Modeling and Thermodynamic Analysis of Municipal Solid Waste Dryer: A Parametric Study

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ABSTRACT: *Due to the landfill leachate and the lack of drainage beds for collecting and directing leachate, especially in developing countries, the need to study Municipal Solid Waste (MSW) dryers is of particular importance. According to the technical literature, so far no comprehensive study has been performed on MSW dryers considering the actual components of the waste and the moisture content above 40%. Here a comprehensive study of wet MSW dryers consisting of three different parts is performed. In the first part, a semi-theoretical mathematical model is developed to calculate the drying rate (internal) of wet MSW. For this purpose, with the laboratory results in the technical literature and Statistica software, a suitable mathematical model for drying MSW is validated and determined. Then, the external drying rate is determined according to the type of dryer selected and after its validation; it is compared with the internal drying rate. In the second and third parts, after validation of EES developed code, energy, and exergy analysis are reviewed and finally, a parametric study is performed to investigate the effects of different parameters on energy and exergy efficiencies of the unsorted wet MSW drying process. The results show that the best model for drying the unsorted MSW is the logarithmic model with a corresponding R^2 of 0.999. The internal and external evaporation rates are 0.157 and 0.165 kg/s and it is seen these two rates are well-matched together and differ by only 5%. The energy efficiency and exergy efficiency of the dryer are 13.92% and 2.91%, respectively. According to the parametric study, the inlet air temperature and the temperature of inlet MSW have the greatest effect on energy efficiency, respectively. Inlet air conditions such as absolute humidity of inlet air and atmospheric pressure have the greatest effect on the exergy efficiency of MSW drying.*

KEYWORDS: *Municipal solid waste; Municipal solid waste dryer; Mathematical modeling; Drying rate; Energy and exergy analysis; Parametric studies.*

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INTRODUCTION

In general, the study of energy and energy sources for daily human life is important from economics, environment, and society inspects. According to available data, the amount of MSW worldwide will reach 2.2 billion tons per year by 2025, and according to The World Bank, the growth rate of waste production will be doubled in developing countries in the next two decades, which will raise concerns about environmental pollution and social and economic problems [1]. The solutions for waste recycling and treatment are directly related to developing countries [2].

To determine the appropriate solution, it is necessary to know the composition of MSW, which has a wide variety of components in different countries. Based on Fig. 1, all countries can be divided into 4 categories (low income, low to medium income, medium to high income, and high income), and the amount of organic waste is higher than other components for all countries, but this amount is higher in low-income countries than in high-income countries. According to the available results, the average amount of moisture is about 41% on average [3, 4]. This moisture is converted into leachate and enters the soil, which in addition to changing the PH of the soil, causes the absorption of heavy metals such as zinc, copper, lead, nickel, and cadmium, which their penetration into surface and groundwater will cause irreparable damage [5]. Due to the high cost of the waste management system, one of the methods of MSW disposal is free dumping, which accumulates waste without any control in the open space and leads to environmental pollution. This method is commonly used in developing countries, a practice that will become obsolete in the not-too-distant future [6, 7]. Due to the increase in urbanization and industrialization of communities, to preserve natural resources and the environment, a fundamental approach to waste management and recycling should be taken into consideration till both environmental pollution and human needs reconcile with each other in some way [8]. Another way to dispose of waste is to convert Waste to Energy (WtE), which reduces the environmental pollution of waste and turns WtE at the same time. Methods of converting WtE can be divided into direct combustion, chemical-physical processes, thermochemical processes, and biochemical processes [9]. Each of these methods has advantages and disadvantages; however, the presence of moisture in the waste always reduces the efficiency of all the methods. The high humidity is due to the high percentage of organic matter (food) in the waste [9–11]. Therefore, the key to increasing the efficiency of the WtE conversion process is to reduce the moisture content in MSW [12]. To reduce the amount of moisture, energy is needed, which should be supplied from external or internal sources through the decomposition of organic matter [13]. The most common methods for MSW drying can be divided into four general categories: Biological, equilibrium, solar, and thermal, each of which has advantages and disadvantages [14]. Studies show that the time required for drying by biological and equilibrium methods is 20 to 60 days, which is quite long. Drying with the sun, in addition to not being available in all areas, has a high cost. Therefore, thermal drying is introduced as the superior method among these methods [14].

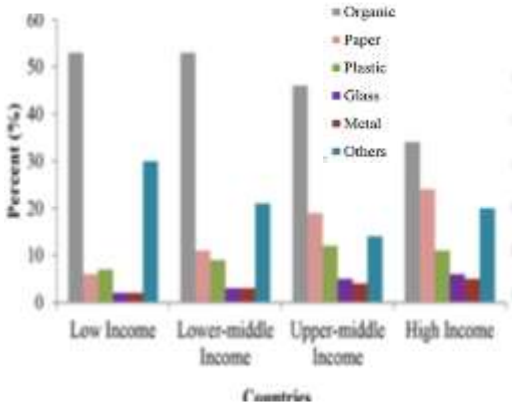

Fig. 1: Percentage of waste components in countries with different incomes [3].

Many researchers in their theoretical and experimental research have used biological methods to dry MSW [15, 16]. Also, more than 70% of municipal solid waste in developing countries is composed of high-moisture organic matter [4], therefore, the following is a review of research on modeling the thermal drying process of MSW. In 2010, *Erbay* and *Icier* [17] presented a review paper on selecting an appropriate model for drying a variety of foods. In this article, 38 types of food, including apples, pistachios, dates, etc. have been studied and a suitable model for the drying process for each of these food items has been presented. Then, after selecting the appropriate model, the activation energy and Arrhenius equation for each food item are obtained and finally it is stated that temperature is the most important parameter in the study of these processes that should be considered in all studies [17]. In 2011, *Zakipour* and *Hamidi* [18] experimentally investigated the drying of fenugreek, mint, and parsley leaves and vegetative parts of leek in a vacuum drying chamber. In this semi-theoretical study, six different types of models were evaluated, and finally, the Page model was introduced as the superior model. In 2011, *Tulek* [19] compared the experimental drying results with the theoretical results obtained from Lewis, Page, Extended Page, Henderson, and Pabis, Logarithmic, Two-term, and Midilli models to select the appropriate theoretical model of the mushrooms drying process. The results show that the suitable model for drying mushrooms is the Midilli model. It was also shown that as the temperature of the air entering the dryer increases, the drying rate will also increase. In 2013, *Chen et al.* [20] theoretically modeled the drying process of six types of material: potato, watermelon skin, wet wood, wet tissue, cabbage stalk, and cloth. In this study, the studied temperature was 100 to 200 ºC and the coefficients of the Arrhenius equation and the equations themselves were obtained for this temperature range. In 2015, *Vukic et al.* [21] experimentally examined corn drying in two types of Packed and Fluidized Bed dryers. The results show that increasing the fluidization number and the velocity of the drying medium is effective only at the beginning of the drying process. In 2016, *Golmohammadi et al.* [22] modeled the paddy rice drying process both experimentally and theoretically. They designed a fluidized bed dryer, and for theoretical kinetic modeling, Midilli, and two-term models were selected as suitable models for paddy rice drying. *Torki Harchegan et al.* [23] in the same year examined the process of drying lemons semi-theoretically. They dried lemons at three different drying temperatures of 50, 60, and 75 ºC and at an air speed of 1 m/s and examined five different kinetic models. According to their results, the Midilli and logarithmic models were introduced as the superior models. *Nzioka et al.* [24] conducted an experimental study on MSW drying in Nairobi in 2016 and gained graphs of moisture ratio-time during the drying process for three different drying temperatures. *Bukhmirov et al.* [25] in experimental research obtained the Sherwood number and mass transfer coefficient for MSW drying after plotting the moisture ratio-time. In 2018, *Polonis et al.* [26] selected three models, Lewis, Henderson, and Page, to model the waste located at the Waste Recycling Center in Krakow, Poland. Where most of the waste is made of plastic, and a small amount of waste is made of organic materials. To select the appropriate model for the drying of the materials, the theoretical and experimental results were compared together for different temperatures and it was concluded that Page model gives the best theoretical results only at 70°C, and another suitable model should be used at other temperatures. In 2018, *Ozcan et al.* [27] determined the appropriate kinetic model for drying dill and parsley. Based on the experimental results obtained from oven drying, they examined 12 different models and finally introduced the Midilli and Wang models for drying dill and parsley as suitable drying models, respectively. In 2019, *Taghinezhad et al.* [28] offered the appropriate model for determining the drying time, color and hardness of rice. According to the experimental results, they showed that the appropriate model for drying time has a linear behavior and the determined model has an acceptable compatibility with the experimental results. In 2019, *Gluesenkamp et al.* [29] conducted an experimental and theoretical parametric study on the clothes drying process. According to the results, the efficiency of the dryer depends on the values of air and clothes rates as well as the residential time. Based on the laboratory results in this paper, correlations for mass transfer efficiency in the dryer were presented. In 2020, *Zhang et al.* [30] conducted theoretical and experimental studies on paper towel drying. The drying results have been reported based on hot air and radiant energy. The results show that the suitable model for drying paper towels is Midilli model and the initial activation energy for this process has been reported as 23.17 kJ/mol.

The drying process requires a lot of energy [14], and this energy must be provided in an economically viable way [31]. Therefore, energy and exergy analysis should be performed on the dryer. Exergy analysis provides useful information about the exergy destruction and losses of different components of a system. Also, to check the actual performance of systems, exergy analysis is performed simultaneously with energy analysis, which in many studies, energy and exergy analysis have been proposed simultaneously [32, 33]. Therefore, in the current study, both energy analysis and exergy are examined. The history of modeling and energy and exergy analysis of the drying process in the relevant literature dates back to 2009. In 2009, *Coskun et al.* [34] by analyzing the energy and exergy of wood chips, experimentally and theoretically achieved energy and exergy efficiencies of 34.07% and 4.39%, and it was observed that the amount of exergy efficiencies is much less than the energy efficiency of this process. In an article published by *Dincer* [35], the fundamentals of energy and exergy analysis were discussed, and they showed that the exergy efficiency would be less than the energy efficiency of the dryer due to its exergy losses and destruction. *Terehovics et al* [36] examined the energy and exergy analysis of wood dryers in different conditions, but for the best conditions, they calculated the energy and exergy efficiencies as 22.69% and 16.47%, respectively. In 2018, *Castro et al.* [37] examined the analysis of exergy during the onion drying process. In this study, exergy analysis has been evaluated parametrically. According to the presented results, it is observed that by increasing the temperature of the dryer and increasing the air speed, the amount of exergy loss increases. In 2019, *Abbaspour et al.* [38], in addition to provide a suitable model for drying quince pieces, and also performed energy and exergy analyses. Based on the obtained results, the Midilli model was introduced as a suitable model for drying quince pieces and by considering the dried fruit as the product of the process, the exergy efficiency of %88 was obtained. In 2020, *Mayokun Odewole et al.* [39] analyzed the process of drying green bell peppers in a cabinet dryer in terms of energy and exergy. In this study, at three temperatures of 50, 55, and 60 ºC for the dryer, it was observed that increasing the drying temperature from 50 to 60 ºC, the exergy efficiency increases from 0.9903% to 0.9928%. However, with increasing dryer temperature, energy efficiency has decreased due to the reduction of useful energy. In recent years, and especially in 2020, energy and exergy analysis was performed for the drying process of fruit [40], crops [41], and other types of materials [42], where each process was specific to a single material. Still, for a mixture of materials, especially MSW, there is no specific energy and exergy analysis on its thermal drying process. As mentioned before, MSW management is vital for conserving natural resources and reducing pollution due to an increase in urbanization and waste generation. Also, due to the high cost of safe disposal of waste, a sustainable approach to MSW management is required, in a way that both the natural sustainability of the environment and human needs are met. For this purpose, methods of energy production from waste are proposed. However, to increase the efficiency of these processes, it is necessary to reduce the moisture content in the MSW. Among the existing methods, the thermal method has been identified as the superior method.

Therefore, modeling and thermodynamic analysis of MSW dryers is the aim of this study, which is important in both developing and developed countries. In developed countries, the MSW is first separated and shredded and transformed into RDF. This product has already lost its water and its production process is costly this material is also used for energy production. While in developing countries, MSW drying is important in terms of leachate removal and preservation of soil and environment. So MSW dryer is important in both cases. A close look the literature reveals certain gaps in the study of MSW dryers, these gaps are:

- Until now, there is no mathematical kinetic model to determine the drying rate of MSW (with a variety of real waste components and with humidity above 40%), at temperatures above 70 ºC.

- The mathematical kinetic models presented in the literature for different single materials are based on internal diffusion and according to Fick's law and provide the mass transfer coefficient based on internal conditions. Based on previous studies, the rate of internal mass transfer has not been compared with the rate of external mass transfer and in fact, external environmental conditions have been ignored.

- Energy and exergy analyses of thermal MSW dryers have not been comprehensively reviewed (with a variety of real components of MSW and with humidity above 40%).

- Less research has been done on the parametric study of MSW thermal dryers (with a variety of real components of MSW and with humidity above 40%) and therefore the parametric study of the MSW drying process seems to be necessary.

To address these gaps, the innovations and achievements of the present article can be presented in three parts:

Part 1- Introducing a mathematical kinetic model suitable for MSW thermal drying, (for 60 to 100 ºC temperature range)

Part 2- Determining the MSW thermal drying rate according to the actual environmental conditions and comparing the internal and external mass transfer rates.

Part 3- Analyzing the energy and exergy of the MSW dryer and performing the parametric study.

Thus, in this paper first, a series of recent laboratory data from the relevant literature (specific for MSW) was selected and then the data was examined by existing statistical software and mathematical models [24]. The MSW data [24] is based on various real components of wet MSW, and the results of the current modeling can be generalized to Iran according to its MSW analysis [43]. With statistical analysis, a suitable model for MSW drying was introduced and validated. Next, due to the practical limitations of designing the MSW dryer, a suitable dryer is designed using EES software [44]. Then the internal and external drying rates were determined and validated by the results of the relevant references. The calculated external mass transfer rate is then compared with the internal mass transfer rate. Next, energy and exergy analysis of the thermal dryer was performed by using the EES-developed code. Also, a parametric study on the performance of the dryer was done according to parameters such as inlet air temperature, absolute humidity of inlet air, residential time, reference ambient absolute humidity, operation pressure, the temperature of inlet MSW, the temperature of outlet air, and outlet MSW moisture.

EXPERIMENTAL SECTION

The main components of MSW include food waste, paper, plastic, and textiles [45], due to the limitations in the reports presented in the literature and the lack of appropriate data on moisture-time diagrams during MSW drying, different percentages of material waste food, paper, plastic, and soil were selected as the main components of MSW in this paper. The experimental data used in the present work are the result of research conducted by *Nzioka et al* [24] on MSW samples with real compounds with a high moisture content of 40%. It should be noted that these data are the closest data to the analysis of Iranian MSW [43]. In this reference, three types of waste with the percentage of different compositions of its components have been selected, and their moisture ratio-time diagrams have been drawn at different temperatures of 60 °C, 80 °C, and 100 °C. Table 1 shows the components of the waste which was chosen and a convective drying oven is used for drying the unsorted MSW [24]. The moisture ratio-time ((MR-t) diagrams during MSW drying are shown in Fig. 2 [24]. After determining the data, the steps of conducting the research and how to perform the work are explicitly presented in the flowchart of Fig. 3, which is examined in detail below.

Development of mathematical modeling equations

In the present study, according to the mentioned innovation, both internal mass transfer rates and external mass transfer rates are calculated and compared. For this purpose, this section is divided into two sub-sections as follows:

a) General methods for mathematically modeling the drying process (inner drying rate),

b) MSW drying rate (outer drying rate).

Internal MSW drying rate

There are three general methods for mathematically modeling the drying process: theoretical [46], experimental [17], and semi-theoretical [42]. The semi-theoretical method is the first step in modeling the drying process that many researchers have used for different materials. In the present study, the semi-theoretical method has been used. In the present study, the semi-theoretical method has been used. In this research, the semi-theoretical method has been used. In this method, first, the modeling of the drying process is done theoretically and after determining the general format of the solution, an equation of that general solution is determined to calculate the amount of moisture. The parameters and coefficients of this equation are determined using the available statistical software and experimental results [17, 47].

Fick's second law will be used to model the MSW drying process. Assuming a constant diffusion coefficient, the fixed equation for different one-dimensional geometries will be as Eq. (1) [48]:

$$\frac{\partial M}{\partial t}=D_{eff}\left(\frac{\partial^2 M}{\partial r^2}+\frac{\beta}{r}\frac{\partial M}{\partial r}\right) \tag{1}$$

$$M(r,0)=M_i \quad \text{at} \quad t=0$$

$$M(0,t)=M_\infty \quad \text{at} \quad r=r_0 \text{ (surface)}$$

$$M(0,t)=\text{finite} \quad \text{at} \quad r=0 \text{ (center)}$$

The value of β in Eq. (1) will vary according to the geometry studied; this value will be zero, 1, and 2 for Cartesian, cylindrical and spherical coordinates, respectively. Eq. (1) with the boundary conditions shown is solved by Crank, and the final solution is obtained as Eq. (2) and Eq. (3) [49]. The assumption that *Crank* used to solve this

Table 1: Drying temperature and MSW compositions for each sample [24].

Sample No.	Soil (%w)	Wood (%w)	Plastic waste (%w)	Paper waste (%w)	Food waste (%w)	Drying temperature (ºC)
1-1	5	5	15	15	60	60
2-1	5	5	15	15	60	80
3-1	5	5	15	15	60	100
1-2	5	5	15	15	60	60
2-2	10	5	15	20	50	60
3-2	5	5	10	10	70	60
1-3	5	5	15	15	60	80
2-3	10	5	15	20	50	80
3-3	5	5	10	10	70	80
1-4	5	5	15	15	60	100
2-4	10	5	15	20	50	100
3-4	5	5	10	10	70	100

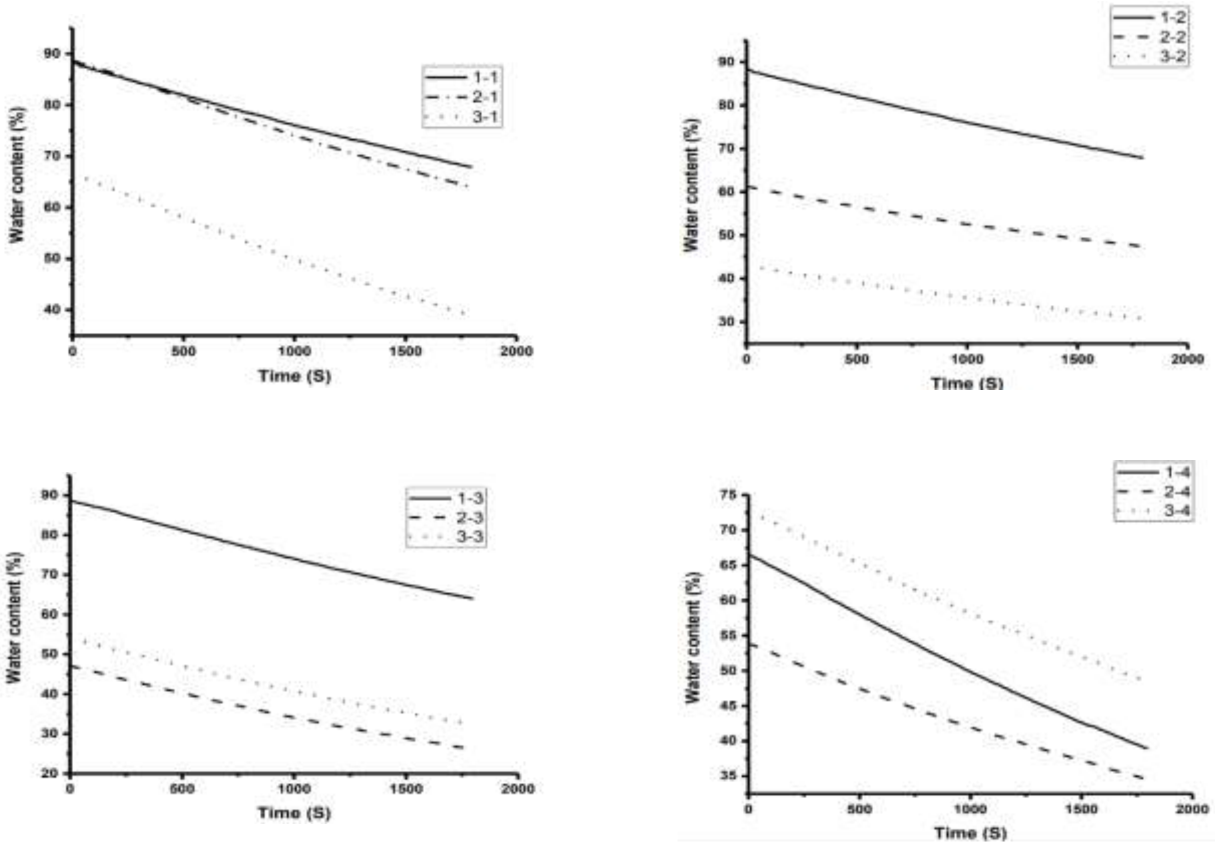

Fig. 2: (a) Moisture ratio-time diagram during the drying process for sample No. 1 at 60 ºC, 80 ºC, and 100 ºC, (b) The drying process for 3 types of MSW at 60 °C, (c) The drying process for three types of MSW at 80 °C, (d) The drying process for three types of MSW at 100°C [24].

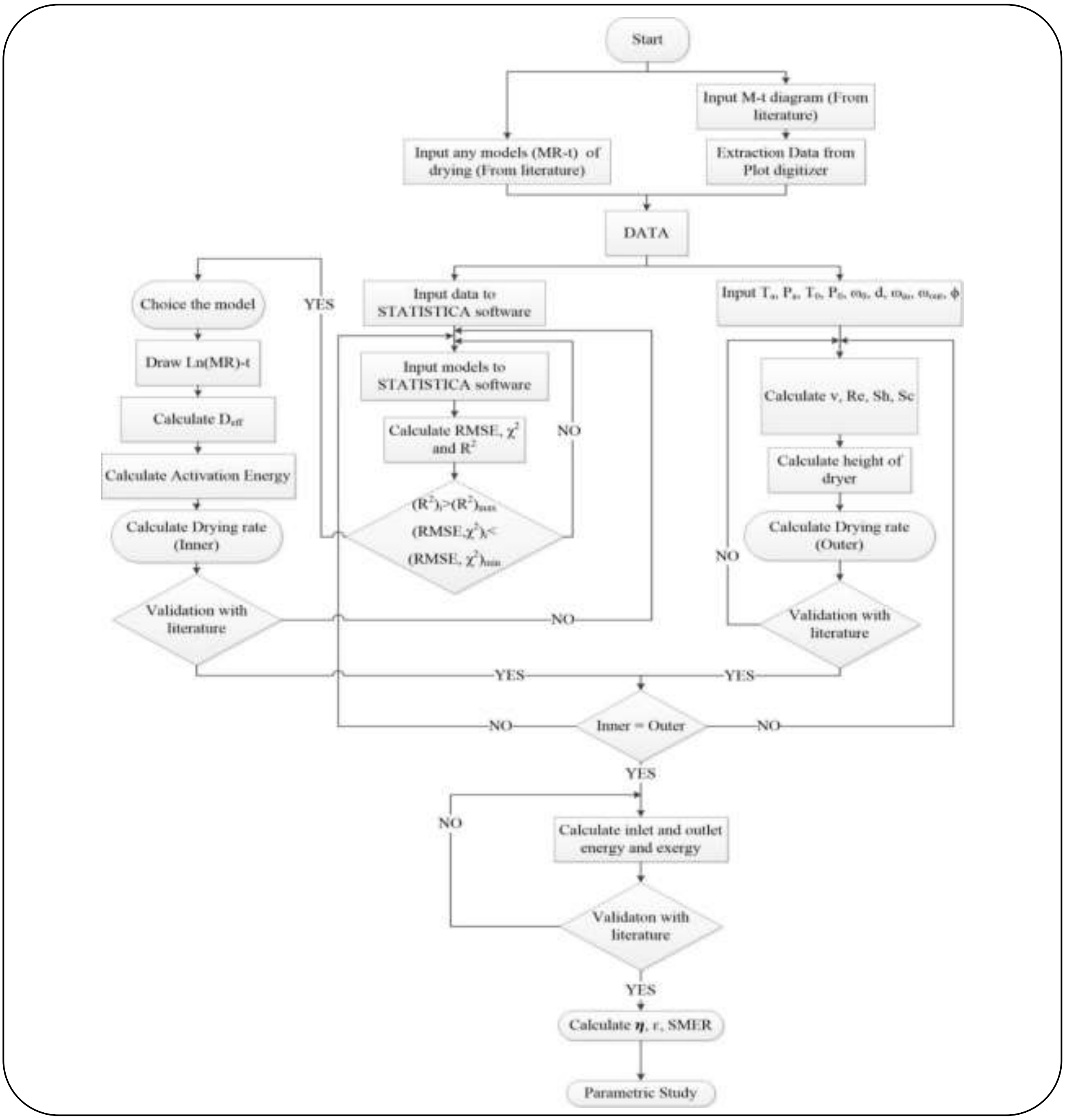

Fig. 3: A flow chart of the mathematical approach used for this study.

the equation was 1. The initial moisture is uniformly distributed 2. There is no external resistance to mass transfer, 3. Moisture is infiltrated from the object under study, 4. During the process, the temperature is equal to the temperature of hot air, 5. The contraction of the body is ignored 6. Spherical coordinates are considered.

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(- \frac{n^2 \pi^2 D_{eff} \ t}{r^2}) \qquad (2)$$

$$MR=\frac{M_t-M_e}{M_i-M_e} \qquad (3)$$

The general form of the theoretical and semi-theoretical models available for drying spherical bodies is the same as in Equation (2), where MR is always a function of exp(t). In this research, the general form of Eq. (2), which is obtained from the theoretical method, is preserved, but its coefficients are determined through the experimental method and laboratory data. Therefore, the relationship between MR and exp(t) is obtained as a combination of theoretical and experimental methods, which is the basis of the semi-theoretical method.

In the semi-theoretical method, according to the form of Eq. (2) and experimental methods, so far different models for the equation of moisture ratio versus time (MR-t) have been introduced according to Table 2. In the semi-theoretical method, in some of these models, only the first term of this series is used and in others, the first two terms or three terms of this series are used for modeling. Usually, each of these models presented in Table 2 is suitable for a specific material, which under certain conditions can be used for other materials [17].

Statistics software [50] was used to determine the coefficients (a, b, k, ...) of the models in Table 2, so the laboratory results obtained from the reference [24] are entered into the software as input data and then the desired model is introduced to the software. Then, by entering the number of iterations (200 to 500) and using the Lenenberg-Marquardt method, the coefficients of the models are determined and finally, the values of the criterion parameters are obtained according to the following equations are obtained by the software [51].

$$\mathrm{RMSE}=\sqrt{\frac{\sum(\mathrm{MR_P}-\mathrm{MR_E})^2}{\mathrm{N}}} \tag{4}$$

$$\chi^2=\frac{\sum(\mathrm{MR_E}-\mathrm{MR_P})^2}{\mathrm{N-n}} \tag{5}$$

$$\mathrm{R}^2=1-[\frac{\sum(\mathrm{MR_P}-\overline{\mathrm{MR}}_\mathrm{E})^2}{\sum(\mathrm{MR_E}-\mathrm{MR_P})^2}] \tag{6}$$

Eq. (4) represents the Root Mean Square Error (RMSE) of *MR* and Eq. (5) represents Reduced chi-squared (χ^2). Eq. (6) shows the Correlation Coefficient (R^2) and $\overline{MR}_E$ indicates the mean of the experimental moisture ratio. With the relations, the mathematical models in Table 2 will be evaluated by Statistics software. Finally, a model will be selected whose R^2, RMSE, and χ^2 are close to one, zero, and zero, respectively.

After determining the appropriate mathematical model for the moisture ratio, the amount of effective moisture diffusion coefficient (D_{eff}) must be determined. To determine D_{eff}, the slope of the normalized lnMR-t diagram (Slop*e*) must be obtained. Thus, Eq. (7) will be used to determine D_{eff} [36, 51]. Where *L* is the size scale of the particle. According to the Arrhenius equation, temperature and diffusion coefficient are related by Eq. (8) [20]. Also, the slope of the graph D_{eff}-1/T, shows the amount of activation energy.

Table 2: *Different models for moisture ratio-time equation [17].*

Model name	Mathematical model
Lewis model	$MR=e^{-kt}$
Page model	$MR=e^{-kt^n}$
Modified Page –II model	$MR=e^{-(kt)^n}$
Henderson and Pabis model	$MR=ae^{-kt}$
Logarithmic model	$MR=ae^{-kt}+c$
Midilli model	$MR=ae^{-kt}+bt$
Modified Midilli model	$MR=e^{-kt}+bt$
Demir et al. model	$MR=ae^{(-kt)^n}+b$
Two-Term Exponential model	$MR=ae^{-k_1t}+ae^{-k_2t}$
Modified Two-Term Exponential model	$MR=ae^{-kt}+(1-a)e^{-kat}$
Modified Two-Term Exponential model	$MR=ae^{-kt}+(1-a)e^{-gt}$
Modified Henderson and Pabis model	$MR=ae^{-kt}+be^{-gt}+ce^{-ht}$
Wang model	$MR=1+bt+at^2$
Kaleemullah model	$MR=e^{-ct}+bt^{(pt+n)}$

$$\mathrm{D_{eff}}=\frac{-\mathrm{Slope}\times\ \mathrm{L}^2}{\pi^2} \tag{7}$$

$$\mathrm{D_{eff}}=\mathrm{D_0}\exp\left(\frac{-\mathrm{E_a}}{\mathrm{R_u T}}\right) \tag{8}$$

External MSW drying rate

Eq. (9) which is obtained from the experimental method, is used to determine the MSW drying rate and $p_{H_2O,\,surf}$ (Pa) is determined by applying Eq. (10) [52].

$$\mathrm{r_{drying}}=\frac{\mathrm{k_m\ a_g\ M_{H_2O}}}{\mathrm{R\ T_g}}(\mathrm{p_{H_2O,surf}}-\mathrm{p_{H_2O}}) \tag{9}$$

$$\ln(\mathrm{p_{H_2O,surf}})=25.541-\frac{521}{\mathrm{T_{wb}}} \quad , \quad 284\le \mathrm{T_{wb}}\le 441\ \mathrm{K} \tag{10}$$

Also, the mass transfer coefficient is related to the Sherwood number and will be determined with the help of Eqs. (11) to (14) [25, 52].

$$Sh=2+1.1Re^{0.6}Sc^{1.3} \quad (11)$$

$$Sh=\frac{k_m d_p}{D_{H/g}} \quad (12)$$

$$Re=\frac{\rho v d_p}{\mu} \quad (13)$$

$$Sc=\frac{\mu}{\rho D_{H/g}} \quad (14)$$

In Eq. (13), the passing air velocity is determined according to the type of dryer. To choose a dryer, there are various parameters such as manufacturing cost, materials to be dried, maintenance cost, material dimensions, and so on. According to the articles in the technical literature, continues fluid bed dryer has been selected as MSW dryer [53]. The velocity of passing air is calculated by Eq. (15) [14, 53].

$$v=\left[(23.7)^2+0.0408\frac{d_p^3\rho_{air}\left(\rho_{MSW}-\rho_{air}\right)g}{\mu^2}\right]^{\frac{1}{2}}-33.7 \quad (15)$$

Also, to determine the dimensions of the dryer, it is necessary to use NTU, LTU relations, which are mentioned in Eq. (16) and Eq. (17). The length of the dryer is obtained by multiplying these two values.

$$LTU=0.026\ C_{p,a}\ G^{0.84}\ D \quad (16)$$

$$NTU=38LTU/(C_{p,a}G^{0.84}D) \quad (17)$$

After determining the internal and external drying rates, these two rates are compared. If these two values are close to good approximations, it indicates the convergence of the answers. Otherwise, according to the flowchart in Fig. 3, by changing the effective parameters in the external mass transfer rate, including correcting the velocity equation (Eq. (15)) and simultaneously changing the model used in calculating the internal mass transfer, the mass transfer rates are recalculated until finally these two rates are obtained close enough to each other.

Energy analysis methods

Based on Fig. 4, hot air enters the dryer in section 1 at 133 ºC and after absorbing moisture from MSW, leaves the dryer in section 3 at 60 °C. MSW enters the dryer at room temperature (30 °C) in section 2 and leaves the dryer in section 4 after removing some of its moisture at 60 °C and its dry mass flow rate is 1000 kg/h with 20% moisture ratio [34, 36, 54].

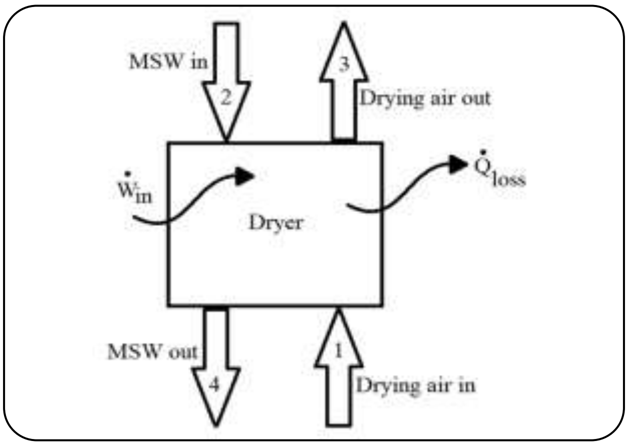

Fig. 4: MSW dryer schematic.

The conservation equations of mass, energy, and exergy are given in Eq. (18) to Eq. (23), respectively. Wet MSW in both inlet and outlet of the dryer is considered a combination of dry waste and liquid water and also inlet and outlet air are considered as the combination of dry air and water vapor. The conservation equations of mass and energy are given by Eq. (18) to Eqs. (22) and Eq. (23), respectively. Also, the enthalpy of the inlet and outlet air at points 1 and 3 are given in Eq. (24) [34, 36, 53–56].

$$\dot{m}_1+\dot{m}_2=\dot{m}_3+\dot{m}_4 \quad (18)$$

$$\dot{m}_{a,1}=\dot{m}_{a,3}=\dot{m}_a \quad (19)$$

$$\dot{m}_{1,3}=(1+\omega_{1,3})\dot{m}_a \quad (20)$$

$$\dot{m}_{msw,2}=\dot{m}_{msw,4}=\dot{m}_{msw} \quad (21)$$

$$\omega_1\dot{m}_a+\dot{m}_{w,2}=\omega_3\dot{m}_a+\dot{m}_{w,4} \quad (22)$$

$$h_1\dot{m}_a+\dot{m}_{msw}h_{msw,2}+\dot{m}_{w,2}h_{w,2}+\dot{Q}_{loss}=h_3\dot{m}_a+\dot{m}_{msw}h_{msw,4}+\dot{m}_{w,4}h_{w,4}+\dot{W} \quad (23)$$

$$h_i=h_{a,i}+\omega_i h_{v,i} \quad (24)$$

According to Eqs. (25) and (26), the drying energy efficiency is defined as the energy used for drying relative to the total input energy [54].

$$\eta=\frac{\dot{m}_{w,ev}[h_3-h_2]}{\dot{En}_{total}} \quad (25)$$

for determining the external drying rate for the selected dryer, and d) Validation of energy and exergy analyses.

$$\dot{E}n_{total}=\dot{E}n_1+\dot{E}n_3+\dot{W} \quad (26)$$

The Specific Moisture Extraction Ratio (SMER) is another parameter of the dryer analysis, which is defined as the ratio of the mass flow rate of water evaporated in the dryer to the total input energy and is given in Eq. (27) [57].

$$SMER=\frac{\dot{m}_{w,ev}}{\dot{E}n_{total}} \quad (27)$$

Exergy analysis methods

According to Fig. 4, the conservation equation of exergy is given in Eq. (28). Also, the exergy of the inlet and outlet air at points 1 and 3 are given in Eq. (29). Also, the exergy of liquid water (in MSW) and the exergy of water vapor in the air are obtained according to Eq. (30) and Eq. (31), respectively. Also, the exergy efficiency is the ratio of the exergy required to evaporate moisture to the total input exergy given in Eqs. (32)-(33) [34, 36, 53, 54, 56].

$$\dot{m}_a ex_1+\dot{m}_{msw} ex_{msw,2}+\dot{m}_{w,2} ex_{w,2}+\dot{E}x_w= \dot{m}_a ex_3+\dot{m}_{msw} ex_{msw,4}+\dot{m}_{w,4} ex_{w,4}+\dot{E}x_{loss}+\dot{E}x_{dest} \quad (28)$$

$$ex_i=\left[c_{p,a}+\omega_i c_{p,v}\right](T_i-T_0)- T_0 \left\{\left[c_{p,a}+\omega_i c_{p,v}\right]\ln\frac{T_i}{T_0}-(R_a+\omega_i R_v)\ln\frac{p_i}{p_0}\right\}+ T_0\left[(R_a+\omega_i R_v)\ln\frac{1+1.6078\,\omega_o}{1+1.6078\,\omega_i}+1.6078\omega_i R_a\ln\frac{\omega_i}{\omega_o}\right] \quad (29)$$

$$ex_{w,msw}=\left[h_f(T)-h_g(T_0)\right]+ v_f\left[p-p_g(T)\right]-T_0\left[s_f(T)-s_g(T_0)\right]+T_0 R_v\ln\frac{p_g(T_0)}{x_v^0(P_0)} \quad (30)$$

$$ex_{w,air}=\left[h\left(T_i,p_{v,i}\right)-h_g(T_0)\right]- T_0\left[s\left(T_3,p_{v,i}\right)-s_g(T_0)\right]+T_0 R_v\ln\frac{p_g(T_0)}{x_v^0(P_0)},\ p_{v,i}=x_{v,i}p_i \quad (31)$$

$$\varepsilon=\frac{\dot{m}_{w,ev}[ex_{w,3}-ex_{w,2}]}{\dot{E}x_{total}} \quad (32)$$

$$\dot{E}x_{total}=\dot{m}_a(ex_1)+\dot{W} \quad (33)$$

Validation procedure

Validation in this study is divided into four parts: a) Validation of the method for determining the appropriate model for the dryer, b) Validation of the methods for determining the D_{eff} and Arrhenius equation, c) Validation. In this section, the hypotheses and working methods are stated and the validation results will be presented in the results and discussion section.

Validation of the method for determining the appropriate model for the dryer

To validate this part, the results of *Doymaz*'s research [58], were used in which the dryer used for figs was a solar dryer. Based on the semi-theoretical method for modeling the fig drying process, and using statistical software from several models (Lewis, Henderson, and Pubis, screw, logarithmic, Two-term, exponential, *Verma et al.*. and Wang and Singh), the model Verma has been identified as a suitable model. To validate the method for determining the appropriate model of the dryer in the current work, the result of the Doymaz research [58] are extracted according to Fig. 5 and the models studied (Lewis, Henderson, and Pubis, screw, logarithmic, the two-term, exponential term, *Verma et al.*, *Wang* and *Singh*) were statistically analyzed with Statistica software to determine the appropriate model for the dryer with the experimental data of Fig. 5 and compared with the results of *Doymaz* research [58].

Validation of D_{eff} determination method and Arrhenius equation

In this section, the method of determining the diffusion coefficient and Arrhenius equation is validated. The result of *Chen et al.* research [20] has been used to evaluate this part. As mentioned in the introduction, *Chen et al.* [20] determined the diffusion coefficient and Arrhenius equation for six different types of materials. Fig. 6 was extracted from *Chen et al.* [20] and has been used to validate this section. The results related to the figure are obtained from drying potatoes at 160 ºC in a fixed bed muffle dryer. For validation, the slope of the graph was determined from this figure and then the penetration coefficient and Arrhenius equation were determined by Eqs. (7) and (8). Also, the diffusion coefficient and Arrhenius equation are compared with the results obtained by *Chen et al.* [20].

Validation to determine the external drying rate for the selected dryer

To determine the validity of an external drying rate, the selected dryer must be MSW-specific and its drying rate must be calculated through empirical relationships based on real conditions of fluid media. For this purpose, in this study, a fluid bed dryer is selected by using Eqs. (9) to (17)

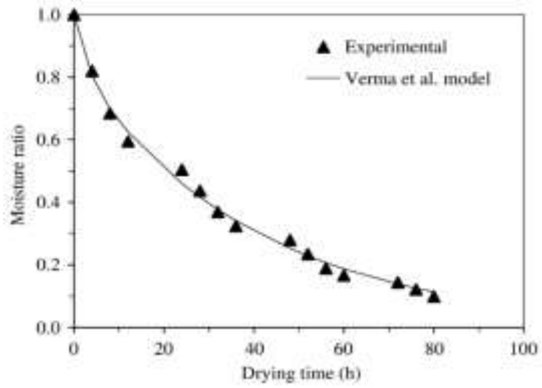

Fig. 5: Experimental result with the result of the semi-theoretical method of Verma et al. model [58].

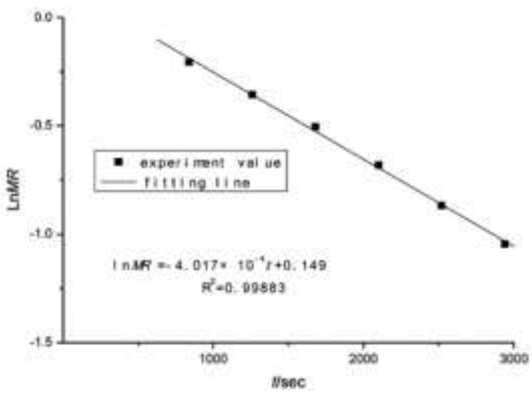

Fig. 6: ln MR-t diagram for drying potatoes at 160 °C [20].

and based on the conditions in this research, the value of the external drying rate is calculated. To validate this part, the results of *Asthana et al.* [52] and *Lawanangkul* [53] are used. In the research conducted by *Asthana et al.* [52], the dryer used is exactly the same type of dryer choice used in the current work (MSW-specific in Thailand), so the results can be used to calculate the external drying rate.

In the work of *Lawanangkul* [53], The mass rate of dry MSW output from the dryer is 1000 kg/h with a moisture content ratio of 20% and the output MSW temperature is 60 ° C, the inlet air temperature to the dryer is 133 ºC and the inlet MSW has 50% moisture ration and a temperature of 30 ºC. According to *Lawanangkul* [53], the drying rate unit is kg/m^3-s, but based on the results of *Asthana et al.* [52], the unit is kg/h. Therefore, in the current work, this rate is considered as kg/h. The results of the current study are obtained by using a code developed by EES software [44] and then the results are compared with the results of *Ashtana et al.* [52].

d) Validation of energy and exergy analytical method

The validation of the energy and exergy analysis method in the current work is based on *Dincer* and *Zamfirescu* [54], where a direct-contact continuous dryer is used to dry the wood. According to Fig. 4, the hypotheses used for energy and exergy analysis are:

• Air and wood input rates are 81.53 and 14.09 kg/s, respectively.

• Input and output wood temperatures are 288 and 363 K, respectively.

• Pressure drop in the dryer is ignored.

• The inlet hot air temperature is set at 739 K.

According to the hypotheses and control volume analysis, a code is written in EES software for energy and exergy analysis and the results are compared with the results of *Dincer* and *Zamfirescu* [54].

RESULTS AND DISCUSSION

According to the divisions made in the Material and method section, the results will be presented in four subsections as below:

- Results of mathematical modeling (which this section is divided into two parts internal drying rate and external drying rate),
- Energy analysis results,
- Exergy analysis results,
- Parametric study.

In each section, the results obtained from the current work are compared with the results presented in the literature. Before discussing the results, first, the validation of developed models is presented as follows.

Results of validation

As mentioned in the validation procedure section, the validation process of the present study was divided into 4 parts, the validation results of which are as follows:

Validation to determine the appropriate model for the drying process

Validation results to determine the appropriate model of the drying process with the results of *Doymaz* [58] are given in Table 3. It can be seen that the results obtained from the current study based on the data of Fig. 5 and

Table 3: Comparison of the Doymaz et al. [58] and this study.

Model name	R^2		χ^2		RMSE	
	Ref. [58]	This study*	Ref. [58]	This study *	Ref. [58]	This study*
Lewis	0.9717	0.9717	0.002119	0.002118	0.122045	0.12200
Henderson and Pabis	0.9838	0.9837	0.001302	0.00131	0.095712	0.09571
Page	0.9912	0.9911	0.000703	0.000702	0.075107	0.075108
Logarithmic	0.9854	0.9855	0.001270	0.001276	0.095909	0.095906
Two-term	0.9944	0.9940	0.000526	0.000529	0.063381	0.063382
Two terms exponential	0.9912	0.9911	0.000706	0.000707	0.074918	0.074919
Verma et al.	0.9944	0.9945	0.000483	0.000481	0.062857	0.062851
Wang and Singh	0.9512	0.9512	0.003935	0.003934	0.157139	0.157138

(*) Based on the Statistical calculation from this study.

Table 4: Comparison of constant values in Verma model from this study with the results of Doymaz et al [58]

	a	k	g
Ref. [58]	0.837681	0.024960	0.312673
This study	0.837689	0.024961	0.312672
Diff (%)	0.00095	0.004	0.0003

Statistics software is consistent with the results of *Doymaz* [58] and has an acceptable level of precision. In the present work, according to Table 3 and the results of Statistica software, the *Verma et al.* model is introduced as the superior model, which is also introduced as the superior model in the results of Doymaz [58]. In Table 4, the constants of the *Verma et al.* model (a, k, g) from the current work as well as those from the results of *Doymaz* [58] are compared, and in the worst case, there is a 0.004% error, which is negligible and indicates acceptable precision of the method used.

Methods Validation for determining the D_{eff} and Arrhenius equation

To validate this section, *Chen et al.*'s research [20] has been used, the results of which are compared with the results of the current work in Table 5. As can be seen, these results are matched quite well.

Validation to determine the external drying rate for the selected dryer

For this validation and concerning the type of dryer, the results of the current work were derived from the developed EES code and the results of the *Lawanangkul* [53] and *Asthana et al.* [52] are compared in Table 6. As can be seen, the error value is 0.16%, which indicates the acceptable accuracy of the calculations.

Validation of energy and exergy analysis methods

To validate the energy and exergy analysis methods, an EES code has been developed according to the hypotheses presented in the study of *Dincer* and *Zamfirescu* [54]. The results of the EES-developed code and the results of *Dincer* and *Zamfirescu* [54] are given in Table 7. The maximum error was 2.89%, which indicates the acceptable precision of the current study.

Results of mathematical modeling

Drying rate results

a) Internal drying rate results

To analyze the drying process, an experimental MR-time graph of the MSW drying is required first. For this purpose, Fig. 2 and Table 1 are used to determine the appropriate model for MSW drying among the various models, which are presented in Table 2. For statistical analysis, the Statistica software was used, and the appropriate modeling results for MSW were presented in Table 8. According to Table 8, it can be seen that the logarithmic

Table 5: Comparison of D_{eff} values and Arrhenius equation derived from Chen et al [20] and the present paper

	$D_{eff}*10^9$ ($\frac{m^2}{s}$)	Arrhenius equation
Ref. [20]	2.605	$D_{eff}=9.479*10^{-7}\exp\left(\frac{-21052}{RT}\right)$
This paper	2.605	$D_{eff}=9.479*10^{-7}\exp\left(\frac{-21051}{RT}\right)$

Table 6: Comparison of results from code developed by EES and references [53] and [52].

	r_{drying} ($\frac{kg}{h}$)
Ref. [53] and [52]	600
This study	599
diff(%)	%0.16

Table 7: Comparison of the results of Dincer and Zamfirescu [54] and the EES-developed code.

	Ref. [54]	This study	Diff (%)
$\dot{En}_1$ (kW)	90385	90375	0.011
$\dot{En}_2$ (kW)	1322	1321.9	0.007
$\dot{En}_3$ (kW)	88610	87549	1.197
$\dot{En}_4$ (kW)	3479	3470	0.258
η(%)	34.5	35.5	2.898
$\dot{Ex}_1$ (kW)	20526	20514	0.058
$\dot{Ex}_2$ (kW)	0	0	0
$\dot{Ex}_3$ (kW)	11964	11946	0.150
$\dot{Ex}_4$ (kW)	323	323	0
ε(%)	8.5	8.7	2.35

model has χ^2 and RMSE is close to zero, and R^2 is close to one. Indeed, this model simulates the MSW drying phenomenon more precisely and accurately than other models, and finally, this model is selected.

The most relevant research to the present study is the work of *Polonis et al.* [26] (2018), where, a model for drying the waste of the Krakow recycling center, which is mainly plastic, is presented. In this study, only three models including Lewis, Henderson, and Page were evaluated and finally, only at a drying temperature 70 °C, the *Page* model was introduced as the preferred model. But in the present study, 14 different models have been evaluated and finally, according to the results of Table 8, the logarithmic model is introduced as the superior model. The logarithmic model introduced by *Chandra* and *Singh* in 1995 was first used in 1999 to dry laurel leaves [17]. In recent years, this model has been widely introduced by researchers as the best model for drying fruits and vegetables [59, 60], and since more than 70% of MSW is composed of organic materials, so the conclusion that the logarithmic model can be used to model the waste drying process is not far from the mind. Also, according to the studies related to the modeling of the food drying process in Iran, it is observed that food materials such as lemon [23], paddy rice [22], and quince pieces [38] have been used and Logarithmic and Midilli models have been introduced as superior models. According to the research background, no model has been proposed for the drying of unsorted MSW.

Fig. 7 is provided to determine the D_{eff} for all three temperatures, also the trend lines are drawn by excel software for all three temperatures and the slope value of each chart is determined. The numerical values of D_{eff} for three desired temperatures (60 ºC, 80 ºC, and 100 ºC) were calculated by EES-developed code and reported in Table 9.

Table 8: Mathematical modeling results of the MSW dryer

Model name	T (°C)	Constants and coefficients	R^2	χ^2	RMSE
$MR=e^{-kt}$ Lewis	60	k=0.00090	0.92418	0.00783	0.08681
	80	k=0.00099	0.92817	0.00718	0.08362
	100	k=0.00100	0.93215	0.00644	0.07892
$MR=e^{-kt^n}$ Page	60	k=1.3407e-5, n=1.61316	0.98974	0.00110	0.03194
	80	k=1.433e-5 , n=1.61345	0.98988	0.00103	0.03138
	100	k=2.107e-5 , n=1.5630	0.98935	0.00104	0.03126
$MR=e^{-(kt)^n}$ Modified Page	60	k=1.340e-5 , n=1.6131	0.98973	0.00110	0.03129
	80	k=1.43e-5 , n=1.6134	0.98988	0.00103	0.03056
	100	k=0.00102 , n=1.5901	0.99095	0.00093	0.02920
$MR=ae^{-kt}$ Henderson and Pabis	60	a=1.1206, k=0.001046	0.95010	0.00535	0.07043
	80	a=1.1245, k=0.0011	0.95015	0.00511	0.06966
	100	a=1.1192, k=0.0011	0.95286	0.00463	0.06578
$MR=ae^{-kt}+c$ Logarithmic	60	a=5.73376, k=0.0001089, c=-4.70757	0.99915	0.00009	0.00916
	80	a=4.13404, k=0.0001605, c=-3.11468	0.99942	0.00006	0.00746
	100	a=3.2656, k=0.0002135, c=-2.24725	0.99982	0.00001	0.00396
$MR=ae^{-kt}+bt$ Midilli	60	a=1.02653, k=0.00027, b=0.000344	0.99915	0.00009	0.00919
	80	a=1.01975, k=0.000347, b=0.0003137	0.99939	0.00006	0.00768
	100	a=1.01918, k=0.00041, b=0.00028	0.99980	0.00002	0.00427
$MR=e^{-kt}+bt$ Modified Midilli	60	k=7.482e-5, b=0.000487	0.99809	0.00020	0.01375
	80	k=0.00025, b=-0.00036	0.99892	0.00011	0.01022
	100	k=0.00033, b=-0.00032	0.99935	0.00006	0.00769
$MR=ae^{(-kt)^n}+b$ Demir	60	a=0.5099 , k=1.22e-5, n=1.6149, b=0.3097	0.99173	0.00100	0.03109
	80	a=0.5054, k=1.23e-5, n=1.6138, b=0.3093	0.99288	0.00093	0.03006
	100	a=0.5038, k=1.24e-5, n=1.6130, b=0.3092	0.99319	0.00083	0.02890
$MR=ae^{-k_1t}+ae^{-k_2t}$ Two-term	60	a=1.1206, k_1=25904, k_2=0.001046	0.95010	0.00582	0.07043
	80	a=0.8568, k_1=2, k_2=0.000836	0.95015	0.00540	0.06966
	100	a=0.55944, k_1=0.001145, k_2=0.001145	0.95286	0.00499	0.06578
$MR=ae^{-kt}+(1-a)e^{-kat}$ Two-Term Exponential	60	a=1.618e-5, k=55.838	0.92417	0.00814	0.08681
	80	a=1.9535e-5, k=51.039	0.92816	0.00737	0.08362
	100	a=1.84e-5, k=54.8438	0.93214	0.00667	0.07891
$MR=ae^{-kt}+(1-a)e^{-gt}$ Modified Two-Term Exponential	60	a=23.519, k=1.7211e-5, g=6.9956e-6	0.99809	0.00021	0.01374
	80	a=30.712, k=5.719e-5, g=3.8332e-5	0.99896	0.00010	0.01004
	100	a=32.6542, k=8.6744e-5, g=6.8878e-5	0.99941	0.00006	0.00735
$MR=ae^{-kt}+be^{-gt}+ce^{-ht}$ Modified Henderson and Pabis	60	a=0.16118, b=4.05361, c=0.18225, k=34.9134, g=1.12063, h=0.00104	0.95009	0.00637	0.07042
	80	a=0.5025, b=0.00079, c=0.5552, k=0.008031, g=0.009740, h=0.001905	0.95014	0.00573	0.06966
	100	a=0.372715, b=0.37272, c=0.37304, k=0.00114, g=0.00114, h=0.00114	0.95286	0.00540	0.06577
$MR=1+bt+at^2$ Wang	60	a=0.0005623, b=2.918e-9	0.99810	0.00020	0.01375
	80	a=0.0006174, b=2.7246e-8	0.99898	0.00010	0.00997
	100	a=0.000650, b=4.412e-8	0.99944	0.00005	0.00717
$MR=e^{-ct}+bt^{(pt+n)}$ Kaleemullah	60	c=5.403e-5, b=0.0002302, p=-1.938e-5, n=1.16392	0.92100	0.00884	0.08681
	80	c=8.292e-5, b=0.0001825, p=-2630e-5, n=1.7723	0.92817	0.00779	0.00350
	100	c=0.00100, b=0.08772, p=-0.28013, n=-2060.87	0.93215	0.00718	0.07892

Table 9: D_{eff} value for dryer temperatures of 60, 80, and 100 ºC

Temperature (ºC)	D_{eff} (m^2/s)
60	7.82867e-09
80	8.43088e-09
100	9.03308e-09

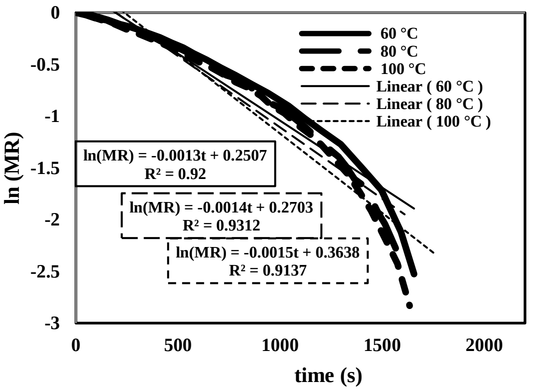

Fig. 7: lnMR-t diagram for three drying temperatures 60 ºC, 80 ºC, and 100 ºC.

As shown in Fig. 7, by increasing the drying temperature from 60 to 100 ° C, the slope of the ln(MR)-t graph (drying rate) increases and then the diffusion coefficient increases. By increasing 67% of drying temperature, according to Table 9, the diffusion coefficient increases by 15.47%. As shown in Fig. 7, by a 67% increase in the drying temperature at a desired period (1600 seconds), 51.4% more moisture is taken from the waste. According to previous studies, the diffusion coefficient

for most food items (even in Iran) in the range of 10^{-12} to 10^{-9} [17, 22], [38]. Also, this coefficient is close to 10^{-7} [26] and 10^{-6} [20] for plastics and textiles, respectively. Due to the fact that most of the components of MSW are organic materials, the MSW penetration coefficient will be close to the range of this amount related to food.

To determine the Arrhenius equation and the activation energy, the diagram ln (D_{eff}) – 1/T is plotted and the activation energy of the method used in the validation of this section is obtained as 36.96 kJ/mol and the Arrhenius equation is determined as Eq. (34). Based on the literature for the drying process, the activation energy for the drying process for plastics is between 28.26-52.07 kJ/mol [26], the activation energy for fabric is 28.06 kJ/mol [20] and finally, the activation energy for food items is in the range of 21 to 62 kJ/mol [17]. Because MSW is a combination of different materials, its activation energy is set at 36.96 kJ/mol.

$$D_{eff}= 2.97*10^{-8} \exp(-\frac{36960.71}{RT}) \quad (34)$$

External Drying Rate Results

As mentioned in the Experimental Section, the assumptions used to determine the external drying rate are: dry waste output rate is 1000 kg/h with a moisture ratio of 20% and MSW output temperature as 60 °C in the continuing fluid bed dryer. To determine the amount of drying rate, the dimensions of the dryer are needed. Since the dimensions of the sheets used for the dryer are 1.240 × 2.440 (m × m), to reduce costs, the diameter of each dryer should be 3 m, which can be achieved with four sheets. Then, the NTU and LTU (Eqs. (16) and (17)) were used to determine the dimensions of the dryer. According to NTU and LTU relations, the number of heat transfer units will be 0.988, and the value of the main height of the dryer should be 9.726 m; thus the value of the final height of the dryer is (0.988 × 9.726) 9.609 m. According to Eq. (15), the velocity of the inlet hot air velocity to the dryer is 0.475 m/s. And according to Eqs. (9) to (17), the amount of external drying rate is 0.002435 kg/m^3-s (or 0.165 kg/s or 594 kg/h).

As mentioned in the introduction, *Lawanangkul* [53] used the Continuous fluid bed dryer to dry Thai MSW. According to the validation section, the external drying rate is reported to be 600 kg/h. In the present study, the rate has been determined by using Eq. (9) to (17), as 594 kg/h. The small difference in the above rates is due to the difference in geographical, and climatic conditions, and the composition of MSW from Thailand to Iran. To ensure the accuracy of the results of the current work, the internal drying rate should be equal to the external drying rate.

To obtain the internal drying rate based on the data used in mathematical modeling, the MR-time graph during the drying process can be achieved as follows Eq. (35) and Fig. 8.

$$M_{water}=-0.157\ t+660.05 \quad (35)$$

It can be seen that the internal drying rate is 0.157 kg/s (factor for *t* in Eq. (35)), and the above-mentioned external drying rate is 0.165 kg/s. The difference between the two values is less than 5%, so it can be concluded that the theoretical results are acceptable.

Table 10: Energy rate values at different inputs and outputs to the dryer.

Energy rate	amount
$\dot{E}n_1$ (kW)	1534
$\dot{E}n_2$ (kW)	1226
$\dot{E}n_3$ (kW)	1157
$\dot{E}n_4$ (kW)	1222
Inlet power	214
$\dot{Q}_{loss}$ (kW)	595
$\dot{E}n_{total}$ (kW)	2974
$\dot{E}n_{used}$ (kW)	414
η(%)	13.92

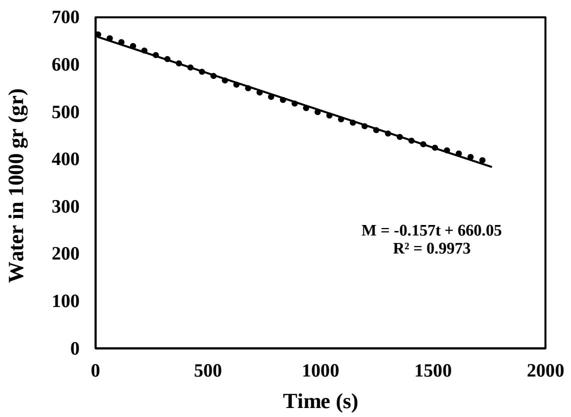

Fig. 8: Graph of the amount of water in the sample versus time during the drying process.

Energy analysis result

Based on Fig. 4, the values of input and output energies are given in Table 10.

Based on Table 10, energy efficiency was calculated by the EES-developed code as 13.92%. The energy flow in the dryer is shown in the Sankey diagram in Fig. 9.

Fig. 9 shows that out of 2974 kW of energy entering the dryer, 214 kW is used by the dryer to bring air and MSW into the dryer, and finally, 2760 kW enters the dryer by air and MSW streams. Then only 414 kW of energy is consumed in the dryer and 595 kW is lost. Finally, the rest of the input energy in the amount of 2379 kW is removed from the dryer by the outlet MSW and the exhaust air. Also, the value of the *SMER* in this study is 0.00006 kg/kWh. This shows that in contrast to the high energy consumed by the dryer, only a small amount of moisture is separated from the waste.

Based on previous studies, the energy efficiency of the dryer does not remain constant during the drying process. In other words, the initial moisture content in the MSW increases or the drying percentage increases, the energy efficiency of the drying process gradually decreases. This is because the energy required for the complete drying of the material is much more than the energy required for incomplete drying [38]. *Dincer* and *Zamfirescu* [54] examined the industrial drying of wood chips and reported the energy efficiency of the dryer as 34.5%. *Odewole et al*. [39] studied the complete drying of green pepper and concluded that in the best case, the energy efficiency is 0.196%. Therefore, it is observed that energy efficiency is variable and depends on the drying percentage of the material. In the present study, when the amount of moisture ratio reaches 50% to 20%, the energy efficiency of the dryer is 13.94%. Of course, another important issue in the field of energy is the air drying temperature, which will be discussed in the parametric study section.

Exergy analysis results

Based on the exergy analysis and the diagram of Fig. 4, the values of input and output exergies are given in Table 11.

Table 11 shows that the exergy efficiency of the dryer is 2.9% and according to the Grassmann diagram in Fig. 10, the amount of exergy used to evaporate moisture is 8.345 kW (the numerator of exergy efficiency), which is much less than the number of exergies entering the dryer. During the drying process, 16.08 kW of exergy is lost and the amount of exergy destroyed is 317.8 kW. According to the literature, the exergy efficiency of the dryer is always lower than its energy efficiency, which is due to the low amount of useful exergy. *Dincer* and *Zamfirescu* [54] obtained the exergy efficiency of a wood chips dryer as 8.7%. *Odewole et al.* [39] found the exergy efficiency for the drying process of green bell pepper in a cabinet tray dryer as 0.9929%. *Abbaspour-Gilandeh et al.* [38] experimentally dried the quince pieces in Iran and showed that the exergy efficiency was 88.2%, and *Castro et al.* [37] obtained the exergy efficiency of the onion drying process as 80%. In the latter two studies ([37, 38]) it is observed that the exergy efficiencies are much higher than

Table 11: Values of input and output exergies to the dryer.

Exergy rate	mount
$\dot{Ex}_1$ (kW)	72.21
$\dot{Ex}_2$ (kW)	3762
$\dot{Ex}_3$ (kW)	60.79
$\dot{Ex}_4$ (kW)	3653
$\dot{Ex}_{des}$ (kW)	317.8
$\dot{Ex}_{loss}$ (kW)	16.08
$\dot{Ex}_{used}$ (kW)	8.345
ε(%)	2.9

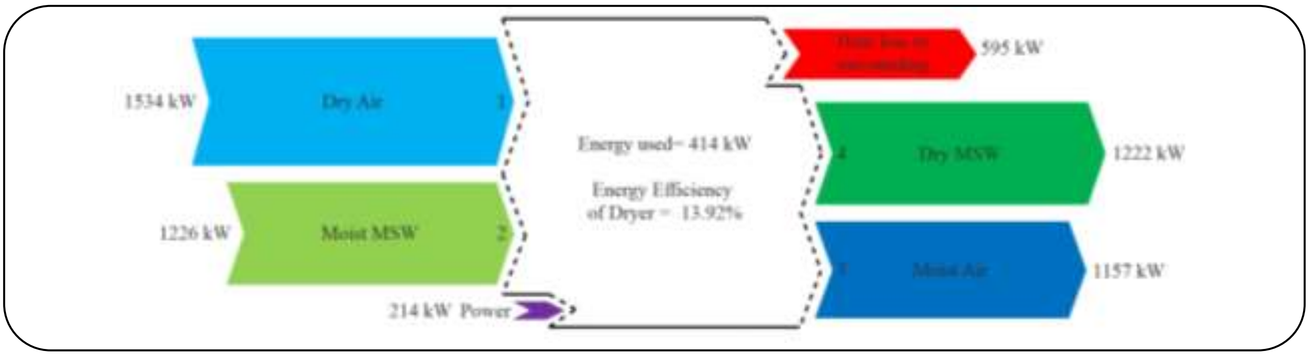

Fig. 9: Sankey diagram of energy flow for the MSW dryer

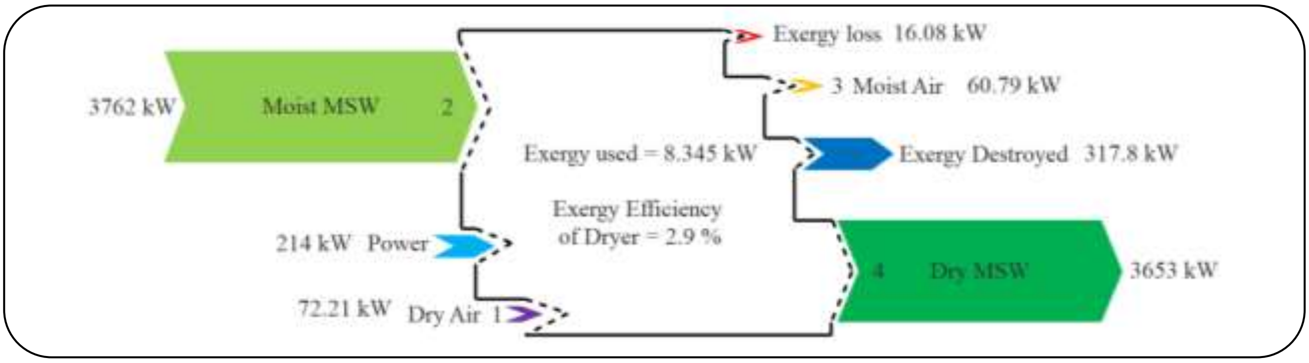

Fig.10: Grassmann diagram of exergy flow for MSW dryer

the values reported in the former references ([54, [39]). The difference in the values of the exergy efficiency is related to the definition of the exergy efficiency so that in the latter references the exergy efficiency is defined according to Equation 36, and if this equation is used in the present work, the exergy efficiency of the dryer is 91.75%. Therefore, it is observed that the definition of efficiency in both Eq. (32) and (36) is logical and their difference is only in determining the produced exergy (target exergy). In Eq. (32), target exergy is considered as useful exergy and in Eq. (36), all output exergies except destruction and loss exergies are considered as produced exergy. Both of the above equations have been used in the literature.

$$\varepsilon=1-\frac{\dot{Ex}_{loss}+\dot{Ex}_{des}}{\dot{Ex}_1+\dot{Ex}_2+\dot{Ex}_{Power}} \quad (36)$$

Parametric study

To determine the effects of the parameters affecting the drying process, a parametric study should be performed for this purpose from energy and exergy aspects. The parametric study in this section is divided into two parts:

a) The first part presents the parameters that affect the energy and exergy efficiencies of the dryer in the relevant literature was examined and the results are compared with the present parametric results. These parameters are shown in Fig. 11, as inlet air temperature, absolute humidity of inlet air, and residential time.

(b) In the second part of the parametric study, parameters whose effects on energy and exergy efficiencies have not yet been studied in the literature are examined. The study of the effect of these parameters is another innovation of the present study and their effects on energy and exergy efficiencies are presented in Fig. 12. These parameters are reference ambient absolute humidity, operation pressure, the temperature of inlet MSW, the temperature of outlet air, and outlet MSW moisture.

Part a

Part a-1) inlet air temperature.

The effect of the inlet air temperature on the energy and exergy efficiencies of the MSW dryer is shown in Fig. 11a. It is observed that with increasing the inlet air temperature to the dryer, both energy and exergy efficiencies decrease. As the inlet air temperature increases, the enthalpy of the incoming air and the total inlet energy to the dryer increase, while the amount of useful energy (the numerator of energy efficiency) remains constant, so by increasing the inlet air temperature from 300 to 500 K, energy efficiency of the dryer decreases from 17.29% to 12.44%.

For exergy efficiency, this process is re-established. By increasing the inlet air temperature from 300 to 500 K, the total amount of input exergy increases, so the exergy efficiency decreases from 4.4% to 1.93%. Due to the changes in energy and exergy efficiencies, the exergy efficiency changes more than the energy efficiency, due to the greater effect of the inlet air temperature on the useful exergy.

Odewole et al. [39] showed with a 20% increase in inlet air temperature, the energy efficiency of the dryer has been decreased by 40%, In the current study with a 67% increase in inlet air temperature, the energy efficiency of the dryer decreases by 28%. Also, in the study of *Odewole et al.* [39], it was shown that due to the complete drying of green pepper, energy efficiency is very small (below 0.02%).

The results of *Castro et al.* [38] were used to investigate the effect of inlet air temperature on exergy efficiency, where the exergy efficiency of the drying process is calculated by Eq. (36). By 60% increase in the inlet air temperature, the exergy efficiency of the drying process decreases by 12.5%, which for the present study, by 67% increasing the inlet air temperature, the exergy efficiency decreases by 9%. According to the results presented in the literature, it is observed that the change in energy and exergy efficiencies in the present study are in good agreement with those of other researchers.

Part a-2) absolute humidity of inlet air

Fig. 11b shows the effect of the absolute humidity of the inlet air on the energy and exergy efficiencies of the MSW dryer. As can be seen in the figure, by increasing the amount of absolute humidity of the inlet air from 0.03 to 0.09 kg/kg, the values of energy and exergy efficiencies decrease from 13.98% to 12.98% and from 2.92% to 0.1%, respectively. As the absolute humidity of the inlet air increases, the energy used (Eq. (25)) does not change, but the amount of the total entering energy into the dryer increases, which lowers the energy efficiency. As the absolute humidity of the inlet air increases, both the amount of useful exergy and the total amount of inlet exergy decrease, but the decrease of useful exergy is greater than the decrease of total input exergy, ultimately the exergy efficiency is ultimately reduced.

Terehovic[36] studied the effect of absolute humidity of the inlet air on energy and exergy efficiencies of the dryer, and with a 9-fold increase in the absolute humidity of the inlet air (from 1 to 9 g/kg), reported that energy and exergy efficiencies decreased by 45% and 98%, respectively. In the present study, with a 3-fold increase in the absolute humidity of the inlet air (from 0.03 to 0.09 kg/kg), the energy and exergy efficiencies decrease by 21.42% and 96.57%, respectively. By comparing the results of *Terehovic*[36] and the present parametric study, it can be seen that the changes in these efficiencies are in line with each other.

Part a-3) residential time duration

One of the most important parameters in determining energy and exergy efficiencies is residential time. If the residential time in the dryer increases, the moisture in the output MSW decreases, and the amount of energy required for drying increases, and vice versa. Fig. 11c shows the effect of residential time on energy and exergy efficiencies, so with increasing the residential time from 447 to 1667 s, energy, and exergy efficiencies increase by 4.3% and 90%, respectively. As the residential time

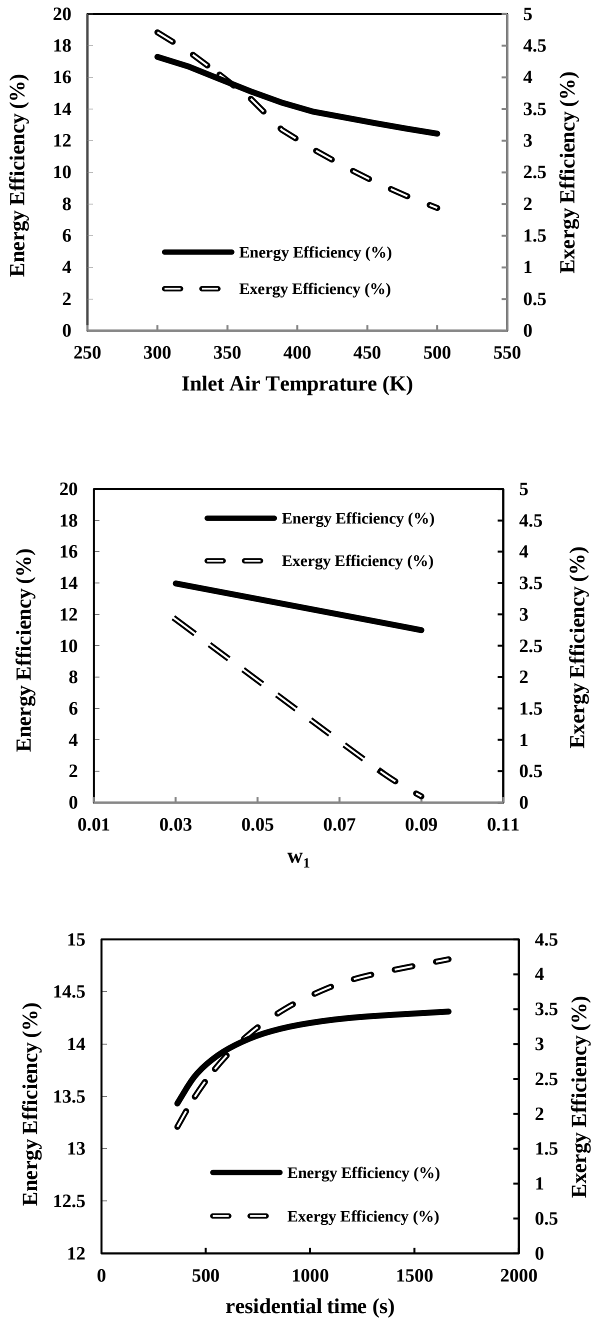

Fig. 11. Parametric studies on energy (η) and exergy (ε) efficiencies, (a) Inlet air dry temperature, (b) Absolute humidity of inlet air, (c) Time.

increases, both the input energy and exergy to the dryer increase; however, the increase in useful energy and exergy are greater than the relative increase of inlet energy and exergy, then the energy and exergy efficiencies increase. Finally, more moisture will be removed from the MSW and the dryer efficiency will increase. To compare the results of the present work, the research of *Hatami et al.* [41] has been used. Both these research shows that with increasing residential time, the energy and exergy efficiencies are increased. It should be noted that in Fig. 11c of the present study, the time range is selected (1664 s) in such a way that the maximum energy and exergy efficiencies can be determined.

Part b

Part b-1) reference ambient absolute humidity

Fig. 12a shows the effect of the absolute humidity of the reference ambient on the energy efficiency and exergy of the MSW dryer (according to Eq. (29)). As can be seen in this figure, absolute humidity does not affect the amount of energy efficiency and will only affect the exergy efficiency. As the absolute humidity of the reference ambient increases, the exergy efficiency decreases due to the increase in the amount of exergy of the dry air inlet to the dryer. It is observed that by increasing the absolute humidity of the reference ambient from 0.02 to 0.09, the amount of exergy efficiency decreases from 2.97 to 2.79%.

Part b-2) operation pressure

Fig. 12b shows the effect of inlet air pressure on the energy efficiency and exergy efficiency of the MSW dryer. It can be seen that with an increase in inlet air pressure, there is not much change in the amount of energy efficiency and the change is insignificant. By increasing operation pressure from 50 kPa to 152 kPa, the exergy efficiency decreases from 6.44% to 2.46%. As the operation pressure increases, both the useful exergy and the total inlet exergy increase. since the amount of total inlet exergy increases more than the amount of useful exergy, then by increasing the operation pressure from 50 kPa to 152 kPa, the amount of useful exergy increases from 5.7 kW to 9.8 kW and the total inlet exergy increases from 87 kW to 402 kW. As a result, the amount of exergy efficiency will decrease with an increase in the operation pressure.

Part b-3) temperature of inlet MSW

The effect of MSW inlet temperature on the energy and exergy efficiencies of the MSW dryer is shown in Fig. 12c. Increasing the MSW inlet temperature, will increase the amount of input enthalpy to the dryer, but the useful energy changes slightly, so the energy efficiency decreases.

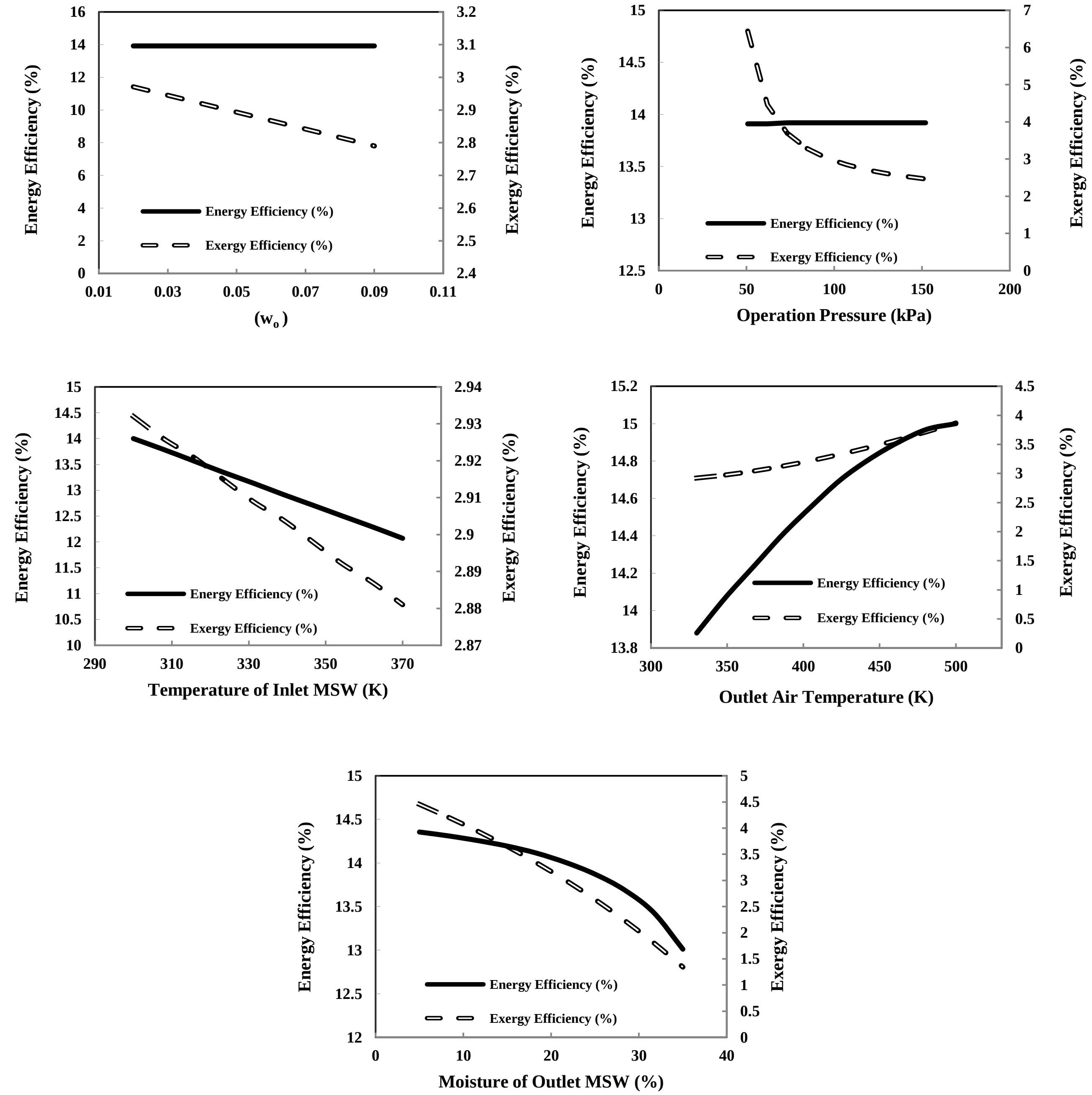

Fig. 12: Parametric studies on energy (η) and exergy (ε) efficiencies, (a) Reference ambient absolute humidity, (b) Operation pressure, (c) Temperature of inlet MSW (d) Outlet air temperature and (e) Moisture of outlet MSW.

Also, with increasing the MSW inlet temperature, due to increasing the total inlet exergy to the dryer, as the useful exergy does not change, the exergy efficiency decreases. Therefore, by increasing the temperature of inlet MSW from 300 to 370 K, the amount of energy efficiency decreases from 14% to 12.07% and the amount of exergy efficiency decreases from 2.9% to 2.88%.

Part b-4) outlet air temperature

Fig. 12d shows that energy and exergy efficiencies increase with increasing outlet air temperature. By increasing the outlet air temperature from 330 to 500 K, the amount of useful energy in the dryer increases, while the amount of input energy remains constant and therefore, the energy efficiency will increase from 13.88% to 15%. Also, by increasing the outlet air temperature from 330 to 500 K, the amount of used exergy in the dryer increases, which leads to an increase in the exergy efficiency from 2.9% to 3.72%.

Part b-5) moisture of outlet MSW

Fig. 12e shows that with increasing moisture of MSW outlet from 8% to 35%, energy, and exergy efficiencies decrease by 9.40% and 69.6%, respectively. According to Eqs. (25) and (32), which represent the energy and exergy efficiencies, by increasing moisture of outlet MSW from the dryer (with constant input energy and exergy), the useful energy and useful exergy decrease, and therefore both energy and exergy efficiencies are reduced. It should be noted the moisture of outlet MSW has a greater effect on exergy efficiency than energy efficiency, as the useful exergy is reduced more than the useful energy.

CONCLUSIONS

The aim of this study is to investigate the modeling and thermodynamic analysis of the MSW dryer process. Since the kinetic mathematical model for the unsorted MSW drying process has not been presented so far, in this research the kinetic mathematical model is presented based on the semi-theoretical method and then the internal drying rate is calculated based on the selected model. In addition, the external drying rate is calculated using the existing experimental equations for the continuous fluid bed dryer and then it was compared with the internal drying rate. Also, energy and exergy analysis was performed for MSW dryer and the effect of different parameters on energy and exergy efficiencies was evaluated. The most important results of the present study are presented below.

Based on the results of Statistica software, the logarithmic model is determined as a suitable mathematical model for the MSW drying. In addition, according to the selected model, the internal drying rate is calculated as 0.157 kg/s. Then, to calculate the external rate of the dryer, the dryer continuous fluid bed dryer was selected as the appropriate dryer for MSW, and the dry MSW rate was chosen as 1000 kg/h, then the diameter and height of the dryer were calculated as 3 and 9.61 m, respectively. Next, the external drying rate was calculated at 0.165 kg/s based on the experimental equations and the real environmental conditions for this dryer. By comparing these two drying rates, it is observed that the internal and external drying rates are 5% different, which indicates that the necessary precision to model the drying process in the current study has been maintained.

The results of the energy and exergy analysis of the dryer show that the energy and exergy efficiencies are 13.94% and 2.9%, respectively. Also, the effect of various parameters such as inlet air temperature, absolute humidity of inlet air, time, reference ambient absolute humidity, operation pressure, the temperature of inlet MSW, the temperature of outlet air, and outlet MSW moisture on energy and exergy efficiencies have been studied. The results of the parametric study show that increasing the inlet air temperature, the absolute humidity of the inlet air, the temperature of inlet MSW, and the moisture of outlet MSW, energy and exergy efficiencies decrease, and by increasing the residential time and outlet air temperature energy and exergy efficiencies increase. Based on the results, increasing reference ambient absolute humidity and operation pressure have no effect on energy efficiency but these parameters reduce the exergy efficiency. Among the studied parameters, the inlet air temperature and the MSW inlet temperature of the dryer have the greatest effect on energy efficiency, respectively. Finally, the results show that the inlet air conditions including absolute humidity and pressure have the greatest effect on the exergy efficiency of the MSW drying process.

Nomenclature

a_g	Specific surface area, m^2/m^3
Cp	Specific heat, kJ/kg -K
d	Diameter, m
D	Diffusion coefficient (m^2/s); Diameter of dryer, m
D_o	Arrhenius equation coefficient, m^2/s
ex	Specific exergy, kJ/kg
$\dot{E}n$	Total energy rate, kW
$\dot{E}x$	Total exergy rate, kW
E_a	Activation energy, kJ/kmol
G	Mass flow rate, kg/m^2-h
h	Specific enthalpy, kJ/kg
k_m	Mass transfer coefficient, m/s
LTU	Length of each thermal unit, m
$\dot{m}$	Mass flow rate, kg/s
M	Moisture content, (kg H_2O/kg dry solid), Molecular mass, kg/kmol
MR	Moisture ratio, %

MSW	Municipal Solid Waste
n	Degree of freedom
N	Number of experiments
NTU	Number of thermal Unit
P	Pressure, kPa
p	Partial pressure, kPa
$\dot{Q}$	Heat transfer rate, kW
r	Radius or location, m
R	Gas constant, kJ/kg-K
R_u	Universal gas constant, kJ/kmol-K
t	Time, s
T	Temperature, K
v	Passing air velocity, m/s
$\dot{W}$	Work rate, kW
x	Mole fraction

Greek letters

β	Parameter
ε	Exergy efficiency, %
η	Energy efficiency, %
μ	Dynamic viscosity, m^2/s
ρ	Density, kg/m^3
ω	Humidity ratio of air

Subscript and superscript

0	Reference point and dead state
∞	Equilibrium, free stream
a	Air, dry air
dest	Destroyed
e	End of a process
E	Measured
ev	Evaporation
f	Saturated liquid state
g	Saturated vapor state
H/g	Water/gas
H_2O	Water
i	Initial
loss	Loss
p	Particle
P	Predicted
surf	Surface
t	Time
v	Water vapor in air
w	Water
wb	Wet-bulb
0	Reference point
x	Mole fraction

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