Investigation of heat flux intensity during composting of organic wastes

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Abstract. The authors present a three-dimensional model of organic agricultural waste, built on the basis of truncated cone. The movement of organic waste energy is modeled using a modified heat transfer equation, which includes volumetric heat capacity, chemical oxidation, and biological growth. Moreover, they carried out the analysis of sensitivity parameter with the aim of predicting temperatures close to those observed in composting of organic waste.

1. Introduction

The current system of agricultural waste management in the country in recent years requires significant changes and using of cost-effective domestic biotechnologies [1]. According to analysts, in Russia, about 150 million tons of waste per year are produced in animal husbandry and poultry farming, and about the same amount is produced when growing fruits and vegetables, that is a serious threat to the environment due to high toxicity, deterioration of storage facilities, untimely waste collection and removal to disposal and disinfection facilities [2]. The reason for the low provision of agricultural enterprises with modern systems for storage and processing organic waste is the huge capital costs for their building and reconstruction. With the growth of import substitution [3], these problems become more intense, while no more than 25% of waste is recycled.

The issues of waste ecologization in world practice acquire increasing economic value, since their processing with a low level of resource and energy costs directly affects the prime cost of manufactured secondary products [4]. Disposal of organic agricultural waste in Russia is a necessity rather than a business, and only producers and ecologists are concerned about this issue, while abroad waste has long been profitable. However, in the near future, the situation may change dramatically – it became possible to clean farmland, enriching it with useful organic substances of its own production, eliminating the enormous cost of expensive mineral fertilizers [5]. The introduction of new specialized
equipment will rationalize biotechnological processing of agricultural waste, thereby contributing to the cost-effective production of biologically active organic fertilizers from secondary raw materials in the Russian Federation, the cost of which will decrease by about 2-2.5 times. Nevertheless, significant progress in the field of waste recycling in the absence of working capital for agricultural producers can be achieved only by attracting investments from large companies using modern technologies obtained in results of relevant scientific research.

2. Research methods

The most common technology for processing organic waste is using it as fertilizer by a process of composting. Such a system of organic waste biological decomposition is an alternative for organic solid waste processing, since this process allows to reduce the volume of organic materials to be disposed [6]. Therefore, industrial compost heaps have become subjects of research and mathematical modeling, some of these models have focused on the phenomenon of spontaneous combustion, in which heating refers to the oxidation of organic matter and biological activity. The constant temperature in these models was predicted in the range from 350 to 530 K and required maintenance of this state for 26 to 31 weeks.

It is known that organic waste contains solid particles and air, therefore, this system can be modeled as a two-phase porous medium. Heating of organic waste makes it possible to reach the energy balance based on the Fourier heat equation, that is modified using additional conditions for calculation: heat from oxidation of organic matter, as well as one of biological processes. The above listed effects are calculated using the Arrhenius equation. Also, effective thermophysical properties are determined for a two-phase system taking into account the organic waste material, which is the solid part, and the air enclosed in the pores inside the solid phase corresponds to the quantitative content of voids or porosity of the substance [7].

\[
(\rho C)_{eff} \frac{\partial T}{\partial t} = k_{eff} \nabla^2 T + (1 - \varepsilon) Q_c \rho_c A_c \exp \left( \frac{-E_c}{RT} \right) + (1 - \varepsilon) Q_b \rho_b \left( 1 + A_2 \exp \left( \frac{-E_2}{RT} \right) \right)
\]

\[
k_{eff} = \varepsilon k_a + (1 - \varepsilon) k_c
\]

\[
(\rho C)_{eff} = \varepsilon \rho_a C_a + (1 - \varepsilon) \rho_c C_c
\]

Expression (1) is the Fourier heat equation, where the second term on the right side corresponds to the fraction of heat from the oxidation of organic substances, and the third term is calculated as the fraction of heat from the biological process. Both expressions are formulated as the Arrhenius equation, where the temperature dependence is clearly expressed.

\[
k = A_1 \exp \left( \frac{-E_1}{RT} \right)
\]

The values of the parameters are given in table 1.

| Table 1. Parameters used in equations (1-3). |
|---------------------------------------------|
| Parameter                                   | Symbol | Value  | Parameter | Symbol | Value  |
| Cellulosic oxidation factor                 | $A_c$  | $1.8 \cdot 10^5$ s$^{-1}$ | Heat capacity of air | $C_a$  | 1005 J kg$^{-1}$K$^{-1}$ |
| Oxidizing biomass growth factor             | $A_1$  | $2 \cdot 10^6$ s$^{-1}$ | Heat capacity of cellulosic material | $C_c$  | 3320 J kg$^{-1}$K$^{-1}$ |
| Slowdown factor for biomass                 | $A_2$  | $6.86 \cdot 10^{30}$ | Activation energy of | $E_c$  | $1.1 \cdot 10^6$ J |
Sidhu [8] used two-dimensional geometry to model a compost heap of size 44 m by 11 m and 80 m by 20 m; in another study, he used various variations with height / length ratios as $1/4$, $1/8$, for these systems he predicted a temperature in the range of 350-380 K. Morag and Zambra [10] have a different geometry, he used a rectangular prism of 9.2 m by 6 m by 3 m, and after 31 weeks of state forecasts, the temperature was 528.26 K. Given that in conventional compost systems the optimal growth conditions for thermophilic microorganisms are achieved at temperatures in the range of 313-343 K [11] and the required compost time is 40-90 days. Then, a simulation of the compost heap was presented relying on the geometry of a truncated cone. The energy balance of compost is described in equations (1-3); in order to predict the temperature and the time from the data that are observed in conventional compost systems, the parameters were replaced based on the analysis of their sensitivity and experimental data.

### 3. Findings

Geometrically, the presented model is a truncated cone with a radius of 4 m and a height of 3 m; initial state temperature is air temperature; limiting conditions are thermal insulation at the base, and the air temperature for side and upper zones. First, the parameters were introduced, that were described by Sidhu [8, 9], then the temperature was predicted to increase by 0.156 K. To obtain the most accurate predictions in the composting system, it is necessary to analyze the sensitivity of the parameters. Based on the work using equations (1-3) [8-10], the values of the changed parameters were between -50% to +25%.

As a result, using sensitivity analysis tools in the COMSOL MULTIPHYSICS package (figure 1), it was found that $E_1$ and $E_2$ have the highest sensitivity during the first day of the experiment. Over time, their sensitivity gradually decreases. In the parameters $K_a$ and $K_c$, compared with the others, the sensitivity growth is observed over time.

According to the analysis results of the parameters sensitivity, they could be classified as follows:

1) The greatest sensitivity throughout the entire duration of the experiment (100 days) have $K_a$, $K_c$;
2) The dependence of the parameters $E_1$ and $C_r$ is less pronounced;
3) The remaining parameters have a relatively small sensitivity index, approximately considered equal to zero.

The last group is considered as the first part of the Arrhenius equation. According to the studies [12], the activation energy for biomass growth ($E_1$) should be in the range from 42 to 84 kJ (biomass

| Parameter                                      | Value       | Description                                      |
|------------------------------------------------|-------------|--------------------------------------------------|
| Activation energy to increase biomass $E_1$   | $6.86 \times 10^{12}$ | 1 J (biomass mol)$^{-1}$  |
| Activation energy to reduce biomass growth $E_2$ | $2 \times 10^{12}$ | 2 J (biomass mol)$^{-1}$  |
| Exothermicity of the oxidation reaction of cellulose material $Q_c$ | $17 \times 10^6$ | J kg$^{-1}$  |
| Effective air thermal conductivity $k_a$       | $0.026$ | W m$^{-1}$ K$^{-1}$  |
| Effective cellulose thermal conductivity $k_c$ | $0.18$ | W m$^{-1}$ K$^{-1}$  |
| Effective soil thermal conductivity $k_{eff}$  | $1.17 \times 10^3$ | kg$^{-1}$  |
| Air density $\rho_a$                          | $575$ | kg m$^{-3}$  |
| Bulk biomass density $\rho_b$                 | $150$ | k m$^{-3}$  |
and the inhibition energy of biomass growth ($E_2$) should be from 250 to 330 kJ (biomass mol)$^{-1}$, in this case $E_2 > E_1$ since the inhibition of biomass activity is more sensitive to high temperatures than the activity of biomass growth. Johnson [12] proposed replacing $E_1$ (100 kJ (biomass mol)$^{-1}$) with a minimum value (42 kJ (biomass mol)$^{-1}$; starting from the minimum value, $E_1$ increased in the shortest time to an intermediate value of 84 kJ (biomass mol)$^{-1}$, which made it possible to obtain a predicted steady state of temperature close to 400 K. Johnson also replaced $E_2$ with a value of 250 kJ (biomass mol)$^{-1}$, but this replacement did not show a significant effect on temperature forecasts. The parameters of the solid phase ($K_a, E_c, A_1, \rho_c, Q_c, C_c$) remained without any changes, since most of them are known values for organic waste used in agricultural compost production.

Figure 1. Graphs of the parameters sensitivity dependence on time (d): a) parameters $K_a, K_c, C_c, C_a, E_c, E_2, A_1, A_2$; b) parameters $Q_c, Q_b, A_2, E_1$

As for porosity, for an optimal composting process, the porosity should be between 32 and 36%; in previous studies [12-14] the authors used the porosity of 30%, a change in the value of this parameter will directly affect the effective volumetric heat capacity ($\rho C_v$)$_{eff}$, as well as the effective thermal conductivity $K_{eff}$, and the porosity of 0.34 leads to the creation of a product where $(1 - \varepsilon)\rho_bQ_b\rho_b$ decreases by 15% compared to others known experimental values. Finally, the values for $\rho_b$ and $Q_b$ were corrected in order to make temperature prediction according to the experimental data of observation. The data of the main changes in the parameters are presented in table 2. Having launched the model into production and using the values (table 2), it was possible to predict the value of the stable temperature of 342.66 K.
Table 2. Data on parameter changes.

| Parameter | Old value     | New value     | Changes   |
|-----------|---------------|---------------|-----------|
| \( A_1 \) | \( 2 \cdot 10^6 \, \text{s}^{-1} \) | \( 1 \cdot 10^6 \, \text{s}^{-1} \) | -50%      |
| \( \varepsilon \) | 0.3 | 0.34 | +13%      |
| \( E_1 \) | \( 1 \cdot 10^5 \, \text{J(biomass mol)}^{-1} \) | \( 8.4 \cdot 10^4 \, \text{J(biomass mol)}^{-1} \) | -16%      |
| \( E_2 \) | \( 2 \cdot 10^5 \, \text{J(biomass mol)}^{-1} \) | \( 2.5 \cdot 10^5 \, \text{J(biomass mol)}^{-1} \) | +25%      |
| \( \rho_b \) | 575 kgm\(^{-3}\) | 546 kgm\(^{-3}\) | -5%       |
| \( Q_b \) | \( 6.66 \cdot 10^6 \, \text{Jkg}^{-1} \) | \( 6.327 \cdot 10^6 \, \text{Jkg}^{-1} \) | -5%       |

As soon as the model worked under stable conditions, a short-term simulation was performed within one day; temperature forecasting for 20 and 60 days is demonstrated in figure 2, that shows how heat is released from the center of the system to the boundaries.

![Figure 2](image)

**Figure 2.** Temperature and heat flux intensity forecasting: a) for the period of the 20-day composting process; b) for the period of the 60-day composting process.

4. Conclusions

With the described modeling approach, satisfactory forecasts were achieved, similar to those observed in conventional compost systems. As a result of the studies was found that it takes no more than 40-90 days to obtain temperatures in the range 313 ÷ 343 K. The received predictions also showed that the composting process shows hypersensitivity to such parameters as: activation energy for organic waste oxidation, activation energy for biomass growth. The average sensitivity affects such parameters as: increase in biomass oxidation coefficient, porosity, compost thermal conductivity, formation of biological heat and biomass density. However, having obtained the positive results, it should be recognized that when developing a model that is as close as possible to the actual conditions of compost systems, it is desirable that the following parameters are taken into account: humidity, pH, volume change due to poor material decomposition; aside from that, in conditions of increased sunlight, energy balance should also include the terms radiation and heat absorption.

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