w3} in Figure 1) are required. For indoor bioreactors operating at a low speed (<50 rpm), the free convection mechanism is considered at the outer surface of the bioreactor and 2 correlations to estimate the convective coefficients (h_{c3} and h_{w3} in Figure 1) were recommended by [13] and given by:

$$h_{w3} = 1.42\left(\frac{T_s - T_{\text{am}}}{D}\right)^{0.25}, \tag{3}$$

$$h_{c3} = 1.32\left(\frac{T_s - T_{am}}{D}\right)^{0.25}, \tag{4}$$

where D is the outer diameter ($2r_o$, m) and T_s (°C) is the temperatures of the outside surface of the bioreactor. Equations (3) and (4) are for the convective heat transfer coefficients on the outer surface of the vertical side walls and on the outer surface of the horizontal cylindrical part of the reactor, respectively. Based on Figure 1, the equivalent heat transfer resistance Ω (m^2 °C W^{-1}) is calculated as: $\Omega = A_s\,(R_c\,R_w)/(R_c+R_w)$; expressions for R_c and R_w are given in Figure 1, in which k_s is the thermal conductivity of the bioreactor material (steel, 46 W m^{-1} °C^{-1}). The convective resistance for the cylindrical and side wall parts between the compost–air mixture and the inner surface of the bioreactor (R_{c1} and R_{w1} in Figure 1) is in most cases equal to zero, because the temperature difference between the inner surface of a rotating bioreactor and the compost–air mixture ($T_c - T_i$) is minor and can be neglected [13]. Then, Q_{con} (W) in Equation (2) can be determined for an uninsulated metallic rotary bioreactor operating indoors at low speed (the influence of ambient air movement is neglected).

For bioreactors operating outdoors under natural weather, wind speed affects the convection heat transfer on the outer surface of the reactor. In this case, the forced convection mechanism is considered and the convective heat transfer coefficient, instead of Equations (3a) and (3b), is given by [22] as:

$$h_{c3} = h_{w3} = max\left(5\ or\ \frac{8.6U^{0.6}}{V^{(2/15)}}\right), \quad (5)$$

where U is the wind speed (m s^{-1}) and V is the inside volume of the bioreactor (m^3).

In Equation (2), ε_s and σ are the ling-wave emittance of the outer surface of the bioreactor (0.66 for steel surface) and the Stefan–Boltzmann constant (5.6696×10^{-8} W·m^{-2}·K^{-4}), respectively. T_s and T_{sky} are the temperature of the outer surface of the bioreactor and the equivalent temperature of the sky dome (K), respectively. For arid climatic conditions, an expression for T_{sky} (in K) as a function of the ambient air temperature, T_{am} (in K), was used in this analysis (unpublished); however, T_{sky} can be approximately calculated by an expression reported in [23] and given by:

$$T_{sky} = 0.0559(T_{am})^{1.5}, \quad (6)$$

The rotating bioreactor is usually cylindrical, and a diameter equal to half the length (D = 0.5 L) is a common design consideration. In such cases, the ratio of surface area to volume (A_s/V) is (2/L + 4/D).

By using Equations (2)–(6), the rate of heat loss (Q_{loss}) from a bioreactor can be estimated as a function of A_s/V for a given compost and ambient temperature (T_c, T_{am}).

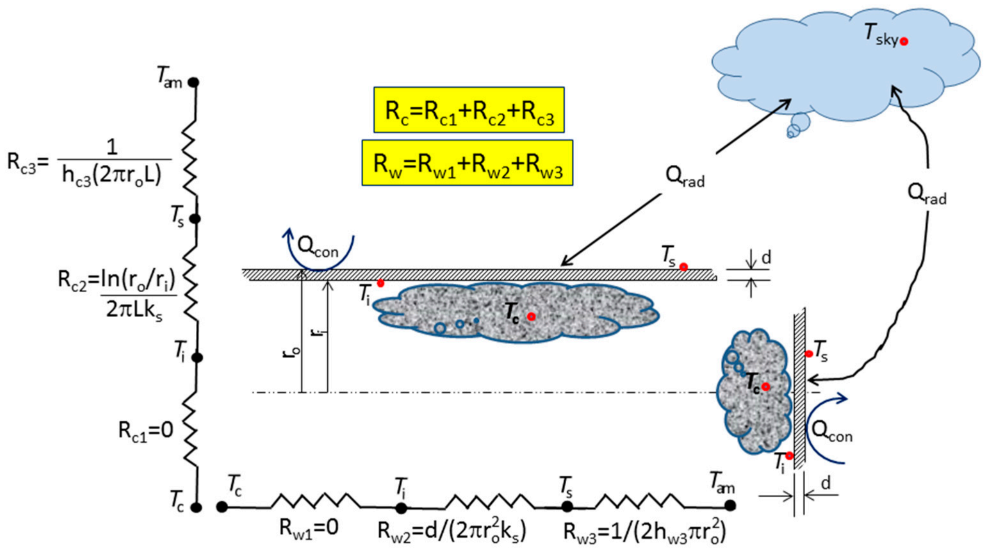

Figure 1. Schematic diagram showing thermal resistance against heat loss from compost–moist air mixture to outside ambient air through the cylindrical part and the vertical circular side walls.

2.2. Experimental Tests

2.2.1. Preparing Plant Residues

Fresh residues of tomato crops grown in greenhouses (leaves, stems, and some green and damaged fruits) were collected from four different fields distributed around the University campus (Riyadh, Saudi Arabia). The average moisture content (MC) of the collected residues was about 80–90%. On sunny days, the collected residues were spread out on the floor under solar radiation and kept to dry for 3 days (MC reduced to 60%). The residues were chopped using a shredder (model FYS-76 shredder, Zhejiang, China) to promote uniform distribution of moisture content and to provide better aeration. Residues were grounded to decrease the particle size to about 1–2 cm in order to improve the microbial degradation process. The grounded residues were left to dry on the floor for an additional

2 days (MC reduced to 15%), then transported to the biological laboratory at the experimental and research station of the Agricultural Engineering Department, King Saud University, Riyadh.

2.2.2. Pilot-Scale Bioreactors

Three identical pilot-scale rotary-drum bioreactors had been constructed at the research station of the Agricultural Engineering Department and used for composting tomato plant residues in previous studies [13]. Two of them were used for the present study. Each bioreactor has a volume of 0.2 m^3, with a ratio of surface area to volume (A_s/V) of 9, able to contain 50 kg of compost materials and keep 25% of the volume as free space. The reactors were made from steel barrels with an inner diameter of 0.585 m, length 0.914 m, and wall thickness about 3 mm. Each reactor includes an opening door 0.50 × 0.40 m for loading, unloading, and sampling compost, and for cleaning purposes. In order to prevent any possible leakage/odors, each door and its opening included rubber gasket linings. Each bioreactor is mechanically rotates around a horizontal fixed axis (i.e., a steel tube with 50 mm outer diameter) at 3 rpm by using a 0.25 HP electric motor (model no. 220-380-3, Zhejiang, China). The motor was connected to a gearbox for speed reduction. The horizontal tube in each reactor includes online holes made longitudinally in the upper side for aeration purpose (Figure 2a,b). Of the two bioreactors, one was kept without insulation and the outer surface of the other was insulated with a layer of 25 mm thick glass–wool blanket (thermal conductivity, k_b = 0.04 W m^{-1} °C^{-1}). A detailed description of these bioreactors installed on a steel-angle frame with the rotating system was reported in [13]. Cross-sectional views of the insulated and non-insulated bioreactors are shown, not to scale, in Figure 2a,b.

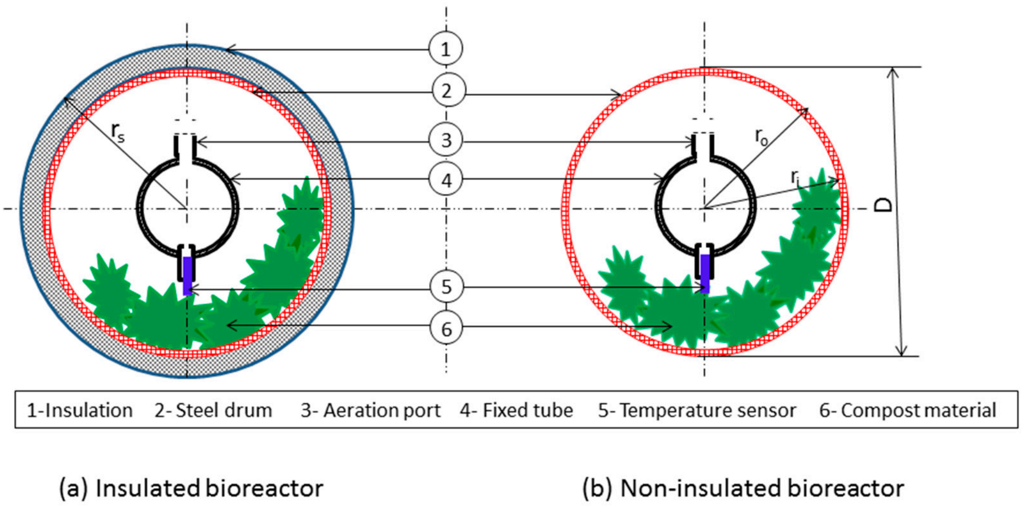

Figure 2. Cross-sectional view of (**a**) insulated and (**b**) non-insulated bioreactors.

2.2.3. Measurement Procedure

The experiment was conducted inside the laboratory building, under indoor conditions. Aeration of the bioreactors was performed by compressed air was continuously supplied at a flow rate of 0.005 ($m^3 \cdot min^{-1}$) from a reservoir (10 bar, 0.2 m^3 volume). For contentious air feeding, the reservoir was connected to an air compressor (Airmac CRM203, 2.2 kW, Parkinson, Australia). The compressed air followed a path to the horizontal tube (i.e., what the bioreactor rotates around) and then to the compost mixture via 4 holes that were made in the upper side of each tube. The compost temperature (T_c) was measured using 3 thermocouple sensors fixed longitudinally in the lower side of each tube (see Figure 2a,b). In each tube, the aeration ports and the thermocouple sensors are located on opposite sides so that the thermocouple sensors are far enough from the inlet air source to minimize the negative influence of air movement on the measured temperature, T_c. The temperature of the outer surface of insulation (T_o) and the outer surface of the barrel (T_s) was measured using 2 thermocouple sensors attached properly to each surface. However, the temperature of the inner surface of the barrel (T_i) was difficult to measure properly, due to the relative motion of compost material in contact with the inner surface. Thus, T_i was assumed to be equal to T_c and the heat transfer resistance between the compost material and the inner surface of the bioreactor (R_{c1} and R_{w1}) was neglected (Figure 1). The thermocouples used were copper–constantan (type-T, Cole-Parmer, Chicago, IL, USA). The wires of the sensors used to measure T_c were passed inside the tube to the outside and connected to a portable data logger (Testo 177-T4 V01-02) fixed at the end of the tube to record the measured temperatures. The wires of the thermocouple sensors used to measure T_s and T_o were connected to another portable data logger (Testo 177-T4 V01-02) fixed on the outer surface of each bioreactor. The ambient temperature (T_{am}) was measured using a thermo-hygrometer (DMA033, LSI-Lastem, Milano, Italy). The measured parameters were recorded every 10 s, averaged every 10 min, and saved in the data loggers. Tomato plant residues and chicken manure (20% dry weight) were mixed properly. Before starting the experiment, the moisture content of the mixture was adjusted to about 60–65% and C/N ratio to about 30:1. Then, the mixture was transferred to the 2 bioreactors (each was filled to 75% of the total volume) to start the composting process. Composting continued until the compost temperature (T_c) dropped below 40 °C. Then, compost materials were taken outside the bioreactors for evaluation. The degree of maturation was measured immediately by using the Dewar self-heating test [24]; 6 representative compost samples (3 from each bioreactor) were taken for testing.

3. Results and Discussion

3.1. General Analysis of Heat Loss from Bioreactors

In order to highlight the relationship between the bioreactor size (represented by A_s/V ratio) and the heat loss rate, Equations (2)–(6) were used to estimate the heat loss rate from an assumed steel bioreactor with a wall thickness of 3 mm, different A_s/V ratios, and different composting temperatures (T_c). The bioreactor was assumed to operate under two different weather conditions. One was calm weather with the wind at low speed ($U < 1$ m s^{-1}) and an ambient temperature (T_{am}) of 25 °C. In this case, the natural convection mechanism takes place on the outer surface of the bioreactor and Equations (3) and (4) are used to calculate the convection heat transfer coefficients (h_{c3}, h_{w3}). The resulting heat loss rates per unit volume of the bioreactor (Q_{loss}, W m^{-3}) are depicted in Figure 3. The figure shows a strong dependent, proportional relationship between Q_{loss} and A_s/V ratio; for a certain temperature difference ($T_c - T_{am}$), Q_{loss} increases with increased A_s/V ratio, and it also increases with increased T_c at a constant A_s/V value. The other condition was windy weather ($U \geq 1$ m s^{-1}), clear sky, and T_{am} of 25 °C; in this case, the wind causes a forced convection on the outer surface of the bioreactor and Equation (6) is used to calculate the convective coefficient. The resulting Q_{loss} (W m^{-3}) as affected by A_s/V ratio is illustrated in Figure 4 at different wind speeds (U) and compost temperatures (T_c). The presence of air movement around the bioreactor even at low speed (1 m s^{-1}) significantly enhances the rate of heat loss from the bioreactor surface (Figure 4). When ($T_c - T_{am}$) is equal to zero (T_c = 25 °C), the heat loss due to convection (Q_{con}) is equal to zero too, and the heat loss illustrated in Figures 3 and 4 is attributed only to radiation heat loss (Q_{rad}) to the sky dome. Figures 3 and 4 confirm the fact that Q_{loss} increases with increased A_s/V ratio, ($T_c - T_{am}$), and U. Based on the results in Figures 3 and 4, insulation is essential for small-volume pilot-scale and laboratory-scale bioreactors ($A_s/V \geq 6$ m^{-1}) to achieve an elevated temperature that can initiate the metabolic reactions and activate the composting exothermic process, and finally to provide mature compost. On the other hand, for pilot-scale bioreactors with A_s/V of 4–6 m^{-1}, the need for insulation may need to be determined, and the cost of insulation against the heat gain should be taken into consideration. In general, and according to 2018 local market prices, the total insulation cost (materials, fixing, and labors) was accounted to be around 6–7 US $ per meter square of the bioreactor surface. However, for commercial-scale bioreactors ($A_s/V \leq 4$ m^{-1}), insulation is not necessary, because the heat loss is low and insulation will add more cost without economic returns.

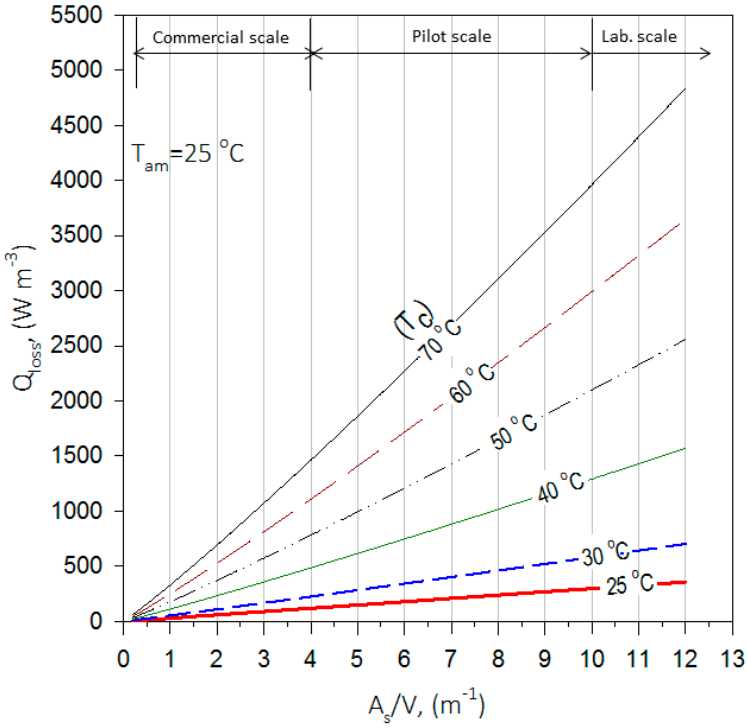

Figure 3. Heat loss per unit volume from a non-insulated steel bioreactor (3 mm wall thickness) as affected by the ratio of surface area to volume (A_s/V), estimated at different compost temperatures (T_c).

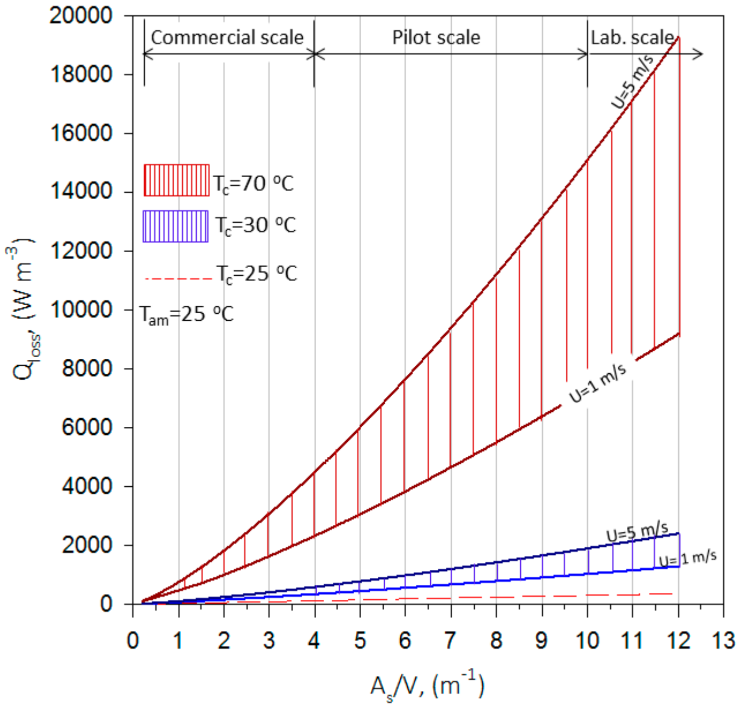

Figure 4. Heat loss per unit volume of the bioreactor, estimated at different composting temperatures (T_c) as affected by ambient air speed (1–5 m s^{-1}) and A_s/V ratio.

3.2. Performance Evaluation of the Two Bioreactors

In order to validate the above assumption (i.e., that the thermal resistance on the inner surface of the bioreactor can be neglected, R_{c1} = R_{w1} = 0) for the insulated and non-insulated bioreactors, the values of compost temperature (T_c), outer surface temperature (T_s), and ambient temperature

(T_{am}) during the experiment are measured, as illustrated in Figure 5. In the insulated bioreactor, the outer surface temperature of the steel drum (T_s) is slightly lower than T_c, which means that the inner surface temperature of the drum (T_i) is nearly equal to T_c. In the non-insulated bioreactor, T_s is slightly higher than T_c after two days of operation; this may be affected by the ambient temperature (T_{am}), which was higher than T_c and T_s during the first two days (Figure 5). Accordingly, for the insulated and non-insulated rotary bioreactors, the assumption $T_i = T_c$ is valid and the internal convective resistance between the compost material and the inner surface of the reactor can be neglected ($R_{c1} = R_{w1} = 0$; Figure 1) without any possible error in the heat transfer analysis. Insulation of the bioreactor keeps the composting materials warm, enhances the metabolic exothermic reactions, generates heat, and increases the internal energy of compost materials. Insulation creates optimal composting conditions and increases the breakdown of the available organic matter and nitrogenous compounds through microbial activity. This rapidly increases the compost temperature (T_c) to reach 55–67 °C, which remains for three days in the thermophilic stage (Figures 5 and 6). However, in the non-insulated bioreactor, the heat loss slows down the microbial activity and depresses the metabolic reaction. This lowers the compost temperature (T_c), and the composting process does not exceed the psychrophilic phase during the whole experiment (Figures 5 and 6). Moreover, in the non-insulated bioreactor, T_c remained below 50 °C, which could not create thermophilic activity in the composting system; this would increase the weed seed viability and pathogen activity in the end product. Insulation provides optimal conditions for the composting process to proceed through the three standard phases, as illustrated in Figure 6. Results in Figure 6 show that by using an insulated rotary bioreactor, the time for the high-temperature phase could be reduced to about three days compared to several days, or even several months, for other composting methods. In addition, a compost temperature (T_c) above 55 °C for a period of three days is enough to satisfy the requirement for the destruction of pathogens and reduce weed seed viability.

During composting, there are reciprocal relations among six interacting sub-processes controlling the exothermic reactions in a thermodynamic cycle. These sub-processes are the change of compost temperature (T_c), microbial activity, metabolic reaction, heat generation (Q_g), change of internal energy of compost (Q_{in}), and heat loss rate (Q_{loss}). These affect each other in a closed loop. The heat loss rate (Q_{loss}) was estimated for the non-insulated and insulated bioreactors based on Equations (2)–(5). For the insulated bioreactor, two conductive heat resistances of the blanket insulation were included. One resistance equal to $d/(2\pi r_s^2 k_b)$ will be added to R_w of the side wall equivalent resistance (Figure 1); the other resistance equal to $[\ln\left(\frac{r_s}{r_o}\right)/(2\pi L k_b)]$ will be added to R_c of the cylindrical equivalent resistance (Figure 1); r_s is the radius of the insulated bioreactor and k_b is the thermal conductivity of insulation. Results of the estimated Q_{loss} for the two bioreactors are illustrated in Figure 7, showing that Q_{loss} from the non-insulated bioreactor was lower than that from the insulated bioreactor. This is because T_c, microbial activity, and the heat generation rate were lower in the non-insulated than in the insulated bioreactor. As shown in Figure 7, during the first 36 h of operation, Q_{loss} in the two bioreactors was in the negative (i.e., heat gain), because the ambient temperature T_{am} was higher than T_c.

The heat generation rate (Q_g) during the composting process in the two bioreactors was estimated by substituting the measured temperatures and the physical properties of compost and air into Equation (1); the results are illustrated in Figure 8a,b for the 190 h of operation. In the insulated bioreactor, as heat was generated, the compost temperature (T_c) increased, reaching 67 °C after 83 h (the peak time) of the composting process. Evolution of heat generation, shown in Figure 8a, depends mainly on the insulation effectiveness, in addition to other parameters such as aeration effectiveness, distribution of humidity in the composted material, concentration of oxygen and nitrogen concentration, etc. Drastic reduction is observed after the temperature of compost (T_c) reached 67 °C (cooling phase). The high level of temperature that may exceed the optimum temperature for thermophilic microorganisms causes the microbial growth and activity declines, and consequently, the rate of heat generation and the temperature of compost drastically decreases. In addition, the metabolic reactions reduced due to the consumption of bioavailable nutrients by the microorganisms [9,13]. In the non-insulated bioreactor, at the beginning of the composting process, heat loss (via convection, radiation, and aeration) even at low rates makes T_c low and in turn depresses the microbial activity and reduces the heat generation rate (Figure 8b). Low heat generation (Q_g) reduced the rate of change of internal energy of the compost (Q_{in}) and then reduced the compost temperature increase and the heat loss (Q_{loss}) (Figure 8b). Moreover, in the non-insulated bioreactor, the maximum T_c was 37 °C, much lower than the required temperature for thermophilic microorganisms; this reduced microbial growth and activity and exothermic reactions, as well as the heat generation rate.

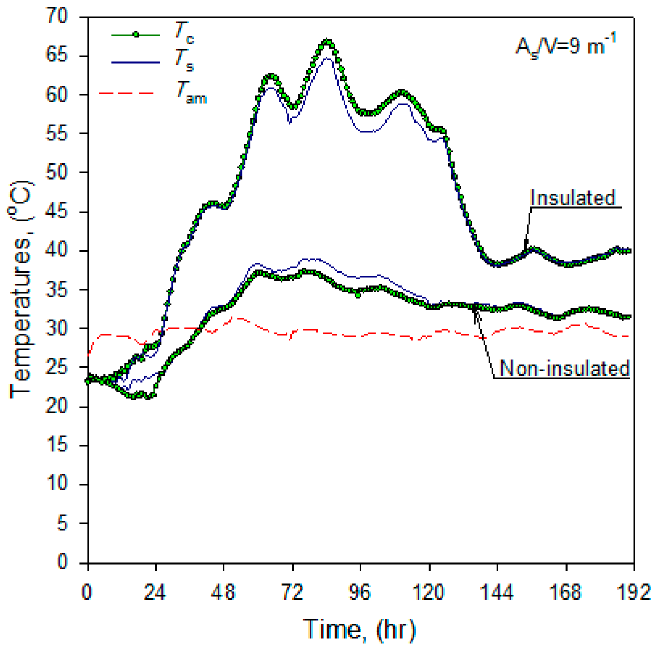

Figure 5. Time course of temperatures (compost, T_c, outer surface of the bioreactor walls, T_s, and ambient air, T_{am}) measured for insulated and non-insulated bioreactors during the composting process.

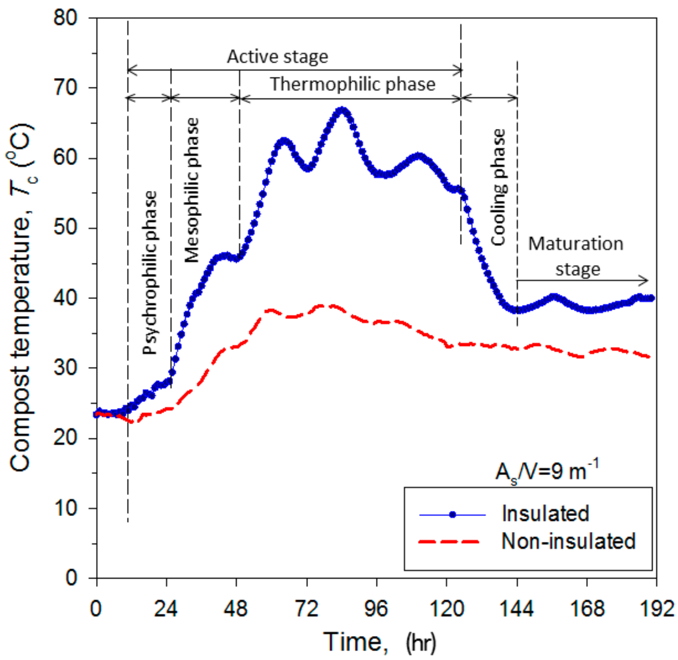

Figure 6. Outline of main phases of composting process based on measured compost temperatures (T_c) in insulated and non-insulated bioreactors.

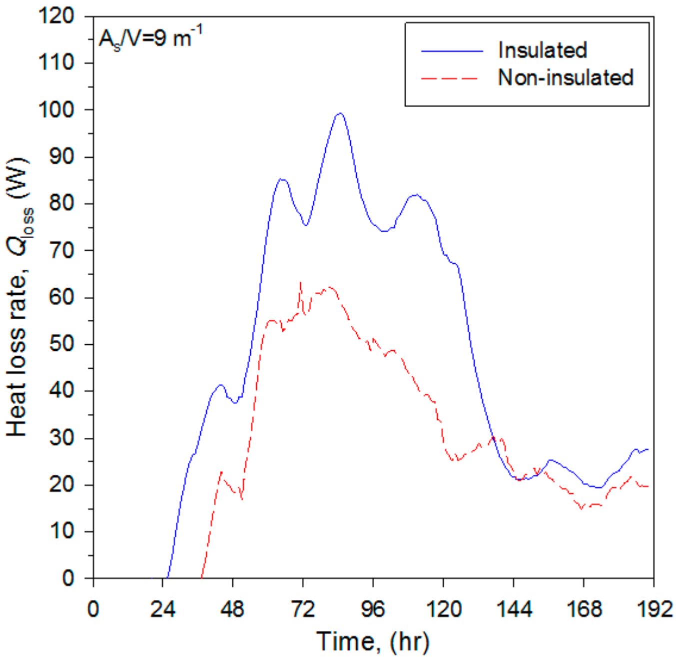

Figure 7. Total heat loss rate (Q_{loss}) from inside to outside insulated and non-insulated bioreactors during the composting process.

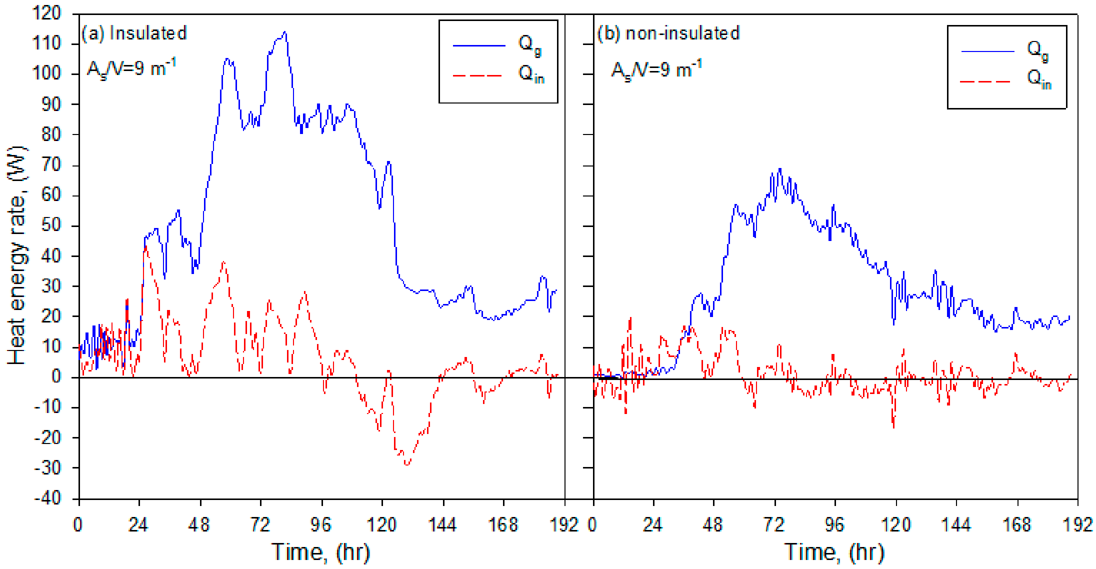

Figure 8. Time course of total heat generation rate (Q_g) and rate of change of internal energy (Q_{in}) of compost were estimated in the (**a**) insulated and (**b**) non-insulated bioreactor during the composting process.

It is well known that insulation increases the resistance to heat transfer; in the present study, the overall heat transfer resistance (Ω) in Equation (2) increased from 0.37 (m^2 °C W^{-1}) for the non-insulated bioreactor to 1.12 (m^2 °C W^{-1}) for the insulated bioreactor. This would significantly reduce Q_{loss} from the insulated bioreactor compared with the non-insulated one, if the heat generation is the same in both. On the other hand, under steady-state conditions, if the heat loss due to aeration (≅2% in the present study) was neglected in Equation (1), this would lead to Q_g being equal to Q_{loss}. This means generated heat contributes to increased compost temperature and is finally released outside the bioreactor as a heat loss, whether the bioreactor is insulated or not.

3.3. Product Assessment

Compost maturity is an important factor that affects the successful application of compost for agricultural purposes [25]. The Dewar self-heating test [24] was used to evaluate the maturity level of compost just after taking the compost material out of the bioreactors. Three samples of compost were taken randomly from each bioreactor, representing all the compost, and the six samples were kept in a refrigerator (at 4 °C) until use. Each sample was kept in a flask for six days, then the maximum temperature (T_{max}) and the corresponding room temperature (T_{room}) were recorded, and consequently the temperature difference ΔT (ΔT = $T_{max} - T_{room}$) was estimated. Results for the six samples from the two bioreactors are illustrated in Table 1. The results show that the maximum temperature of the compost from the insulated bioreactor was very close to room temperature. Values of ΔT were much lower than 10 °C, which means the mixture completed the active phase and was ready for maturation [24]. Compost samples taken from the non-insulated bioreactor had higher increments of ΔT and exceeded 10 °C on average. This means that the materials were still decomposing (active). These results show the importance of insulation for laboratory and pilot-scale bioreactors.

Table 1. Results of Dewar self-heating test for three samples of compost from insulated and non-insulated bioreactors.

Dewar Self-Heating Test								
Sample no.	Insulated bioreactor				Non-insulated bioreactor			
	T_{max} (°C)	T_{room} (°C)	ΔT (°C)	Remarks	T_{max} (°C)	T_{room} (°C)	ΔT (°C)	Remarks
1	22.9	20.5	2.4	Compost class V (mature)	32.1	20.9	11.2	Compost class IV (immature)
2	23.1	21.7	1.4		31.3	21.3	10	
3	23.9	21.8	2.1		30.3	21	9.5	
Average	23.3	21.33	1.97		31.23	21.07	10.17	
SD	0.53	0.72	0.51		0.9	0.21	0.96	

4. Conclusions and Recommendation

The relationship between bioreactor size (represented as the A_s/V ratio) and heat loss from the bioreactor surfaces was identified under different operating conditions. Heat loss significantly increases as the volume of the bioreactor decreases (the A_s/V ratio increases). Air movement around the bioreactor significantly increases the convective heat loss from the bioreactor surfaces, especially at high composting temperature, T_c. Insulation is necessary for the small volumes of pilot-scale and laboratory-scale bioreactors ($A_s/V \geq 6$ m^{-1}) to achieve appropriate conditions for the production of good-quality compost. However, for commercial full-scale bioreactors ($A_s/V \leq 4$), insulation is not necessary, because heat loss is low as the A_s/V ratio is low. For a large pilot-scale bioreactor (A_s/V: 4–6), the cost of insulation should be evaluated and compared with the impact of insulation in saving energy and enhancing the duration and quality of composting.

The effect of insulation on the bioreactor performance and composting process was evaluated by using two identical pilot-scale rotary drum bioreactors, ($A_s/V = 9$ m^{-1}), one insulated and the other kept without insulation. The temperature of compost, T_c, in the non-insulated bioreactor was low (max 37 °C); this reduced microbial activity and the maximum composting temperature was in the mesophilic range. However, insulation warmed up the composting material, generated heat from the degradation of organic matter, and quickly increased T_c. The evolution of T_c created the three main phases of the composting process and reduced the composting time. In addition, in the insulated bioreactor, a composting temperature of 55–67 °C could be achieved and remained for three days. This was enough time to satisfy the requirement for the destruction of pathogens and reduction of weed seed viability, consequently producing high-quality compost. Insulation increased the overall heat transfer resistance from 0.37 (m^2 °C W^{-1}) of the non-insulated bioreactor to 1.12 (m^2 °C W^{-1}) for the insulated bioreactor; this reduced the heat loss and enhanced compost quality. The active phase can be completed within a short time using the insulated bioreactor. Further studies are required to examine the effect of insulation on bioreactors that have an A_s/V ratio of 4–6 to emphasize the necessity of insulation in this range of bioreactor volume.

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