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Parameter Optimization for the Maximum Conversion of Organic Matter in Composting Process

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ABSTRACT
In this paper, the optimization of process parameters for the composting process in a batch reactor was performed. Optimized process parameters are airflow and the initial moisture content. The objective function for the optimization problem the maximization of degradation of organic matter is selected. The mathematical relation for the objective function was derived from experimental data and data obtained by numerical simulations. The experimental data of variables were fitted using the multiple regression analysis and found it was statistically significant.Experimental data include a wide range of values for airflow and initial moisture content, which give a maximum degradation of organic matter of 50.1% for a process that lasts (the longest) continuously for 23 days. The optimization problem was solved by applying nonlinear optimization within the Matlab programming package. The obtained optimum values of airflow and moisture content are 0.296 m3/(kgom·h) and 61.6%, respectively. Verification of the process for optimized process parameters was performed in the pilot batch reactor with controlled conditions (SD + 5% of the maximum conversion of organic matter).
KEYWORDS: Mathematical modeling, numerical optimization, process parameters, composting.

I. INTRODUCTION

The collection and disposal of waste are necessary, both for hygienic and space reasons, because large amounts of solid waste occupy enormous areas [1]. Disposal of organic waste is necessary, considering the population growth and speed of urbanization, which leads to the generation of large quantities of waste in the world [2]. According to ecological laws, the composting process is a key process in the waste management hierarchy and plays a major role in reducing the volume of biodegradable solid waste [3]. For the above reasons, it is necessary to speed up the processing of municipal solid waste, in proportion to the amount of newly-generated waste. Therefore, it is important before the beginning of the composting process, to determine the waste composition (especially the nitrogen and carbon contents, moisture, but also other parameters such as pH and electrical conductivity) and to establish the proportion of different waste types for obtaining the desired C/N ration [4]. After that, it is necessary to obtain optimal values of key process variables as initial moisture content, airflow, etc. The feasible composting condition may avoid leachate production, thus achieving the success of the composting process [5].

Mathematical modeling and optimization of process and process parameters for the composting is the key to accelerating the process in order to reduce the accumulation of waste at the landfills. The composting process can be characterized as a sustainable waste management method [6] and obtained compost can be used for fertilization and conditioning of soil [7, 8]. In municipal waste composting facilities, only green waste from parks and gardens is currently being used. Thus, it can be appreciated that the utilization of food waste through composting is insignificant [9].

For the study of composting mechanisms, and for the composting kinetics research, laboratory and pilot reactors of different constructions are used. Mathematical models can serve as a basic tool for faster and better process design and system analysis [10]. Mathematical modeling of the process affects the reduction of the need for performing expensive experiments, better understanding, and control and process optimization is

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achieved. By numerical and experimental optimization, as well as numerical simulations of the composting process, the optimum values of key parameters such as C/N ratio, pH value, moisture content, temperature, aeration rate, etc. are determinate. Also, it comes to important findings of the influence of various additives that promote aeration or acceleration of the process in the initial phase, thereby reducing the duration of the overall process. Researchers who dealt with the numerical optimization of the composting process have optimized the costs of designing and operating bioreactors, then the consumption of energy and the emission of harmful gases [11]. Some authors performed experimental optimization by performing a large number of experiments [12-16]. Also, in the case of optimization of process parameters, the researchers performed experiments in reactor systems of different dimensions, from laboratory to pilot scale. Several researchers have given optimal values for moisture content [17, 18]. This value ranges from 55-60%. Modeling of the composting process [19] began in the 1970s, so in the course of forty years, there were several hundred papers that dealt with this issue. However, only a few researchers dealt with the optimization of process parameters for the composting process in reactor systems. The reason for this is fact that the mathematical models which are credibly describing the composting process consist of a large number of nonlinear differential and algebraic equations, which represents a real challenge and requires knowledge of the process itself, understanding physicochemical processes, knowledge of mathematical modeling and programming. Research concerning the numerical optimization of the composting process can be found in the literature [11,20-27]. In a few papers Keener [11] investigated the influence of the design of the composting system on the stability of the final compost, by reducing the cost of the process itself. They used data from a large number of experiments along with multiparameter kinetic models. Xu et al. [26] developed a model for municipal waste management under uncertainties, based on optimization and linear programming. The model carries out simultaneous costing, cost variability, and risk of restrictions. Similar research was carried out by Proietti [27] wich are taking into account the physicochemical parameters in order to obtain as high-quality compost as possible. Abdullah et al. [22] optimized the ratio of different types of waste for the composting process using a simplex-centroid mixture design method in order to achieve optimum values for the initial moisture content and the C/N ratio. Similar to the previous authors, Cabeza et al. [23] have optimized the proportion of municipal solid waste and residues from leguminous plants in the process of co-composting. Several authors dealt with the optimization of process parameters in the way that a large number of numerical simulations were performed, by varying the parameters at certain intervals that have a physical meaning for the composting process [28,29]while Iqbal [25]optimized process parameters performing Box-Behnken, after response surface methodology (RSM). For the response variables, the moisture content and C/N ratio were selected. A few authors also research the influence of initial moisture content and airflow on the composting process [30].

Moisture content is a very important parameter for the composting process. In the case of a non-controlled process, moisture content can become a limiting factor. Excess water interferes with oxygen access, while low water content limits the diffusion of soluble molecules and reduces microbiological activity. Aeration in excess air is usually not harmful to the composting process, but in this case, it is difficult to maintain optimum temperature, and excessive moisture evaporation or substrate drying may also occur. The aim of this paper is to optimize key process parameters that are important for the beginning and flow of the process. Accordingly, the selected process parameters were the initial moisture content in the material and the airflow in the batch reactor.

II. MATERIALS AND METHODS

Experimental protocol

During the experiment, an organic fraction of municipal solid waste (OFMSW), poultry manure, sawdust, and waste yeast and waste acidity from the brewing industry was used. Physico-chemical characteristics of the materials are shown in Table 1. Composting was performed in pilot rectors, 57 liters of volume. Reactors are specially designed and equipped with temperature sensors at four levels in reactors (three levels and free air space, FAS). The temperature was measured every half hour. During the experiments, the concentrations of carbon dioxide and oxygen, organic matter content, moisture content, pH value, and electrical conductivity are measured at three levels in the reactor every day. Gas concentrations are additionally measured at the exit of the rector. The confirmation experiment lasted seventeen days and the mass of organic matter was measured atthree different heights in the reactor.

TABLE 1 Physico-chemical characteristics of composting materials

Material	Water content (% w.b.)	Organic matter (% d.b.)	pH	Electrical conductivity (dS m^{-1})	C/N
OFMSW	72.44	88.17	6.70	1.790	52.73
Poultry manure	77.03	75.13	7.53	2.317	5.83
Sawdust	10.03	99.90	5.31	0.240	77.19
Waste yeast from the brewing industry	95.61	91.55	6.46	2.795	21.19
Waste kieselguhr from the brewing industry	69.06	10.47	5.39	0.220	11.36

w.b. wet basis, d.b. dry basis

Further details of the experiment and the performed analyzes were given in the literature [31].

Mathematical modeling and optimization

As the most important variables of the state for the composting process are solid-liquid temperature, moisture content, and oxygen concentration (airflow). The percentage of organic matter decomposition primarily depends on these variables and therefore the production of carbon dioxide and other gases. With respect to the substrate as a reactant, the reactor can be modeled as a batch. In the mathematical model of the composting process, the basic principles of the process kinetics are represented, and then the processes of mass and heat change in the system consisting of three phases: liquid, solid, and the gaseous phase. Details of the developed model and model constraints can be found in the literature [31].

The rate of composting is expressed as the rate of decomposition of organic matter and can be described using the following expression:

$$\frac{dm_{OM}}{dt} = -k \cdot m_{OM}^{n} \qquad (1)$$

Wherein:

m_{OM} – Mass of organic matter (kg),

t – Time (h),

k – Reaction rate constant (kg^{1-n} h^{-1}),

n – Reaction order (-).

The developed and verified model was used for numerical simulation of the composting process. Based on the data obtained by numerical simulation and data obtained experimentally, the mathematical relation for the conversion of organic matter is dependent on the airflow and the initial moisture content in the material. The experimental data were taken from two experiments with three batch reactors (the physicochemical characteristics of the mixtures at beginning of the process are given in Tables 2 and 3). Experimental data for the conversion of organic matter are shown in figures 1 and 2. The data obtained by numerical simulations were used to obtain a large number of data for mathematical relation with small changes in the airflow and initial humidity content within the literature values.

TABLE 2 Characterization of initial mixtures in reactors (first experiment)

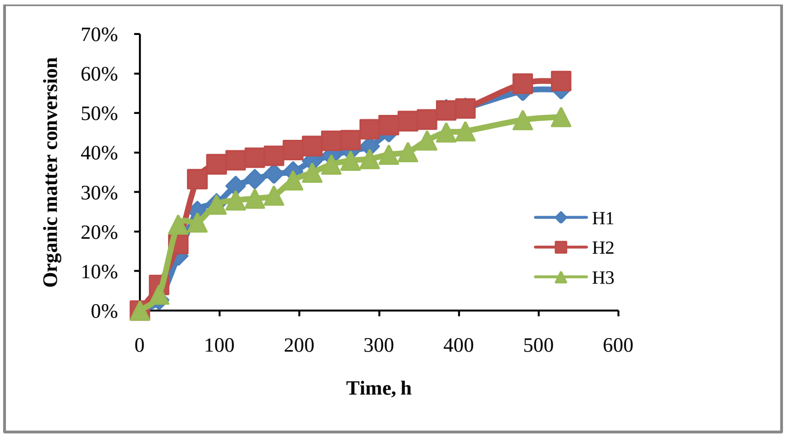
Reactor	Moisture content (% w.b.)	Organic matter (% d.b.)	pH	Electrical conductivity(dS m^{-1})	C/N
1	71.09	90.00	6.72	1.299	71.09
2	63.09	92.96	6.80	1.303	63.09
3	65.65	89.27	6.98	1.280	65.65

w.b. wet basis, d.b. dry basis

TABLE 3 Characterization of initial mixtures in reactors (second experiment)

Reactor	Moisture content (% w.b.)	Organic matter (% d.b.)	pH	Electrical conductivity(dS m^{-1})	C/N
1	67.13	83.09	7.10	0.605	43.70
2	59.53	79.30	7.36	0.638	40.40
3	62.35	82.35	7.32	0.679	34.50

w.b. wet basis, d.b. dry basis



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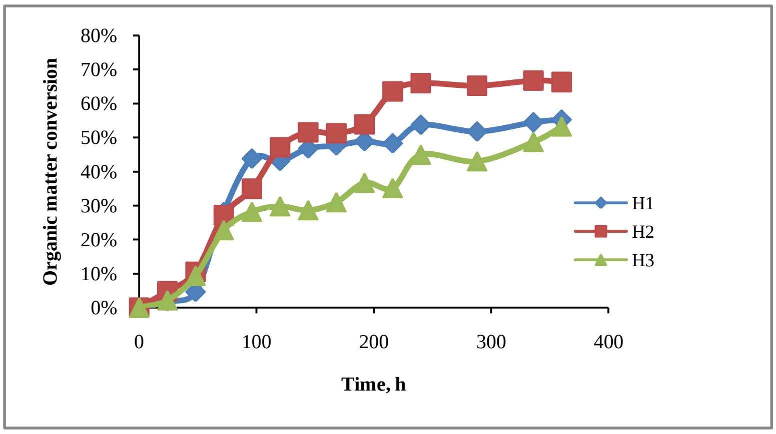

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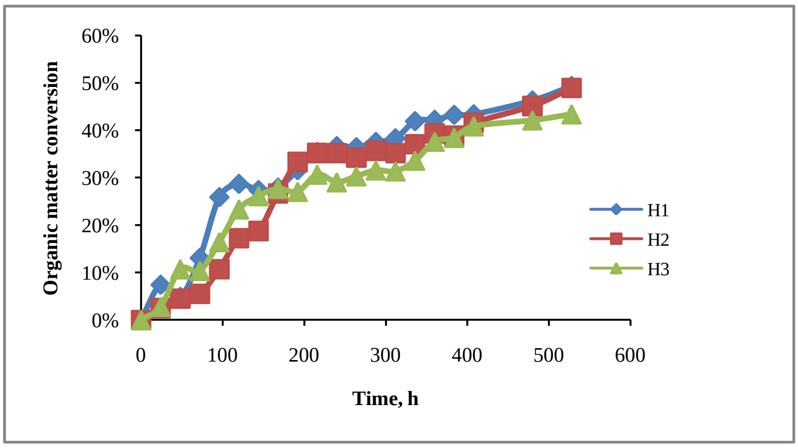

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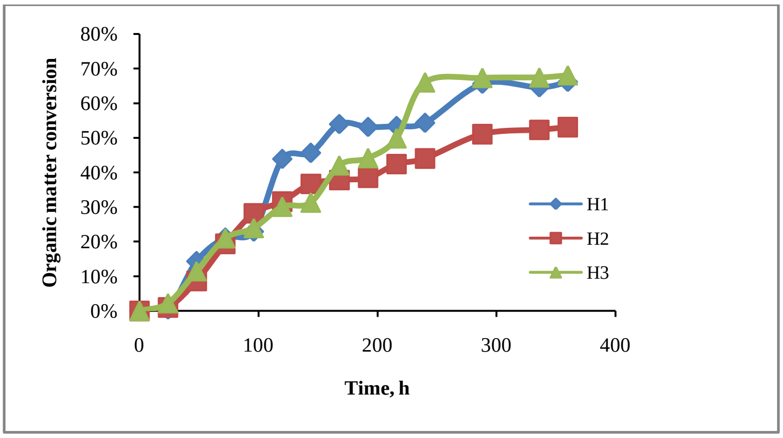
Figure 1. Organic matter coversion for the first experiment in three reactors at three differnet heights



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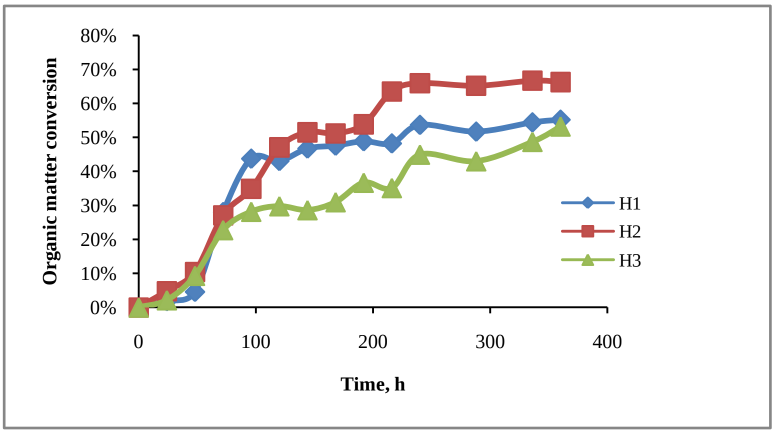

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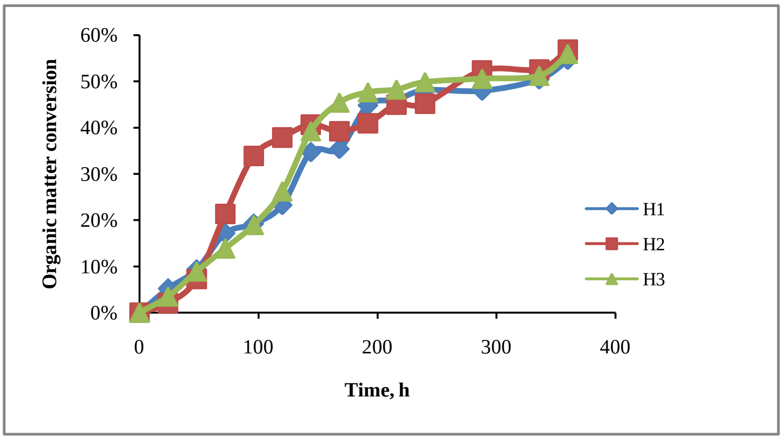

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Figure 2. Organic matter conversion for the second experiment in three reactors at three differnet heights

The objective function is to maximize the conversion of organic matter. The optimization problem was solved by unconstrained nonlinear optimization, so Matlab used several functions to solve it, such as fminserch and fminunc wich are nonlinear programming solvers. Searches for the minimum of a problem specified by: $\min_{x} f(x)$ $f(x)$ is a function that returns a scalar, and x is a vector or a matrix. Solver fminserch is a direct search method that does not use numerical or analytic gradients as fminunc solver.

In order to verify the results of the numerical optimization, an experiment in the batch pilot reactor was performed. Process parameters were adjusted according to the results of the optimization. Table 4 shows the masses of composting mixtures in both experiments. The first experiment lasted 23 days and the second 14 days.

TABLE 4 Mass of substrate in the reactors

	First experiment		Second experiment	
Reactor	**Mass at the beginning (kg)**	**Mass at the end (kg)**	**Mass at the beginning (kg)**	**Mass at the end (kg)**
1	26.1	15.82	25.24	22.10
2	19.5	12.32	24	19.29
3	24.4	17.54	20.5	17.61

III. RESULTS AND DISCUSSION

The functional dependence of the conversion of organic matter on the air flow and the initial moisture content is shown in Figure 3. Based on the function appearance (Fig. 3), it can be assumed that it is a sinusoidal function, so a sinusoidal function (equation 2) is proposed. The selected mathematical expression that was used as an objective function in the optimization problem was fitted in Polymath 6.0 (Michael Elly, 2004, USA) [32] using non-linear regression (mrqmin solver) and showed satisfactory statistics (Table 5). Numerical simulations were performed in the Matlab numerical programming package [33] (MathWorks, R2008a, USA).
The mathematical relation for the organic matter conversion is given by the expression:

$$K = sin\left(\frac{a \cdot X_w{}^b}{Q^c}\right) \cdot d^e + f \qquad (2)$$

Wherein:
- Q airflow($m^3 \cdot (kg_{OT}{}^{-1} \cdot h^{-1})$)
- X_w moisture content (-).

The experimental and simulated data for OM loss was calculated according to the following equation [2, 34]:

$$K = \left(\frac{(\%OM_i - \%OM_e)}{\%OM_i \cdot (100 - \%OM_e)}\right) \cdot 100 \qquad (3)$$

Wherein:
$\%OM_i$ and $\%OM_e$ - organic matter mass at the beginning and end of the process.

The goal of optimization was to maximize the conversion of organic matter into values that have a physical sense (up to 60% for one month of the process). A nonlinear regression determines the values of the constants a, b, c, d, e, and f in relation 2. The relation was obtained by performing a large number of numerical simulations (over 300) with limitations from experimental conditions and literary values. Results of numerical simulation are given in the Appendix.The success of the fits (Fig. 4) is confirmed by the correlation coefficient that is R^2=0.94, which represents a very good value regarding the complexity of the mathematical expression. The moisture content ranged from 30 to 70%, while the airflow varied in the range of 0.12 to 0.3 $m^3 \cdot (kg_{OM}{}^{-1} \cdot h^{-1})$. As previously stated, moisture values below 30 and above 70% lead to slowing down and stopping the composting process [35-37]. When it comes to airflow, the interval gives the values of the conversion of organic substances that have a physical meaning. A small concentration of oxygen in the air leads to slowing down the process and creating anaerobic conditions, while excessive oxygen concentration, or excessive air flow, leads to cooling of the system, and thus anaerobic conditions can be created.The composting process is greatly affected by environmental factors [38](temperature, moisture content, pH, and aeration).

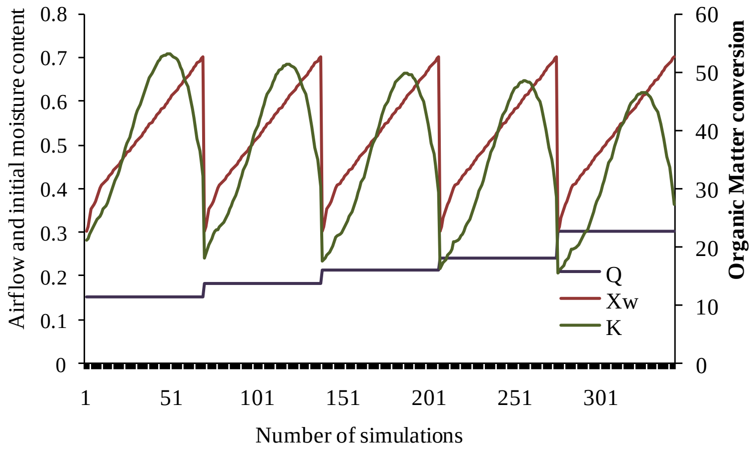


Figure 3 Functional dependence of the organic matter conversion on air flow *($m^3 \cdot (kg_{OT}^{-1} \cdot h^{-1})$)* and initial moisture content (-)

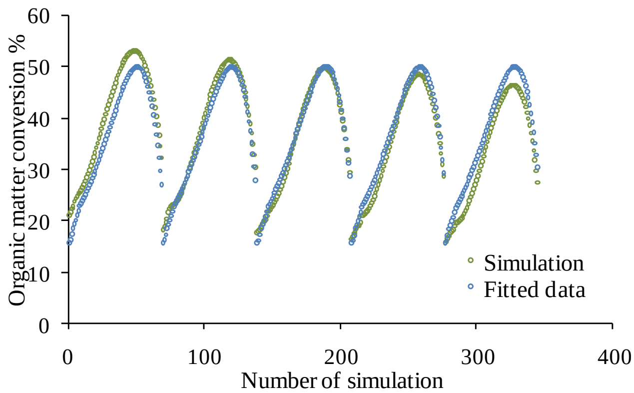


Figure 4 Fitted function for the maximum conversion of organic matter

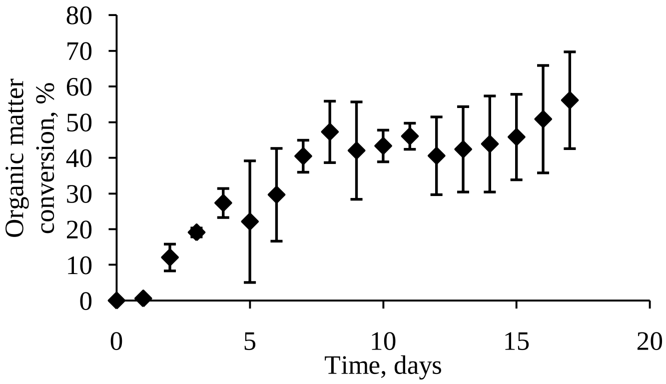
Optimization of any process including the composting process requires a mathematical expression of the objective function. This function would be expressed as a mathematical equation of decision variables and other parameters that minimize or maximize the need for a problem, in addition to a set of constraints [39]. Authors proposed a nonlinear mathematical relation which additionally increases the complexity of solving the optimization problem.

TABLE 5 Confindence intervals for coefficients in eq.2

Variable	Value	95% confidence
a	10.59168	0.256231
b	4.070954	0.049803
c	0.053347	0.014543
d	66.92491	2.020123
e	0.863602	0.006201
f	12.38194	0.553139

For optimization, two optimization solvers in Matlab were used. Both solvers are used for nonlinear programming and optimization of unconstrained multivariable functions by searching for a minimum of the function. Since the goal is to maximize the organic matter conversion, a negative value is assigned to the objective function. Both solvers at the output have given the same values for moisture content and airflow for the „minimum value“, of the objective function. In accordance with the limitations, the obtained optimum values of airflow and moisture content are 0.296 ($m^3/(kg_{OM} \cdot h)$) and 61.6% with the maximum value of organic matter conversion of 50.1%. As can be seen from Table 4, the experimental data used to fitt objective function, indicate different values of organic matter conversion.

Experimental verification of the optimal values of process parameters was carried out in a batch pilot reactor. The mixture that was synthesized in the laboratory, in order to verify the obtained optimal values, consisted of 66.53% OFMSW, 7.97% poultry manure, 11.95% sawdust, and 13.55% waste yeast, the moisture content of the prepared mixture was 62.72% (deviation from optimum 1.8%), while organic matter amounted to 92% on a dry basis. The composition of the mixture used for composting was calculated by the known physical and chemical composition of the components. The composition of used municipal solid waste is the same as the waste composition used in the experiments on which the verification of the developed mathematical model was performed [31]. The mass of the mixture in the reactor at the beginning of the process was 23.2 kg and at the end of the process 17.3 kg. Figure 5 shows the conversion of organic matter obtained experimentally after process variable optimization. Data were measured at three heights in the reactor so that the mean value with standard deviation is shown. The experimentally determined value of the maximum conversion of organic matter was 47.8%. The deviation of the conversion of organic matter between the value obtained by numerical optimization and the value obtained in the pilot reactor is 5%.



Since this is an optimization problem in which besides the mentioned limitations there is a time limit on the conversion of organic matter, in this case, it can be said that the obtained values represent a local minimum depending on the length of the process. The data used in this paper relate to processes that lasted up to a month, which represents the intense phase of the organic matter degradation process. Also, considering the fact that airflow is converted to the mass of organic matter, the obtained values can be interpreted as global optimum. Regardless of the variety of composting compositions, the same values should be obtained. The mathematical form of the functional dependence of the organic matter conversion on the initial moisture content and airflow indicates that the function itself has several local maxima (Figures 1 and 2), making it difficult to talk about a global maximum/minimum of this function. Considering the fact that it is a "live" system which would require the standardization of the mixtures used for the composting process to find a global optimum, these results make a significant contribution in the sense that it is possible to accelerate the process by adjusting the obtained values before the starting the process. As the composition of the composting components is known, it is possible to adjust the ratio and composition of the composting mixture to allow the process to be guided in the desired direction. The optimization models focus primarily on waste management, including the energy system [40]. Most researchers performed the optimization of the composting process focused on waste management and the energy aspect of the process. Lukyanova [41] developed a model based on modeling spatial gradients, which can serve as an excellent tool for optimizing the composting process and designing the plant. The model is verified by data from several reactors, and then on a full-scale plant. Korucu et al. [24] used the MILP, to minimized waste management costs. Since municipal solid waste consists of different types of waste components with different physical and chemical properties, the model is designed to cover all appropriate treatments and methods for the disposal of various waste components. Iqbal et al. [25] have optimized moisture content and C/N ratio in their work. These two parameters were selected as response variables in the second-order polynomial, using multiple regression analysis. The optimum moisture content by these authors is 50%.As quoted by Pilkington et al. [42]it is not possible to define a single optimumfora process since it can change depending on the level of otherfactors.

The current literature is based on optimization models used as technical and economical tools for decision-making that address the strategic and tactical supply chain in waste management [43]. These tactical models are useful for short periods of time (i.e. less than a year), but they offer long-term strategies [44]. Recommendations for optimal airflow intervals (0.05-0.175 L air $kg^{-1}\cdot min^{-1}$) and moisture content (40-55%) in order to maximize the organic matter conversion in the process of co-composting of municipal solid waste and residues of leguminous plants can be found in papers [27,45]. The model was developed to minimize costs by taking into account the optimal physical-chemical parameters of the process. These authors have developed a method for optimizing with the application of a mathematical model for the composting process. The model was tested for several examples.

The advantage of this research is that the presented methodology and models could be used for modeling and optimizing process parameters for mixtures of different compositions, given the fact that the initial moisture content and airflow are converted per mass of organic matter. With small corrections in relation to the initial composition and process conditions, the applied methodology can predict the optimal values of process parameters and the maximum value of conversion for the organic matter.

IV. CONCLUSIONS

The paper proposes a mathematical relation of the functional dependence for organic matter conversion from the initial moisture content in the material and the airflow per kilogramof the organic matter (R^2=0.94). The given relation was used as an objective function in the optimization problem, whereby the optimal values of the airflow and initial moisture content were obtained: 0.296 ($m^3/(kg_{OT}^{-1} \cdot h^{-1})$) and 61.6% respectively. The obtained values represent the local optimum, because the composting process is performed for mixtures of very heterogeneous composition, which gives satisfactory results in controlled conditions (SD 5% for the organic matter conversion batch reactor). These results can help to adjust the process parameters before the composting process is performed and thus allows the maximization of the degradation process of organic matter. The applied methodology in a simple way enables obtaining important process conditions, which shortens the time of preparation and execution of the process.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

REFERENCES

[1]. R. Atalia, M. Buha, A. Bhavsar, K. Shah, IOSR J. Environ. Sci., Toxicol. Food Technol. 9 (2015) 20-29.
[2]. R. Külcü, O. Yaldiz, Ecol. Eng. 69 (2014) 220-225.
[3]. LJ. Brewer, M. Sullivan, Compost Sci. Util. 2 (2003): 96-112.
[4]. C. Ghinea, A. Leahu, Processes, 8 (2020) 302.
[5]. MS. Jain, M. Daga, AS. Kalamdhad, Sustain. Environ. Res. 3 (2020) 302.
[6]. A. Bonoli, A. Dall’Ara, J. Biotechnol. 4 (2012) 499-504.
[7]. R. Külcü, O. Yaldiz, Ecol. Eng. 69 (2014) 220-225.
[8]. A. Zorpas, E. Kapetanios, A. Zorpas, P. Karlis, A. Vlyssides, I. Haralambous, M. Loizidou. J. Hazard. Mater. 1-3 (2000) 149-159.
[9]. National Waste Management Plan. Available online: http://www.mmediu.ro/app/webroot/uploads/files/PNGD_vers5.pdf (accessed on 12 November 2020).
[10]. H.V. Hamelers, Doctoral thesis, Department of Environmental Technology, Wageningen University, Wageningen, (2001).
[11]. H.M. Keener, RC. Hansen, C. In Hoitink, H. A. J., Keener, H. M. Ed Science and Engineering of Composting, Worthington, (1992) 59-94
[12]. A. Trémier, C. Teglia, S. Barrington, Bioresour. Technol. 15 (2009) 3751-3758.
[13]. R. Yañez, P. Bueno, A. Rivera, A. García-Barneto, M.J. Díaz, Waste Manag. 30 (2010) 755-763.
[14]. L. Rodríguez, M.I. Cerrillo, V. García-Albiach, J. Villaseñor, J. Environ. Manage.112 (2012) 284-291.
[15]. V.S. Varma, A.S. Kalamdhad, B. Kumar. Waste Manag. Res. 35 (2017) 101-109.
[16]. X. Song, J. Ma, Gao J, Y. Liu, Y. Hao, W. Li, R. Hu, A. Li, L. Zhang, J. Mater. Cycles Waste Manag. 19 (2017) 496-504.
[17]. S. Kumar, A. Sakhale, S. Mukherjee. Pract. Period. Hazard. Toxic Radioact. Waste Manage. 13 (2009) 179-186.
[18]. C. Sundberg, D. Yu, I. Franke-Whittle, S. Kauppi, S. Smårs, H. Insam, M. Romantschuk, H. Jönsson.Waste Manag. 33 (2013) 204-211.
[19]. S.M. Finger, R.T. Hatch, T.M. Regan, Biotechnol. Bioeng. 18 (1976) 1193-1218.
[20]. H.M. Keener, F.C. Michel, D.L. Elwell, In Proceedings of 2003 Annual International Meeting of the Institute of Biological Engineering, Athens, USA (2003).
[21]. H.M. Keener, K. Ekinci, F.C. Michel, Compost Sci. Util. 13 (2005) 288-299.

[22]. N. Abdullah, N.L. Chin. Bioresour. Technol. 21 (2010) 8205-8210.
[23]. I.O. Cabeza, R. López, M. Ruiz-Montoya, M.J. Díaz, J. Environ. Manage. 128 (2013) 266-273.
[24]. M.K. Korucu, A. Cihan, A. Alkan, I. Ozbay, A. Karademir, Z. Aladag, Waste Manage. Res. 32 (2014) 1073-1082
[25]. M.K. Iqbal, A. Nadeem, F. Sherazi, R.A. Khan, Int J. Environ. Sci. Technol. 12 (2015) 1759-1768.
[26]. Y. Xu, G. Huang, J. Li. Eng optimiz. 48 (2016) 1869-1886.
[27]. P. Proietti, R. Calisti, G. Gigliotti, L. Nasini, L. Regni, A. Marchini, J. Clean. Prod. 137 (2016) 1086-1099.
[28]. E. Avdihodžić, Magistarski rad, Univerzitet u Tuzli, Tehnološki fakultet Tuzla, Tuzla, (2011).
[29]. I. Petric, N. Mustafić. J. Environ. Manage. 161 (2015) 392-401.
[30]. T. Luangwilai, H.S. Sidhu, M.I. Nelson, Food bioprod process. 108 (2018) 18-26.
[31]. E. Paprańanin. Technol. Acta 2 (2019): 9-16.
[32]. *Polymath*, Educational Version 6.0, Michael Elly, The CACHE Corporation USA. (2004)
[33]. MathWorks *Matlab*, Version 7.6.0.324, USA, (2008).
[34]. R.T. Haug, The practical handbook of compost engineering. Lewis Publishers. Boca Raton, (1993) 385-436.
[35]. M.D. Bertoldi, G.E. Vallini, A. Pera, Waste Manag. Res. 2 (1983) 157-176.
[36]. K. Das, H.M. Keener, J. Environ. Eng. 123 (1997) 275-281.
[37]. A.L. Cronjé, C. Turner, A.G. Williams, A.J. Barker, S. Guy, Compost Sci. Util. 12 (2004): 119-129.
[38]. M.E. Silva, L.T. de Lemos, O.C. Nunes, A.C. Cunha-Queda, Waste Manag. 34 (2014): 21-27.
[39]. T. Nakata, D. Silva, M. Rodionov, Prog. Energy Combust. Sci. 37 (2011) 462-502.
[40]. S.C. Torres, J.P. Miranda, C.A. Ubaque, J. Environ. Prot. Sci. 1 (2016) 138-47.
[41]. A. Lukyanova. Master thesis, Department of Mathematical and Statistical Sciences Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta (2012).
[42]. J.L. Pilkington, C. Preston, R.L. Gomes, Ind. Crops Prod. 58 (2014) 15-24.
[43]. C. Fernández, C. Mateu, R. Moral, F. Sole-Mauri, Environ. Model Softw. 79 (2016) 156-166.
[44]. W.F. Cong, E. Hoffland, L. Li, B.H. Janssen, W. van der Werf Plant Soil. 391 (2015) 399-411.
[45]. I.O. Cabeza, R. López, M. Ruiz-Montoya, M.J. Díaz, J Environ Manage. 128 (2013): 266-273.

APPENDIX

Results of the numerical simulations used to develop objective function for the optimization

Airflow	Moisture content	Organic matter conversion	Airflow	Moisture content	Organic matter conversion	Airflow	Moisture content	Organic matter conversion	Airflow	Moisture content	Organic matter conversion	Airflow	Moisture content	Organic matter conversion
0.15	0.3	21.1	0.18	0.3	18.23	0.21	0.3	17.56	0.24	0.3	16.332	0.3	0.3	15.57
0.15	0.31	21.5	0.18	0.31	18.78	0.21	0.31	17.88	0.24	0.31	16.78	0.3	0.31	15.86
0.15	0.33	22.3	0.18	0.33	19.56	0.21	0.33	18.24	0.24	0.33	17.42	0.3	0.33	16.45
0.15	0.35	22.8	0.18	0.35	20.33	0.21	0.35	18.75	0.24	0.35	17.85	0.3	0.35	16.87
0.15	0.36	23.7	0.18	0.36	21.54	0.21	0.36	19.25	0.24	0.36	18.53	0.3	0.36	17.63
0.15	0.37	24.33	0.18	0.37	22.33	0.21	0.37	19.74	0.24	0.37	18.87	0.3	0.37	17.88
0.15	0.38	24.8	0.18	0.38	22.78	0.21	0.38	20.23	0.24	0.38	19.1	0.3	0.38	18.25
0.15	0.39	25.1	0.18	0.39	23.04	0.21	0.39	20.86	0.24	0.39	19.57	0.3	0.39	18.87
0.15	0.4	25.39	0.18	0.4	23.12	0.21	0.4	21.75	0.24	0.4	20.84	0.3	0.4	19.55
0.15	0.405	25.8946	0.18	0.405	23.403	0.21	0.405	21.9482	0.24	0.405	20.9821	0.3	0.405	19.6558
0.15	0.41	26.4526	0.18	0.41	23.7592	0.21	0.41	22.2257	0.24	0.41	21.2064	0.3	0.41	19.844
0.15	0.415	27.0606	0.18	0.415	24.1848	0.21	0.415	22.5783	0.24	0.415	21.5087	0.3	0.415	20.1104
0.15	0.42	27.7153	0.18	0.42	24.6756	0.21	0.42	23.0018	0.24	0.42	21.8846	0.3	0.42	20.4506
0.15	0.425	28.413	0.18	0.425	25.2275	0.21	0.425	23.492	0.24	0.425	22.3298	0.3	0.425	20.8606
0.15	0.43	29.1505	0.18	0.43	25.8364	0.21	0.43	24.0447	0.24	0.43	22.8402	0.3	0.43	21.3361
0.15	0.435	29.9242	0.18	0.435	26.4984	0.21	0.435	24.6555	0.24	0.435	23.4115	0.3	0.435	21.8729
0.15	0.44	30.7306	0.18	0.44	27.2092	0.21	0.44	25.3203	0.24	0.44	24.0393	0.3	0.44	22.4667
0.15	0.445	31.5664	0.18	0.445	27.9648	0.21	0.445	26.0349	0.24	0.445	24.7194	0.3	0.445	23.1134
0.15	0.45	32.4281	0.18	0.45	28.7612	0.21	0.45	26.795	0.24	0.45	25.4475	0.3	0.45	23.8087
0.15	0.455	33.3122	0.18	0.455	29.5943	0.21	0.455	27.5964	0.24	0.455	26.2194	0.3	0.455	24.5485

0.15	0.46	34.2154	0.18	0.46	30.46	0.21	0.46	28.4349	0.24	0.46	27.0307	0.3	0.46	25.3285
0.15	0.465	35.134	0.18	0.465	31.3542	0.21	0.465	29.3062	0.24	0.465	27.8773	0.3	0.465	26.1444
0.15	0.47	36.0648	0.18	0.47	32.2728	0.21	0.47	30.2061	0.24	0.47	28.7548	0.3	0.47	26.9922
0.15	0.475	37.0041	0.18	0.475	33.2119	0.21	0.475	31.1305	0.24	0.475	29.6589	0.3	0.475	27.8675
0.15	0.48	37.9487	0.18	0.48	34.1672	0.21	0.48	32.075	0.24	0.48	30.5854	0.3	0.48	28.7662
0.15	0.485	38.895	0.18	0.485	35.1347	0.21	0.485	33.0354	0.24	0.485	31.5301	0.3	0.485	29.684
0.15	0.49	39.8397	0.18	0.49	36.1105	0.21	0.49	34.0075	0.24	0.49	32.4886	0.3	0.49	30.6167
0.15	0.495	40.7791	0.18	0.495	37.0902	0.21	0.495	34.9871	0.24	0.495	33.4566	0.3	0.495	31.5601
0.15	0.5	41.71	0.18	0.5	38.07	0.21	0.5	35.97	0.24	0.5	34.43	0.3	0.5	32.51
0.15	0.505	42.6288	0.18	0.505	39.0457	0.21	0.505	36.9519	0.24	0.505	35.4044	0.3	0.505	33.4622
0.15	0.51	43.5321	0.18	0.51	40.0132	0.21	0.51	37.9286	0.24	0.51	36.3755	0.3	0.51	34.4124
0.15	0.515	44.4165	0.18	0.515	40.9686	0.21	0.515	38.8958	0.24	0.515	37.3391	0.3	0.515	35.3565
0.15	0.52	45.2785	0.18	0.52	41.9076	0.21	0.52	39.8494	0.24	0.52	38.291	0.3	0.52	36.2902
0.15	0.525	46.1146	0.18	0.525	42.8263	0.21	0.525	40.7852	0.24	0.525	39.2267	0.3	0.525	37.2094
0.15	0.53	46.9214	0.18	0.53	43.7205	0.21	0.53	41.6988	0.24	0.53	40.1421	0.3	0.53	38.1097
0.15	0.535	47.6955	0.18	0.535	44.5861	0.21	0.535	42.586	0.24	0.535	41.033	0.3	0.535	38.987
0.15	0.54	48.4334	0.18	0.54	45.4192	0.21	0.54	43.4427	0.24	0.54	41.8949	0.3	0.54	39.8371
0.15	0.545	49.1317	0.18	0.545	46.2156	0.21	0.545	44.2646	0.24	0.545	42.7237	0.3	0.545	40.6558
0.15	0.55	49.7869	0.18	0.55	46.9713	0.21	0.55	45.0475	0.24	0.55	43.515	0.3	0.55	41.4387
0.15	0.555	50.3955	0.18	0.555	47.6821	0.21	0.555	45.7871	0.24	0.555	44.2646	0.3	0.555	42.1819
0.15	0.56	50.9542	0.18	0.56	48.344	0.21	0.56	46.4793	0.24	0.56	44.9683	0.3	0.56	42.8809
0.15	0.565	51.4594	0.18	0.565	48.953	0.21	0.565	47.1197	0.24	0.565	45.6217	0.3	0.565	43.5316
0.15	0.57	51.9077	0.18	0.57	49.5049	0.21	0.57	47.7042	0.24	0.57	46.2207	0.3	0.57	44.1298
0.15	0.575	52.2957	0.18	0.575	49.9956	0.21	0.575	48.2286	0.24	0.575	46.7608	0.3	0.575	44.6713
0.15	0.58	52.6199	0.18	0.58	50.4212	0.21	0.58	48.6886	0.24	0.58	47.2378	0.3	0.58	45.1518
0.15	0.585	52.8769	0.18	0.585	50.7775	0.21	0.585	49.0799	0.24	0.585	47.6476	0.3	0.585	45.5671
0.15	0.59	53.0632	0.18	0.59	51.0605	0.21	0.59	49.3984	0.24	0.59	47.9857	0.3	0.59	45.9131
0.15	0.595	53.1754	0.18	0.595	51.266	0.21	0.595	49.6399	0.24	0.595	48.2479	0.3	0.595	46.1854
0.15	0.6	53.21	0.18	0.6	51.39	0.21	0.6	49.8	0.24	0.6	48.43	0.3	0.6	46.38
0.15	0.605	53.1636	0.18	0.605	51.4284	0.21	0.605	49.8746	0.24	0.605	48.5277	0.3	0.605	46.4925
0.15	0.61	53.0327	0.18	0.61	51.3772	0.21	0.61	49.8595	0.24	0.61	48.5366	0.3	0.61	46.5188
0.15	0.615	52.8139	0.18	0.615	51.2323	0.21	0.615	49.7504	0.24	0.615	48.4526	0.3	0.615	46.4547
0.15	0.62	52.5037	0.18	0.62	50.9896	0.21	0.62	49.543	0.24	0.62	48.2714	0.3	0.62	46.2958
0.15	0.625	52.0987	0.18	0.625	50.645	0.21	0.625	49.2333	0.24	0.625	47.9886	0.3	0.625	46.0381
0.15	0.63	51.5954	0.18	0.63	50.1944	0.21	0.63	48.8169	0.24	0.63	47.6	0.3	0.63	45.6773
0.15	0.635	50.9904	0.18	0.635	49.6339	0.21	0.635	48.2895	0.24	0.635	47.1014	0.3	0.635	45.2092
0.15	0.64	50.2802	0.18	0.64	48.9592	0.21	0.64	47.6471	0.24	0.64	46.4885	0.3	0.64	44.6295
0.15	0.645	49.4615	0.18	0.645	48.1663	0.21	0.645	46.8853	0.24	0.645	45.7569	0.3	0.645	43.9341
0.15	0.65	48.5306	0.18	0.65	47.2512	0.21	0.65	46	0.24	0.65	44.9025	0.3	0.65	43.1188
0.15	0.655	47.4843	0.18	0.655	46.2098	0.21	0.655	44.9869	0.24	0.655	43.9209	0.3	0.655	42.1792
0.15	0.66	46.319	0.18	0.66	45.038	0.21	0.66	43.8417	0.24	0.66	42.8079	0.3	0.66	41.1113
0.15	0.665	45.0312	0.18	0.665	43.7317	0.21	0.665	42.5603	0.24	0.665	41.5592	0.3	0.665	39.9107
0.15	0.67	43.6177	0.18	0.67	42.2868	0.21	0.67	41.1383	0.24	0.67	40.1706	0.3	0.67	38.5734
0.15	0.675	42.0748	0.18	0.675	40.6994	0.21	0.675	39.5717	0.24	0.675	38.6377	0.3	0.675	37.095
0.15	0.68	40.3991	0.18	0.68	38.9652	0.21	0.68	37.8562	0.24	0.68	36.9562	0.3	0.68	35.4714
0.15	0.685	38.5873	0.18	0.685	37.0802	0.21	0.685	35.9874	0.24	0.685	35.122	0.3	0.685	33.6983
0.15	0.69	36.6358	0.18	0.69	35.0405	0.21	0.69	33.9613	0.24	0.69	33.1308	0.3	0.69	31.7715
0.15	0.695	34.5412	0.18	0.695	32.8417	0.21	0.695	31.7736	0.24	0.695	30.9782	0.3	0.695	29.6868
0.15	0.7	32.3	0.18	0.7	30.48	0.21	0.7	29.42	0.24	0.7	28.66	0.3	0.7	27.44