Title: The Simplified Method for the Assessment of the Potential for Thermal Energy Recovery from the Manufacturing Processes of Mushrooms Compost

Author: Dušan Radojičić, Dušan Radivojević, Ivan Zlatanović, Kosta Gligorević, Milan Dražić, Miloš Pajić

PII: S2210-6707(16)30773-9
DOI: http://dx.doi.org/doi:10.1016/j.scs.2017.03.028
Reference: SCS 625

To appear in:

Received date: 22-12-2016
Revised date: 2-3-2017
Accepted date: 30-3-2017


This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
THE SIMPLIFIED METHOD FOR THE ASSESSMENT OF THE POTENTIAL FOR THERMAL ENERGY RECOVERY FROM THE MANUFACTURING PROCESSES OF MUSHROOMS COMPOST

Dušan Radojičić, Dušan Radivojević, Ivan Zlatanović*, Kosta Gligorević, Milan Dražić, Miloš Pajić

University of Belgrade – Faculty of Agriculture

*Corresponding author: ivan@agrif.bg.ac.rs

Abstract

This study deals with the manufacturing process of compost production, followed by the release of large amounts of heat. The wheat straw and manure of broilers were the basic components of the raw mixture, monitored during the 80 hours period. The simplified assessment method was developed along with suitable mathematical model. The potential for recovery of the heat released to the surroundings was evaluated indirectly based on compost temperature measurements during the one full production cycle. Temperature-time mathematical model was developed and used as time indicator for the analysis of distribution of energy that was generated in exothermic processes. The emissions of N (<1% dry basis) and C through CO2 (~3% dry basis) was neglected in mass balances. During composting treatment material temperatures were in range 80±2°C, making it a reliable heat source of constant temperature. The amount of total generated heat during the 80 hour time period was calculated to be 1325 KJ•10⁶, of which 76.4% was released to surroundings. The specific value of generated heat was 1.32 KJ•g⁻¹ of raw mixture, of which 1.01 KJ•g⁻¹ was available for recovery. The results pointed to the existence of significant amounts of released energy available for recovering.

Keywords: thermal energy, heat recovery, temperature model, compost, mushrooms.

1. INTRODUCTION

According to the European Union (EU) targets for 2020, at least 20% of the energy need in EU must come from renewable energy. The energy content of waste and sustainability of industrial and agricultural processes will be in focus in 21st century (Brebbia et al., 2014). The development of energy recovering technologies became highly desirable (Stehlík, 2009), especially in agricultural production (Shu et al., 2015). The modern agricultural production is energy challenging and in recent years increasingly relies on use of the different forms of renewable energies (Esen and Yuksel, 2013) and wastewater heat recovery potentials (Kretschamer et al., 2016).

Composting of solid poultry manure, by creating mixture of secretions and wheat straws, significantly simplifies the care of manure and represents an efficient solution for various manure problems. Composting is the process of creating a nutritionally and ecologically organic
Fertilizer, with the release of large amounts of heat (Boniecki et al., 2013). The final product of the composting can be a substrate for the seed culture of the mycelium in the production of mushrooms. (Burton and Turner, 2003). In this case, wheat straw and manure of broilers are the basic components of the raw compost mixture. The quantity of straw used for the composting process affects the ratio of C:N (carbon: nitrogen ratio) (Petric et al., 2009). This ratio should be in the range of 18:1 to 20:1. The total dry matter content depends on the amount of the straw in mixture, whose content can go up to 40%. (Radivojević et al., 2012). Composting is based on the aerobic treatment of the mixture. The aerobic microorganisms (thermopiles) cause turbulent exothermic reactions and increment in temperature of compost during the organic matter decomposition. During the mechanical treatment in the open air, the maximum achieved compost temperature is in the range 75-85°C (Ahn et al., 2007; Chroni et al., 2009).

The recycling of used compost can be done in many different ways. The building materials insulation properties can be improved by recycling and adding the used compost in to the material (Velasco et al., 2014). Also, compost can be used as substitution for common solid fuels through fluidized-bed combustion of spent compost (Finney et al., 2009) or pelletisation of spent compost (Ryu et al., 2008). The high temperature compost material has features of the steady-state energy source that can be used for heat energy production. The possibilities of recovering the heat ejected with the exhaust air arising from the aerobic conversion of organic waste (Di Maria et al., 2014a and 2014b) as well as use of the power plant for waste heat recovery in stationary applications (Cipollone et al., 2014) were successfully investigated before. The many studies were directed towards exploring the potential of sensible or latent heat recovery released in the process of composting (Sciubba, 2003). Thermodynamic analysis of the energy recovery from the aerobic bioconversion of solid urban waste organic fraction showed that it is possible to couple the bioconversion process with the energy recovery process (Di Maria et al., 2008). The aeration of composting material brings huge amounts of humid air emitted into the environment. The heat recovery from the humid air can be done efficiently with cooling and condensing processes (Vasilyev et al., 2016; Tang et al., 2016) or by designing specific heat exchangers for this purpose (Liu et al., 2011; Gendebien et al., 2013). The comprehensive analysis of the energy and environmental performance of a production system must be done before the efficient utilization and recycling of used compost or waste energy (Bühle et al., 2012).

The data presented in this paper refers to two compost treatments (primary and secondary) which were each built one upon the other. However, the primary compost treatment was in the focus of this research because almost all the heat generated during this treatment was released to the surroundings without control. Therefore, there is an obvious potential for harvesting this dissipated energy. This study deals only with the investigation of the potential to recover the wasted heat without disturbing the composting process. The analysis are directed toward the discovering and modeling the heat dissipation at different stages of manufacturing process. By providing the all necessary information regarding the potential for recovering the heat from this industrial process, this research will be of great use for further energy development and upgrade of process technology and reduction of environmental influence.
2. MATERIALS AND METHODS

The raw mixture was made of solid poultry manure and wheat straw and exposed to open air natural aeration process in bunkers. The properties of raw mixture components are presented in Table 1.

Table 1. The properties of the raw mixture components

<table>
<thead>
<tr>
<th>Mixture component</th>
<th>Mass, t</th>
<th>Moisture content, kg_w/kg_dB</th>
<th>Chemical composition recipe (Amanullah et al., 2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid poultry manure</td>
<td>266</td>
<td>0.665</td>
<td>3.1% N, 3% P_2O_5, 2% K_2O, 0.4% Ca, 0.4% Mg, 0.7% S</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>214</td>
<td>0.202</td>
<td>0.65% N, 0.23% P_2O_5, 1.5% K_2O</td>
</tr>
<tr>
<td>Gypsum</td>
<td>0.09</td>
<td>-</td>
<td>100% CaSO_4·2H_2O</td>
</tr>
<tr>
<td>Water</td>
<td>520</td>
<td>1.0</td>
<td>100% H_2O</td>
</tr>
</tbody>
</table>

According to the compost production technology (Champicomp Ltd., 2017), solid poultry manure and wheat straw were mixed 1:0.8 ratio respectively. The moisture content of wheat straw may vary in range 10-25% due to the open storage conditions. Gypsum was added to the mixture in order to improve its pH properties and reduce ammonia nitrogen losses during composting (Kenner et al., 2014). The mass of added gypsum was neglected in overall mass balance.

Table 2. The properties of the raw mixture and compost product

<table>
<thead>
<tr>
<th>Material</th>
<th>Raw mixture (in)</th>
<th>Compost (out)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m, kg</td>
<td>1000·10^3</td>
<td>500·10^3</td>
</tr>
<tr>
<td>M, kg/kg_dB</td>
<td>0.716</td>
<td>0.704</td>
</tr>
<tr>
<td>m_w, kg_w</td>
<td>716·10^3</td>
<td>352·10^3</td>
</tr>
<tr>
<td>m_dB, kg_dB</td>
<td>284·10^3</td>
<td>148·10^3</td>
</tr>
<tr>
<td>M_V, m^3/m^3</td>
<td>0.4773</td>
<td>0.2347</td>
</tr>
<tr>
<td>Organic C, kg_c/kg_dB</td>
<td>0.4149</td>
<td>0.3847</td>
</tr>
<tr>
<td>m_c, kg_c</td>
<td>11783·1.6</td>
<td>5693·5</td>
</tr>
<tr>
<td>Organic Matter, kg_OM/kg_dB</td>
<td>0.853</td>
<td>0.7833</td>
</tr>
<tr>
<td>m_OM, kg_OM</td>
<td>24225·2</td>
<td>11592·8.4</td>
</tr>
<tr>
<td>Total N, kg_n/kg_dB</td>
<td>0.0145</td>
<td>0.0225</td>
</tr>
<tr>
<td>m_N, kg_N</td>
<td>4118</td>
<td>3330</td>
</tr>
<tr>
<td>pH</td>
<td>5.73</td>
<td>6.18</td>
</tr>
<tr>
<td>C:N</td>
<td>28.6:1</td>
<td>17.1:1</td>
</tr>
<tr>
<td>c, J/kgK</td>
<td>2580</td>
<td>1277</td>
</tr>
<tr>
<td>T, °C</td>
<td>5</td>
<td>40</td>
</tr>
</tbody>
</table>

The properties of the raw mixture and compost was determined using several laboratory methods with repetition to assure accurate average values (Table 2). The moisture content was determined using the oven-drying method (Willits, 1951). The content of the organic matter is determined using the dry ashing method (Peters et al., 2003), by calculating the difference between the mass of dry matter and the mass of ash obtained by annealing the dry matter at 550°C. The content of organic C was determined using the Tyurin method (Angelova et al., 2014) and the content of organic N was determined using the Kjeldahl method (Stoffella and Khan, 2001). The pH value was measured potentiometrically using the pH/mV meter (Peters et al., 2003).

2.1 Compost production
The experiment measurements were conducted at the industrial facility for compost production (Fig. 1) which consists of two facilities for primary and secondary compost treatment. Primary compost treatment was carried out in 6 bunkers (1000 tons of raw compost per bunker) and lasted for 12 days. The volume of single bunker was 1500 m$^3$. The bunker was fully charged with compost material. After 4$^{th}$ and 8$^{th}$ day, the compost was mechanically mixed and rearranged in next bunker. This contributes to the material aeration during the composting process. The exothermic reactions depended on micro-organisms breaking down organic matter into compost. The temperature of the raw material in bunker raised up to 80°C, causing the intensive free moisture surface evaporation into environment and 50% of material mass reduction.

Secondary compost treatment was carried out in 6 pasteurization tunnels (1500 tons of material per tunnel) and lasted for 7 days. The pasteurization process (continuation of the exothermic process that started in bunkers) was performed with full control of compost aeration process (by controlling the amount of tunnel recirculated air) in which the temperature of the material was maintained between 45°C and 50°C, and material mass reduction went down to 30%. The heat released to surroundings during the secondary compost treatment was not considered in this study because of the pasteurization process specifics that could not be disturbed during the production process and corresponding monitoring activities.

2.2 Measuring equipment and accuracy

The temperatures of compost material during primary and secondary treatments were measured with K-type thermocouple probes attached to BTM-4208SD acquisition unit. Probes were
positioned in bunker at 1 meter depth with 5 meters distance between. Temperatures were measured in real time and the reading interval was 10 minutes. Measurement accuracy was ±0.1°C.

2.3 Process monitoring

During the primary compost treatment, compost temperatures were recorded in real time at 3 bunker control points, as well as environmental temperature. Similar temperature profiles were established after each mixing process (Fig.2). It was observed that raw material temperature at the beginning increased rapidly from 5°C to 80°C, and then maintained in range 80±2°C next 3 days until the next mixing process. The process was repeated in a similar manner. All exothermic heat was transferred from the inner layers of the material and released to the surroundings, i.e. wasted.

![Figure 2. Recorded values of the bunker stored compost material temperatures](image)

2.4 Process modelling

The organic matter contained in raw mixture was decomposed aerobically within a biological process which can be represented with the (Eq.1) (Levis and Barlaz, 2013).

\[
\text{Raw mixture + } O_2 = \text{Compost} + H_2O + \langle CO_2 \rangle + \langle NO_x + NH_3 \rangle + \text{Heat}
\]  

(1)

The loss of N through NO\textsubscript{x} and NH\textsubscript{3} was determined by using the properties of the raw mixture and compost (Table 2) and it was less than 1% dry basis, so it was acceptable to be ignored in the mass balance. This negligence can be explained with the presence of thermophiles causing the high composting temperatures. The efficiency of N utilization was supported with the results reported in (Carney, 1996) where NH\textsubscript{3} emission was intensive only just when \( pH > 8.5 \). Similar results were reported in (Hartz, 2009). Based on the difference between the content of the
organic C in the raw mixture and compost (Table 2), the loss of C was determined to be around 6% dry basis, of which only approximately 50% was released to the environment through CO\textsubscript{2}. The estimation of the amount of C released through CO\textsubscript{2} was based on previously published results: \(~50\%\) (Stoffella and Khan, 2001), 39-55\% (Steger et al., 2005), \(~50\%\) (Brunstermann, 2007) and \(~40\%\) (Petric et al., 2009b). The remained amount of the lost C was consumed by bacteria during the microbiology processes along with the 10\% of the initial raw mixture mass. Similar results was reported by (Tiqua et al., 2002) and (Gebeyehu and Kibret, 2013). Therefore, the estimated value of the emission of C through CO\textsubscript{2} was only 3\% dry basis and it was acceptable to be ignored in the mass balance. This approach brought a certain simplifications, but also increased the imprecision of this assessment method.

The mass balance can be described with (Eq.1),

\[
m_{in} = m_{out} + m_{w} + m_{(CO_2)} + m_{(NO_x+NH_3)}
\]

where: \(m_{in}\) - mass of the raw mixture; \(m_{out}\) - mass of the compost, \(m_{w}\) - mass of the water vapor due to the free water surface evaporation process released to the surroundings, \(m_{(CO_2)}\) - mass of CO\textsubscript{2} released to the surroundings; and \(m_{(NO_x+NH_3)}\) - mass of NO\textsubscript{x} and NH\textsubscript{3} released to the surroundings.

The integral energy balance can be described with (Eq.2), introduced by (Robinzon et al., 2000),

\[
\left\langle Q_{m} \right\rangle_{energy\ accumulated\ in\ material} = \left\langle Q_{g} \right\rangle_{energy\ input\ in\ rad \ m} - \left\langle Q_{air} \right\rangle_{energy\ output\ in\ rad \ air} - \left\langle Q_{rad, out} \right\rangle_{energy\ output\ in\ rad \ out} - \left\langle Q_{w} \right\rangle_{energy\ output\ in\ w}
\]

where: \(Q_{m}\) - energy accumulated in material; \(Q_{g}\) - energy generated during the micro-biological exothermic processes; \(Q_{rad, in}\) - total radiation energy input; \(Q_{air}\) - energy removed due to change in enthalpy of the air flowing through the material; \(Q_{rad, out}\) - radiation energy output; and \(Q_{w}\) - heat loss due to water evaporation and heat convection from the pile surface.

Based on (Eq.2), the available energy output can be calculated as difference between the energy accumulated in the material and energy input (Eq.3).

\[
E_{out} = E_{in} - Q_{m}
\]

The energy output represents the available energy that could be recovered with hypothetic heat recovery device of proper efficiency coupled with the composting reactor. The design and performance of such device are not subject of this research. However, the assumption (A1) has been made that that device will be able to prevent a greater amount of radiation energy input and be able to capture a larger part of radiation energy output from/to surroundings. This approach and assumption can be justified with previously applied composting technologies (CH2M Hill,
2013) related with different types of awnings, shields, covers and hoods that are widely used in different types of composting facilities.

The energy accumulated in the material depends on the properties of raw mixture and compost, and can be calculated from (Eq.4),

\[ Q_{\text{in}} = c_{\text{in}} \cdot (m_{\text{in}} T_{\text{in}} - m_{\text{out}} T_{\text{out}}) \]  

where: \( c_{\text{in}} \) - specific heat of the raw mixture; \( T_{\text{in}} \) - temperature of the raw mixture; and \( T_{\text{out}} \) - temperature of the compost. Similar approach was presented by (Angelova et al., 2014; Stoffella and Khan, 2001; and Robinzon et al., 2000).

For the easier discovering the amount of heat generated due exothermic processes, the period between two mixing processes was divided on two periods (Eq.5),

\[ Q_g = Q_{g,1} + Q_{g,2} \]  

where: \( Q_{g,1} \) - energy generated during the first period and used only for heating the material after mechanical mixing process and \( Q_{g,2} \) - energy generated during the second period when compost reached the steady state temperature condition at \( T_{c,\text{max}} \) and spent on intensive free surface water evaporation. The temperature profiles recorded during primary compost treatments was found to be highly similar after each process repetition. This was caused by earlier interruption of composting process with mechanical mixing. Also, the production technology requires that the product is not fully composted at the end of the process.

The change of the compost temperature in time, between two mechanical mixing processes, can be mathematically modeled (Fig.3) by fitting the appropriate curve. The best fit is represented with the (Eq.6),

\[ T_c(\tau) = a + b\tau + c\tau^{1.5} + d\tau^2 + e\tau^3 \]  

where: \( \tau \) – time (hours); a, b, c, d, and k – numerical constants. The model equation is valid within time interval \( 0 \leq \tau \leq 80 \) hours. The model equation was deduced by using the SYSTAT® TableCurve 2D software at a 95% confidence. The best model was held on basis of the highest coefficient of determination \( r^2 = 0.99479 \) and the lowest standard error \( \text{Std Err} = 2.82454 \) values. According to the (Eq.6), the steady temperature state was reached approximately 32 hours after mixing process and this time was marked as the beginning of the second period. This approach is not entirely justified because these two periods are continuous and strictly linked, however separate consideration of these processes makes the assessment of available heat simpler.
Therefore, with sufficient accuracy $Q_{x,1}$ can be determined by assuming (A2) that during the time period $0 < \tau < 32$ there was no raw material mass reduction due to free water surface evaporation (Eq.7),

$$Q_{x,1} = m_{in} c_{in} (T_{c,\text{max}} - T_{in})$$

where: $T_{c,\text{max}} = 80^\circ C$ - highest temperature of the raw mixture at the end of the first period and $T_{in}$ - temperature of the raw mixture at the beginning. The assumption A2 can be justified with a fact that there was obvious similarity between drying process and composting process, i.e. the material temperature at the beginning of the both processes in both cases increased up to the value when intensive water evaporation started.

The correlation (Eq.8) was used for calculation of the material specific heat during the primary compost treatment (Mudhoo and Mohee, 2007),

$$c_{in} = 1000 \cdot \left( -15.79 \cdot M_{V}^2 + 12.53 \cdot M_{V} + 0.189 \right)$$

where: $M_{V}$ - volumetric moisture content (Table 2). The specific heat was considered constant during the time period $0 < \tau < 32$ hours. Similar approach was applied by (Ranasinghe et al., 2002 and 2003). During the time period $32 \leq \tau < 80$ hour moisture content decreased due to the intense free water surface evaporation. The reduction of the moisture content during this stage was very similar to the process of convective drying of the material at a drying temperature.
Similar results were reported by (Mudhoo and Mohee, 2007), where the compost mass decreased exponentially in time. The energy $Q_{g.2}$ was used to heat the fresh air up to the temperature $T_{c,max}$ when the dying process of the compost material occurred (Assumption A3).

The air used for aeration process was heated during the passage through the warm compost material. It may be assumed that the air layers directly above the material reached material temperature. However, it was more likely that this temperature was slightly lower because exothermic generated heat was higher in inner layers of the material where it reached its maximum. The generated energy was calculated indirectly by using the (Eq.9) properties of aerating air and water,

$$Q_{g.2} = m_a(h_{a,\text{out}} - h_{a,\text{in}}) + m_w h_w = m_w \left[ \frac{h_{a,\text{out}} - h_{a,\text{in}}}{x_{a,\text{out}} - x_{a,\text{in}}} + h_w \right]$$

where: $m_a$ - mass of the air used for material aeration; $h_a$ - specific enthalpy of the air (in/out); $x_a$ - humidity ratio of the air (in/out); $m_w$ - mass of the evaporated water; and

$h_w = 334.9 \text{ kJ/kg}$ - specific enthalpy of the water at $T_{c,max}$ and atmospheric pressure $p_{atm} = 1\text{ bar}$. Similar methodology was applied by (Sundberg, 2005).

The temperature and relative humidity of the air entering the material was adopted from the hydrometeorology statistical data for experimental site geolocation (N 44.739337, E 20.884380) for 30 year averages (Table 3). The humidity ratio of the air entering the material was found to be $x_{a,\text{in}} = 0.00611 \text{ kg/kg}$ and enthalpy was $h_{a,\text{in}} = 28 \text{ kJ/kg}$, based on the overall annual average (Year). Accordingly, the humidity ratio of the air varied between $0.00325 \leq x_{a,\text{in}} \leq 0.0107 \text{ kg/kg}$, i.e. with the specific enthalpy of the air varied between $9.6 \leq h_{a,\text{in}} \leq 50.3 \text{ kJ/kg}$.

| Table 3. Meteorological elements for the specific location (RHSS, 2017; Radičević et al., 2009) |
|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| **Temperature, °C**            | Jan    | Feb    | Mar    | Apr    | May    | Jun    | Jul    | Aug    | Sep    | Oct    | Nov    | Dec    | Year   |
| Average max.                   | 4.6    | 7.0    | 12.4   | 18.0   | 23.5   | 26.2   | 28.6   | 28.7   | 23.9   | 18.4   | 11.2   | 5.8    | 17.4   |
| Average min.                   | -1.1   | -0.1   | 3.7    | 8.3    | 13.0   | 15.8   | 17.5   | 17.6   | 13.5   | 9.0    | 4.2    | 0.2    | 8.5    |
| Normal values                  | 1.4    | 3.1    | 7.6    | 12.9   | 18.1   | 21.0   | 23.0   | 22.7   | 18.0   | 12.9   | 7.1    | 2.7    | 12.5   |
| **Relative humidity, %**       |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Average                        | 78     | 71     | 63     | 61     | 61     | 63     | 61     | 61     | 67     | 71     | 75     | 79     | 68     |

The air leaving the material was assumed (A4) to have humidity ratio at saturation at the temperature $T_{c,max} = 80^\circ\text{C}$ and atmospheric pressure $p_{atm} = 1\text{ bar}$. The humidity ratio of the air leaving the material was found to be $x_{a,\text{out}} = x_{a,\text{sat}} = 0.5469 \text{ kg/kg}$ with the enthalpy $h_{a,\text{out}} = h_{a,\text{sat}} = 1528.7 \text{ kJ/kg}$ (ASHRAE, 2013). This assumption allowed the aerating air to absorb moisture from the material with the maximum theoretical potential.
3. RESULTS AND DISCUSSION

The raw mixture and compost properties presented in Table 2 was used for solving the mathematical model equations. The mass flow of the material was calculated for the time period of 80 hours. The results obtained for the specific heat agrees well with the similar results reported by (Ahn et al., 2007; Mudhoo and Mohee, 2007; Kazunouri, 2009; Ahn et al., 2009; and Barrington, 2002). Table 4 shows the calculation results for energy balance based on the model equations.

Table 4. Calculation results which refer to 80 hours period in bunker

<table>
<thead>
<tr>
<th>Energy balance variables</th>
<th>%</th>
<th>Heat, KJ•10^6</th>
<th>Specific heat, KJ•g^-1 of raw mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy input (generated)</td>
<td>100</td>
<td>1325</td>
<td>1.32</td>
</tr>
<tr>
<td>0&lt;τ&lt;32 hour</td>
<td>14.5</td>
<td>193.3</td>
<td>0.2</td>
</tr>
<tr>
<td>32≤τ&lt;80 hour</td>
<td>85.5</td>
<td>1132</td>
<td>1.13</td>
</tr>
<tr>
<td>Energy accumulated in material</td>
<td>23.6</td>
<td>312.7</td>
<td>0.31</td>
</tr>
<tr>
<td>Energy output (available)</td>
<td>76.4</td>
<td>1013</td>
<td>1.01</td>
</tr>
</tbody>
</table>

The amount of total generated heat during the 80 hour time period was calculated to be 1325 KJ•10^6, of which 76.4% was released to surroundings. The specific value of generated heat was 1.32 KJ•g^-1 of raw mixture, of which 1.01 KJ•g^-1 was available for recovery. The energy accumulated in the material was found to be 0.31 KJ•g^-1 of raw mixture and this energy was being transferred along with the material to the composting tunnels, i.e. to the second phase of the compost production. The heat loss due free surface water evaporation was found to be good source of heat, by taking 85.5% of total generated heat.

The agreement with the results found in the literature was satisfactory (Table 5). The agreement of the results found in literature and the own results was better in the domain of the minimal specific heat values. This can be explained with the fact that the composting process in bunkers was not fully completed by the end and that process was frequently interrupted with mechanically mixing.

Table 5. Comparison with other results found in literature

<table>
<thead>
<tr>
<th>Specific heat, KJ•g^-1 of raw mixture</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3-1.8</td>
<td>(Guljajew and Szapiro, 1962)</td>
</tr>
<tr>
<td>1.01</td>
<td>Own results</td>
</tr>
<tr>
<td>1.136</td>
<td>(Klejment, 2008)</td>
</tr>
<tr>
<td>1.7-6.3</td>
<td>(Bernstad, and La Cour, 2012)</td>
</tr>
<tr>
<td>7-11</td>
<td>(Irvine et al., 2010; Steppa, 1988)</td>
</tr>
<tr>
<td>15-19.7</td>
<td>(Weppen, 2001; Ahn et al., 2007; Lee et al., 2014)</td>
</tr>
</tbody>
</table>

Bearing in mind all the previously mentioned assumptions, it may be considered that, in the reality, the heat available for recovery will be lower than calculated amount of heat. The efficiency of the process of heat recuperation will depend on the efficiency of the reactor itself, i.e. of device performing this operation (heat exchanger, water vapor condensing device, etc.) as well as of insulation properties of bunker walls and all related heat losses. According to
(Themelis, 2005) only 13.4% of the heat generated within a compost pile is contained in the hot air, while 63% of the energy balance is in the hot water vapor, with the remaining heat being lost from the pile through natural convection and radiation (Smith and Aber, 2001). Similar researches showed that 60% of the heat was conducted from their reactor surfaces even though they were well insulated (Weppen, 2001; Bach et al., 1987). In small-scale composting reactors, surface cooling by conduction was the dominant way of extracting the heat. However, when surface cooling is limited, the major heat transfer process is by airflow. Both sensible heating of dry air and latent heat from water evaporation account for this heat transport. In large-scale reactors 4-11% of the heat dissipated through surface and walls, while the rest was removed with the air (Hogan et al., 1989). A limited number of experimental studies on direct and indirect methods of compost heat recovery have been reported, showing the great potentials for utilizing heat produced by composting process. (Zhao et al., 2015).

4. CONCLUSION

This research was about the investigation of the potential to recover the heat released to the surroundings, during the primary stage of mushroom compost production, without disturbing the composting process. The simplified assessment method was developed along with suitable mathematical model. The energy output available for heat harvesting was estimated indirectly through the generated heat assessment. Mathematical model of the compost temperature change in time was used for the analysis of generated heat distribution during the composting process. It was observed that there was great similarity between composting process and drying process methodology, whereby the exothermic heat was used for heating the material during the entire duration of the process. The composting technology specifics included earlier termination of the composting process and frequent material mixing. As a result of such production technology, the emissions of N (<1%) and C through CO2 (~3%) could be neglected in mass balances.

There was an obvious potential for harvesting this dissipated energy, because almost all the heat generated during this treatment was released to the surroundings without control. The amount of total generated heat during the 80 hour time period was calculated to be 1325 KJ·10^6, of which 76.4% was released to surroundings. The specific value of generated heat was 1.32 KJ·g^-1 of raw mixture, of which 1.01 KJ·g^-1 was available for recovery. The agreement of the results found in literature and the own results was better in the domain of the minimal specific values. By comparing own results with the similar studies found in literature, it may be concluded that there is a possibility to recover significant amount of wasted heat depending on the type and efficiency of the reactor.

This assessment method weak points are assumptions (A1 to A4) that have been made. The model presented in this paper is meant to be simple and fast, and those facts increase possibility of error appearance itself. Therefore, the accuracy obtained is sufficient for discussed theoretical and practical applications.
ACKNOWLEDGEMENT

Authors are grateful to Ministry of Education, Science and Technological development of the Republic of Serbia for funding this research (in frame of project TR 31051) and company Champicomp Ltd. Serbia for participating in this research.

NOMENCLATURE

A assumption, 1,2…
a, b, c, d, k numerical constants, -
c_p specific heat capacity, J/kgK
E energy, J
h specific enthalpy, J/kg
m mass, kg or t
M moisture content, kg/kg
M_v volumetric moisture content, m^3/m^3
p pressure, Pa
Q heat, J
r^2 coefficient of determination, -
StdErr standard error, -
T Temperature, °C
τ time, hour

Subscripts
in input
out output
w water
g generated
c compost
max maximum
1, 2 parts of generated heat
a air
atm atmospheric
sat saturated
rad radiation

REFERENCES


Hartz, T. (2009). Compost use: opportunities and limitations. Soil Fertility Management, Division of Agriculture and Natural Resources, University of California, USA.


Production technology of Champicomp Ltd. Serbia (2017),
http://www.champicomp.rs/production.html
Doctoral thesis at Deparment of chemical and process engineering, University of Canterbury, New Zealand.


• The potential for recovery of the heat released to the surroundings was evaluated indirectly based on compost temperature measurements during the one full production cycle.
• Temperature-time mathematical model was developed and used as time indicator for the analysis of distribution of energy that was generated in exothermic processes.
• The specific value of generated heat was 1.32 KJ•g⁻¹ of raw mixture, of which 1.01 KJ•g⁻¹ was available for recovery.
• The heat loss due free surface water evaporation was found to be good source of heat, by taking 85.5% of total generated heat.