

An artificial neural network modeling of solar drying of mint: Energy, exergy, and drying kinetics

Fevzi Gülçimen

Munzur University

Hakan Karakaya

hakan.karakaya@batman.edu.tr

Batman University

Aydın Durmuş

Ondokuz Mayıs University

Research Article

Keywords: Exergy analysis, Energy analysis, Solar drying, Artificial neural network, Kinetics of drying, Mint

Posted Date: May 13th, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-4373121/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

An artificial neural network modeling of solar drying of mint: Energy, exergy, and drying kinetics

Fevzi Gülçimen¹, Hakan Karakaya^{2*}, Aydın Durmuş³

¹*Munzur University, Mechanical Engineering Department, Tunceli, 62000, Turkey.
(e-mail: fgulcimen@gmail.com)

²Batman University, Mechanical Eng. Department, Batman, 72100, Turkey.
(e-mail: hakan.karakaya@batman.edu.tr)

³ Ondokuz Mayıs University, Mechanical Eng. Department, 55139, Samsun, Turkey.
(e-mail: adurmus@omu.edu.tr)

*Correspondence: hakan.karakaya@batman.edu.tr, hkarakaya2323@gmail.com

ORCIDs:

¹Fevzi Gülçimen: <https://orcid.org/0000-0002-2401-1981>

²Hakan Karakaya: <https://orcid.org/0000-0001-9242-6233>

³Aydın Durmuş: <https://orcid.org/0000-0002-0616-567X>

Abstract: The energy and exergy analysis of thin-layer drying of mint leaves was performed in a forced convective solar dryer with new design solar collector. The effects of inlet airflow rates on the energy utilization ratio (EUR), energy generated by the solar air collector, exergy losses, exergy efficiency, and kinetics of drying were determined. The EUR varied between 7.45 to 87.1% and it increased when the flow rate decreased. The average exergy loss for the air with mass flow rates of 0.012, 0.026, and 0.033 kg/s was calculated as 16.2 W, 8.2 W, and 6.88 W, respectively. Unlike other studies, exergy and EUR data obtained from experimental data were modeled with an artificial neural network (ANN). The experimental data were modeled by an artificial neural network (ANN) via a feed-forward back-propagation network. The values obtained from ANN modeling were significantly closed to the experimental values. In both experimental and ANN models, EUR and exergy loss decreased with increasing airflow rate. The importance of airflow rates was promising to modify EUR and exergy losses.

Key words: Exergy analysis, Energy analysis, Solar drying, Artificial neural network, Kinetics of drying, Mint.

Nomenclature

A	area, m ²
C_p	specific heat, kJ/ kg K
E	emissive power
EUR	energy utilization ratio, %
Ex	exergy rate, kW
F	shape factor
g	gravitational acceleration, m/s ²
g_c	constant in Newton's law
h	enthalpy, kJ/kg
I	solar radiation, W/m ²
J	joule constant
$\dot{m}$	mass flow rate, kg/s
N	number of species
P	pressure, kPa
Q	net heat rate, W
s	specific entropy, kJ/kg K
t	time, minute
T	temperature, °C
U	specific internal energy
v	specific volume, m ³ /kg
V	velocity, m/s
w	specific humidity, g/g
z	altitude coordinate, m

Subscripts

1	a	air
2	c	chemical
3	col	collector
4	cp	connection pipe
5	da	drying air
6	f	fan
7	i	inlet
8	dc	drying chamber
9	L	loss
10	mp	moisture of product
11	o	outlet
12	sat	saturated
13	∞	surrounding or ambient
14	<i>Greek letters</i>	
15	ϕ	relative humidity, %
16	η_{ex}	exergy efficiency, %
17	μ	chemical potential, kj/kg

1. Introduction

Since the harvest periods of medicinal and aromatic plants vary depending on their intended use, the best preservation method is drying. Medicinal and aromatic plants such as mint cannot be kept fresh for a long time due to the active substances they contain. By drying, the water content of the plant is reduced to a certain value, and its enzymatic and microbiological activities are slowed down or stopped. Thus, the storage period of the product is extended. At the same time, the aroma, color and many quality criteria of the plant are preserved. Today, one of the most important post-harvest processes that affects the active ingredients in medicinal and aromatic plants is drying. The therapeutic properties of dried medicinal plants last for about a year [1].

Drying mint leaves and other leafy products in the sun is different from drying other agricultural products due to their characteristics such as Drying Speed and Time, Fragrance and Essential Oils, Color and Appearance, Adhesion and Dispersion, Medicinal and Cosmetic Uses, etc. These differences are based on the characteristics of the plant, its intended uses and the specific requirements (appropriate temperature values, drying method, protection from external influences, etc.) of the drying process, which must be carefully managed.

Mint is an aromatic plant from the genus *Mentha* (*Mentha L.*) which due to its unique aroma and bio-components, is widely used in different industries such as food, beverage, and cosmetics [2]. Mint contains 75-85% water which makes it vulnerable to storage [3]. Drying of agriculture products is an ancient method that can protect them from chemical deterioration, enzymatic degradation, and microbial spoilage and it can decrease the packaging and storage costs by removal of moisture from the foods [4]. Open sun drying which is generally used to dry agriculture products under direct sunlight can produce dried products rich in color [5], but it leads to the growth of harmful microorganisms, produce toxic compounds by fungi [6], and contamination of food by environmental pollutants (such as dust, dirt, and insects)[5]. In contrast, solar drying as an environmentally friendly and green technology [7] can improve the quality parameters of food and decrease the risk of microbial, chemical, and environmental contamination [8]. Solar drying of various agriculture products has been studied by different authors [7,9-16].

Exergy and energy analysis is an important tool to evaluate the performance of solar drying systems. These analyzes are used to understand and optimize energy flows in the system. Solar drying systems are designed to dry agricultural products using solar energy, and exergy and energy analysis provides benefits such as efficiency evaluation, optimization possibility, saving of energy resources, estimation of system performance, reduction of environmental impacts, etc. to increase the efficiency of these systems. For these reasons, solar energy It is important to use exergy and energy analyzes in the design, development and operation of drying systems. These analyzes help systems become more efficient, economical and environmentally friendly. The thermodynamic analysis, particularly the analysis of the exergy helps to improve the performance and decrease the loss of energy in the dryer via optimization of the usage energy [17]. The energy analysis which is determined according to the 1st law of thermodynamics represented the fundamental of the conservation of energy, but it gives no data concerning the irreversibility. As the energy

analysis can't identify the different qualities of energy, a powerful tool is preferred along with energy analysis at the engineering evaluation which named exergy analysis. The exergy is the highest value of work that produced from a flow of substance, heat, or work when system reaches a thermodynamic equilibrium with a reference surroundings. Increases in the irreversibilities of thermal processes can destroy the exergy, thus to increase the exergy of a dryer, the irreversibilities need to be decreased [18]. Researchers examined how the design of the absorber plate affects an indirect solar dryer's thermal performance while taking temperature dependence into account [19]. The exergy analysis is used to find the origins of inefficiency, to identify the quality of energy utilization, and to provide information for optimization of drying conditions to reduce the environmental problems which produce by the dryers [20]. Researchers aimed to increase system efficiency by using energy and exergy analysis in drying food products. [21-25].

Artificial neural networks (ANN), a machine learning method that has found wide use in recent years, are used to solve complex problems in various tasks, from parameter and function estimation to classification. ANNs have been reported to be useful for tasks involving partial data sets, ambiguous and insufficient information. Networks are capable of using different inputs to predict multiple output variables, even without prior knowledge of process relationships [26]. Unlike many machine learning methods, the basis on which ANN is based is to consider the hidden relationships between the attributes (variables) that constitute the data. ANNs learn by using a set of parameters or classification categories that can be observed before or whose actual answer is known, and accordingly, the data that the ANN model has not seen before can be predicted with the hidden network structure created as a result of learning. With this approach, ANN imitates the biological nervous system. Layers consisting of neurons constitute the ANN. The input layer contains as many neurons as the number of features in the training data. Target output values are represented by one neuron in the output layer. Hidden layers are located between the input and output layers. Neurons collect the information that reaches them through activation or transfer functions and transmit it to the next neurons they are connected to [27]. Thus, in each training iteration that provides this information flow, neuron weights are updated according to a rule and a hidden relationship order is formed within the network. Since drying is a complex process, there are many approaches that model the drying rate and product moisture ratio according to the drying process under various drying conditions [28-29]. Due to the mentioned advantages, artificial neural networks have also been used by different researchers in studies on drying agricultural products. Modeling of drying processes by the artificial neural network (ANN) can solve nonlinear and complex equations [30]. Various authors applied ANN for modeling the drying process of fruits and vegetables: solar drying of potato [31], convective infrared drying of kiwi fruit [32], convective drying of apple [33], microwave drying of orange slices [34], and infrared drying of carrot [35]. Azadbakht et al. studied the energy/exergy analysis of fluidized bed drying of potato by ANN methods [36]. The results revealed that energy utilization, and EUR had a positive correlation with the velocity of dry air and depth of the bed. Furthermore, increases in the air velocity, temperature, and depth of the bed caused an improvement in the exergy loss and efficiency. Özdemir et al. used convective-infrared drying at different temperatures (40-55°C) for drying kiwi fruit. The energy efficiency was between 2.85% and 32.17% and the ANN method was successful in the estimation of the values of energy consumption and optimization of drying conditions [32].

Solar drying of mint leaves was studied by some authors but the ANN modeling was not used in their research [12,37,38]. The most important feature that distinguishes this research from the before studies are modeling of energy/exergy by the ANN method. This research aims to predict and simulate the energy/exergy parameters and thermodynamic aspects of solar drying of mint leaves by ANN modeling. The effect of different mass flow rates and solar radiations on the energy analysis of new designed collector and drying chamber, the EUR, the exergy loss, exergy efficiency and drying kinetics were investigated. Also, the ANN was used to verify the accuracy of experimental data of the solar dryer.

2. Materials and Methods

2.1. Materials

The fresh mint leaves were provided from a local market (Elazığ, Turkey) and then washed with water. A filter paper was used to remove excess water from the surface of mint leaves.

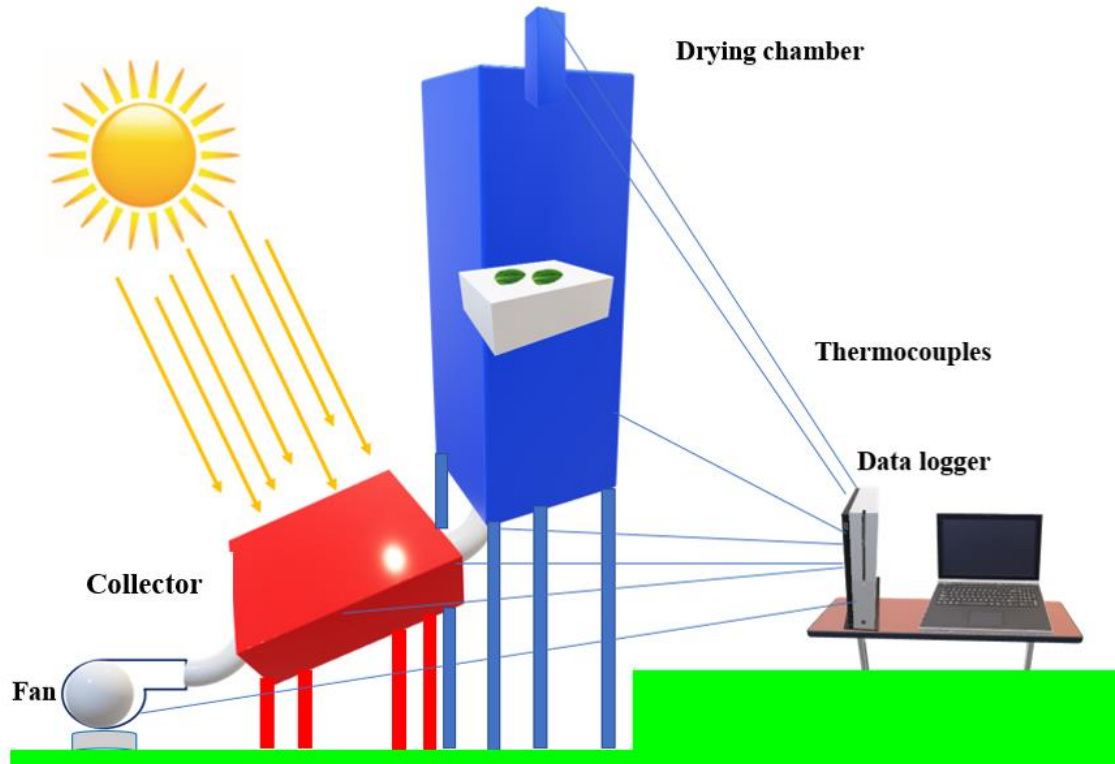
2.2. Experimental set-up

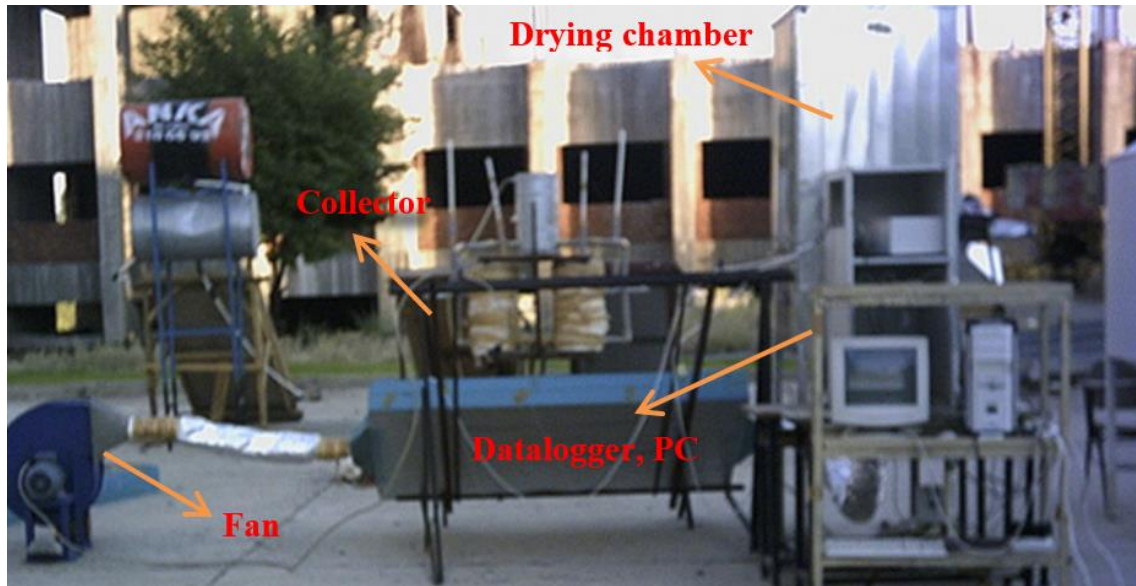
Drying experiments were performed from 9:00 AM-5:00 PM in Firat University, Technical Education Faculty, Elazig, Turkey. The solar cabinet dryer ("Fig. 1A") has been used in this study.

In the first stage of this study, collector efficiency experiments were carried out in order to increase the performance of solar air collectors. Manufactured from standard collector cases, collectors with dimensions of $0.93 \times 1.93 \text{ m}^2$ were produced by modifying the flow channel ("Fig. 1C"). Fins were added to the flow channel, positioned at different angles: 30° , 45° and 60° . The effect of these fins on collector efficiency was primarily examined. Based on the results of the experiments, the most effective collector type was determined and used in drying experiments.

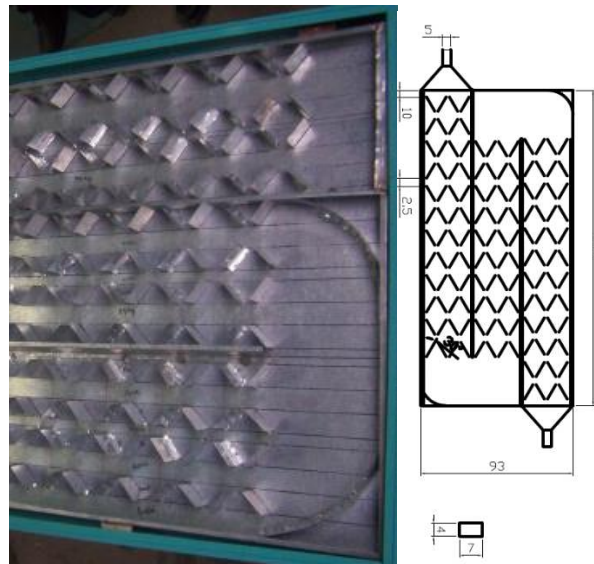
The inner chamber of the dryer unit was produced using a 0.8 mm thick stainless steel sheet in the dimensions of $1.2 \times 0.74 \times 0.74 \text{ m}$, which was respectively enclosed in an outer chamber (stainless steel) in the dimensions of $1.5 \times 0.75 \times 0.75 \text{ m}$. Polystyrene insulating materials were filled in the space between the two chambers for insulating. A centrifugal fan was utilized for blowing air into the collector via an aluminum duct (with a diameter of 82 mm) and an AC-type hertz converter was used for controlling the airflow. The air passed through the chimney with the dimensions of $0.3 \times 0.2 \times 0.2 \text{ m}$ leaving the heating chamber, and this process ensured the mixing and having a uniform temperature distribution before going into the drying area ("Fig 1B").

The data about air temperature, inlet and outlet temperatures of both solar collector and drying chamber, the temperature of mint (the central point of mint) during drying, and relative humidity of the air inside the drying chamber (right about the surface of mint) were recorded every 5 minutes. The below elements were used for measuring the different variables: 1) Temperatures (accuracy $\pm 0.1^\circ\text{C}$): a combination of the thermocouples of copper-constant T Type, ZA9000FST connector element, 5990-0 Almemo digital data logger. 2) Air speed (0.1-15 m/s): the thermo anemometer (FVA645TH3). 3) The pressure change within the collector: FDA612MR pressure module. 4) Weigh loss of mint (accuracy $\pm 0.1 \text{ kN}$): the strain strength FKA0251 within 0.02-10 kN range. 5) Solar radiation: Kipp and Zonen solarimeter. 6) Collection of all data: By interfacing data logger Almemo 5990-0 to a PC.





B



C

Figure 1. A. Experimental set up (schematic)
B. Experimental set up (photo)
C. Collector stream line .

3. Analysis

3.1. Energy analysis

An energy analysis has been selected within the context of the 1st law of thermodynamics. The drying is considered as the steady flow operations, thus general equations of mass conservation (dry and moist air), and energy conservation in a steady flow state [9] were defined by the “Eqs. (1-3)”.

Mass conservation of drying air is calculated using “Eq. (1)”:

$$\sum \dot{m}_{da,i} = \sum \dot{m}_{da,o} \quad (1)$$

Moisture balance is determined by using “Eq. (2)” [21]:

$$\sum (\dot{m}_{da,i} \cdot w_i + \dot{m}_{mp}) = \sum \dot{m}_{da,o} \cdot w_o \quad (2)$$

Energy conservation is calculated by “Eq. (3)”:

$$\dot{Q} - \dot{W} = \sum \dot{m}_{da,o} \left(h_o + \frac{v_o^2}{2} \right) - \sum \dot{m}_{da,i} \left(h_i + \frac{v_i^2}{2} \right) \quad (3)$$

The kinetic and potential energy in the drying system were omitted except for the kinetic energy of the fan [9]. Also, the mass flow rate is considered constant during drying and any change in it is negligible (“Eq. (4)”)[39].

$$\dot{m}_{da,o} = \dot{m}_{da,i} = \dot{m}_{da} \quad (4)$$

3.1.1. Properties of air

The relative humidity (ϕ) and enthalpy (h) of drying air for energy and exergy analysis were determined by “Eq. (5)”, and “Eq. (6)”, respectively.

$$\phi = \frac{wP}{(0.622+w)P_{sat@T}} \quad (5)$$

$$h = C_{pda} T_{da} + w h_{sat@T} \quad (6)$$

Where P , $P_{sat@T}$ and w are the atmospheric pressure, the saturated vapor pressure and specific humidity of drying air. Also, C_{pda} , $h_{sat@T}$, and T_{da} represent the specific heat of drying air, enthalpy of the saturated vapor, and temperature of drying air, respectively [9,21].

3.1.2. Solar air collector

It was presumed that there was no heat loss in the pipes which are used for the connection of the solar collector and the fan. Thus, the specific humidity, temperature, and relative humidity of air exit from the fan were equal to the inlet condition of the solar collector which was shown by “Eq. (7)” [9].

$$w_{col,i} = w_{fo}, \quad T_{col,i} = T_{fo}, \quad \phi_{col,i} = \phi_{fo}, \quad h_{col,i} = h_{fo} \quad (7)$$

The energy gained from the collector was determined according to the “Eq. (8)”:

$$Q_{col} = \dot{m}_{da} \cdot C_{pda} (T_{col,o} - T_{col,i}) \quad (8)$$

However, according to the temperature measurement, certain losses of heat were observed between the collector outlet and drying chamber inlet which is connected by the connection pipe. Therefore, the heat losses throughout this pipe are calculated by “Eq. (9)”:

$$Q_{L,cp} = \dot{m}_{da} \cdot C_{pa} \cdot (T_{col,o} - T_{dc,i}) \quad (9)$$

3.1.3. Drying chamber

The heat used for drying mint samples at the solar drying chamber was determined by “Eq. (10)”.

$$Q_{dc} = \dot{m}_{da} \cdot (h_{dci} - h_{dco}) \quad (10)$$

The EUR is the ratio of energy utilization in the drying chamber to the provided energy by a collector which was calculated by “Eq. (11)”[40]:

$$EUR = \frac{\dot{m}_{da} (h_{dci} - h_{dco})}{\dot{m}_{da} \cdot C_{pa} (T_{col,o} - T_{col,i})} \quad (11)$$

3.2. Exergy analysis

Some amount of exergy which enters the drying chamber can be destroyed due to irreversibility [10]. Therefore, the overall inlet, outlet, and loss exergy were predicted according to the 2nd law of thermodynamics at the steady-state points. The general equation of exergy (“Eq. (12)”) in a steady-state system can be defined according to the energy balance as follows [6]:

$$Exergy = \left(\underbrace{u - u_{\infty}}_{\text{internal energy}} \right) - T_o \left(\underbrace{s - s_{\infty}}_{\text{entropy}} \right) + \frac{P_o}{J} \left(\underbrace{v - v_{\infty}}_{\text{work}} \right) + \underbrace{\frac{v^2}{2gJ}}_{\text{momentum}} + \left(\underbrace{z - z_{\infty}}_{\text{gravity}} \right) \frac{g}{g_c J} + \sum_c \left(\underbrace{\mu_c - \mu_{\infty}}_{\text{chemical}} \right) N_c + E_g A_g F_g \left(\underbrace{3T^4 - T_{\infty}^4 - 4T_{\infty}T^3}_{\text{radiation emission}} \right) + \dots$$

Where the reference conditions are denoted by the subscript ∞ . “Eq. (12)” can be used as a general equation for the determination of the exergy of various systems. However, for solar drying systems, some values in the “Eq. (12)” such as momentum (kinetic energy), gravitation term (potential energy), chemical energy, and radiation emission can be neglected [10]. Also, the alterations in the pressure values within the system should be neglected because of $v = v_{\infty}$. Furthermore, for solar drying systems with steady-state flow, enthalpy can be used instead of internal energy and flow works (mechanical energy)[12,13]. Therefore, for solar dryer “Eq. (12)” is simplified as “Eq. (13)”[10,24].

$$Exergy = \dot{m}_{da} c_{pda} \left[(T - T_{\infty}) - T_{\infty} \ln \frac{T}{T_{\infty}} \right] \quad (13)$$

3.2.1. Exergy losses

The exergy losses (Ex_L) is calculated by the “Eq. (14)”:

$$\sum Ex_L = \sum Ex_i - \sum Ex_o \quad (14)$$

Where Ex_i and Ex_o represent the inlet and outlet exergy, respectively.

Both the inlet and outlet exergy of dryer is determined based on the inlet and outlet temperature of the dryer by using “Eq. (15)”, and “Eq. (16)”, respectively [6].

$$Ex_{dci} = \dot{m}_{da} c_{pda} \left[(T_{dci} - T_{\infty}) - T_{\infty} \ln \frac{T_{dci}}{T_{\infty}} \right] \quad (15)$$

$$Ex_{dco} = \dot{m}_{da} c_{pda} \left[(T_{dco} - T_{\infty}) - T_{\infty} \ln \frac{T_{dco}}{T_{\infty}} \right] \quad (16)$$

Where c_{pda} represent the average specific heat capacity of drying air [12].

3.2.2. Exergy efficiency

The exergy efficiency (η_{Ex}) of the solar dryer is the ratio of the outlet exergy to the inlet exergy of the drying chamber which is shown by “Eq. (17)” [13]:

$$\eta_{Ex} = \frac{Ex_o - Ex_L}{Ex_i} = 1 - \frac{Ex_L}{Ex_i} \quad (17)$$

3.3. The analysis of ANN

ANN, a powerful computational system, is based on the structure and learning characteristics of the biological neuron cell [41]; it also is a highly powerful classifier in pattern recognition. We can define ANN as a parallel processing structure by the following features [30]:

- 1) It explains a mathematical model that is inspired by a biological neuron.
 - 2) It consists of many interdependent process elements.
 - 3) Information is kept with connection weights.
 - 4) There is a processing element that dynamically reacts to the input warnings while the response is entirely dependent on local information (respective processing element affected by link weights and an input signal through the connections).
 - 5) It also consists of the ability to learn, remember, and generalize regarding the use of the connection weights specified by the training data. The talent to solve complex problems in artificial neural networks is guaranteed by these relevant outstanding characteristics.
- “Figure 2.” shows ANN model of the processing element inspired by the biological neuron [42]. “Figure 2A.” represents a simple ANN model. In this model, the output of the i. processing element is given in “Eq. (18)”.

$$y(t+1) = a\left(\sum_{j=1}^m w_{ij}x_j(t) - \theta_i\right) \quad (18)$$

where; $a(.)$ represents the activation function while θ_i is the threshold value of the i . processing element. There can be talked about two parts as input and output composing the information processing of the process elements. A net value is produced by a processing element by combining the x_j input information that is obtained from the w_{ij} weights to which they are linked “Eq. (19)” computes the net value of the i . processing element

$$net_i = \left(\sum_{j=1}^m w_{ij}x_j - \theta_i\right) \quad (19)$$

Each processing element performs the second process to find the output value by passing its net value through an $a(.)$ activation function. A wide range of the output of the processing elements is dragged by activation functions to certain intervals. In this manner, the word, soft, can be used for the response of each processing element while the values are smaller. Consequently, error change is prevented from diverging, and stability is assured.

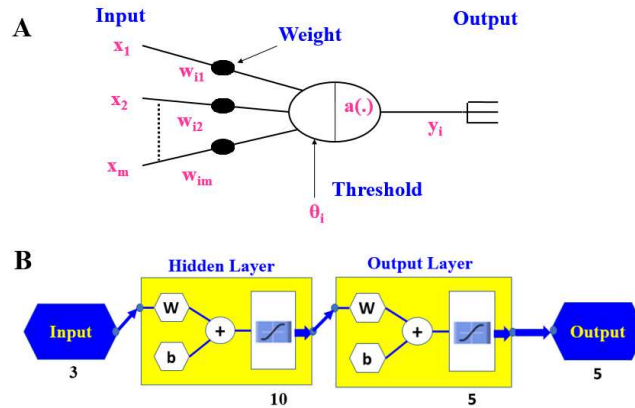


Figure 2. A) Model of a neuron cell [42], B) The structure of ANN Model

“Figure 2B” is the structure of the created ANN model. The model was created in the Matlab program and consists of 3 layers. These are the input hidden and output layers. The input layer consists of 3 parameters: instantaneous solar radiation, drying time and flow rate, and the output layer consists of 5 parameters: collector heat gain, dryer cabin heat gain, energy use rate, exergy efficiency, exergy loss. The hidden layer consists of 10 layers. Different functions and neurons were tried for the properties of the network, and the best results were obtained when the network type was feed-forward backprop, the training function was train LM, the adapt learning function was LearnGDM, the performance function was MSE and the transfer function was TANSIG. And the processing was done according to these functions and neurons. Initially, the system selected the weights randomly. And the network has started to be trained. 80% of the experimental parameters were trained and 20% were used for testing. Training continued until the number of iterations was fixed. And the results were achieved by optimizing the initially randomly determined weights.

3.4. Kinetics of drying

3.4.1. Drying rate (DR) and Moisture ratio (MR)

The drying rate and moisture ratio of mint leaves were computed by “Eq. (20)” and “Eq. (21)”, respectively.

$$DR = \frac{M_{t2} - M_{t1}}{t_2 - t_1} \quad (20)$$

$$MR = \frac{\bar{M} - M_e}{M_0 - M_e} \quad (21)$$

where DR , M_{t2} and M_{t1} , are drying rate (kg water/kg dry solid. min), the moisture contents of mint samples at the time of t_2 and t_1 (min), respectively. Also, MR , $\bar{M}$, M_e , and M_0 are moisture ratio (dimensionless), average, equilibrium, and initial moisture contents (kg water/kg dry solid), respectively [43].

3.4.2. Diffusion coefficient (D_{eff})

The diffusion coefficient of mint samples was determined according to the Fick's second law of diffusion for plate shape by "Eq. (22)".

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left\{ -\frac{(2n+1)^2}{4} \frac{\pi^2 D_{eff} t}{x_1^2} \right\} \quad (22)$$

where, D_{eff} is diffusion coefficient (m^2/s), n , is a positive integer, t represents the time (s) and x_1 is the thickness of the sample (m), respectively [4].

4. Results

On the days of the experiment, the temperature values in the Elazığ region were approximately 450 W/m^2 in the morning, reaching its maximum value between 12-14 o'clock and reaching approximately 760 W/m^2 , and after 16 o'clock the temperature values decreased rapidly and reached 200 W/m^2 at 18 o'clock. Based on the data obtained as a result of the collector experiments, it was determined that the most efficient collector type was the air collector with a 30° wing angle and was used in the drying experiments. Drying parameters for mint were examined under different mass flow rates. This process was carried out as part of research aimed at optimizing both the collectors and the drying process.

Depending on the temperature values, the collector efficiency for $\dot{m}=0.012 \text{ kg/s}$ is 29% at 9 o'clock, while it rises to 42% at 13 o'clock. This maximum efficiency achieved for $\dot{m}=0.012 \text{ kg/s}$. The value is 51% for $\dot{m}=0.026 \text{ kg/s}$ and 63% for $\dot{m}=0.033 \text{ kg/s}$. From the data obtained, it can be said that the air flow rate and collector efficiency are directly proportional. Considering that the efficiency values of classical flat surface solar collectors vary between 20-25%, it is seen that the efficiency values obtained for the collectors we developed have increased significantly. The change graph of the efficiency, average radiation and collector temperature values of the most efficient collector depending on the flow rate of $\dot{m}=0.033 \text{ kg/s}$ over time is given in "Fig. 3".

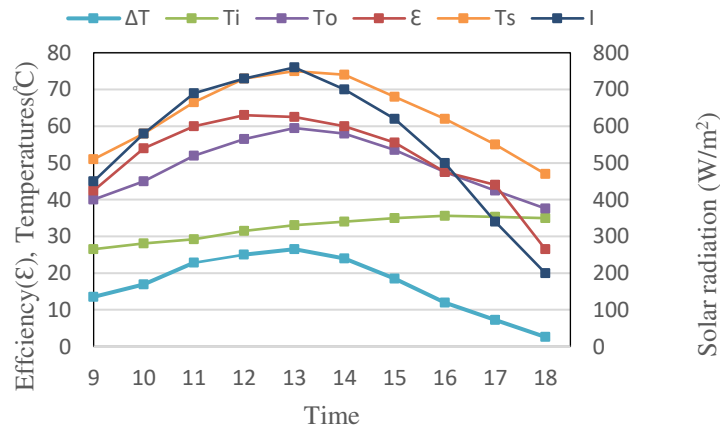


Figure 3. Change of efficiency, solar radiation and temperature values over time (for $\alpha=30^\circ$ and $\dot{m}=0.033 \text{ kg/s}$)

As mentioned above, as the mass flow rate of the air increases, the energy received from the system increases. In the light of the obtained data and formulas, there is an inverse proportion between the energy gain from the system and the collector surface temperature. That is, as the heat gain increases, the collector surface temperature decreases. This is valid for approximately equal heating values. However, there is a direct proportion between the heat gain and the collector inlet-outlet temperature difference (ΔT). However, the weather It can be said that there is an inverse proportion between mass flow rate and collector inlet-

outlet temperature difference. For an air collector with a 30° blade angle and a flow rate of $\dot{m}=0.033\text{kg/s}$ the collector inlet temperature (T_i) is in the range of 24.5 °C-35.6 °C, the collector outlet temperature (T_o) is in the range of 37.6 °C-59.5 °C, the collector surface temperature (T_s) is 47 °C-75 °C measured in the range (“Fig. 3.”). The collector inlet-outlet temperature difference was determined as maximum 26.5 °C.

4.1. ANN

ANN model was created according to the data obtained from the experimental study. Calculations were also made by using energy and exergy formulas. ANN and experimental results were compared. The regression graph produced by the ANN model for actual and estimated values is given in “Fig. 4.”, which shows that actual and estimated values were achieved very close to one another. The parameters obtained from experimental studies and ANN are given in “Table 1.”.

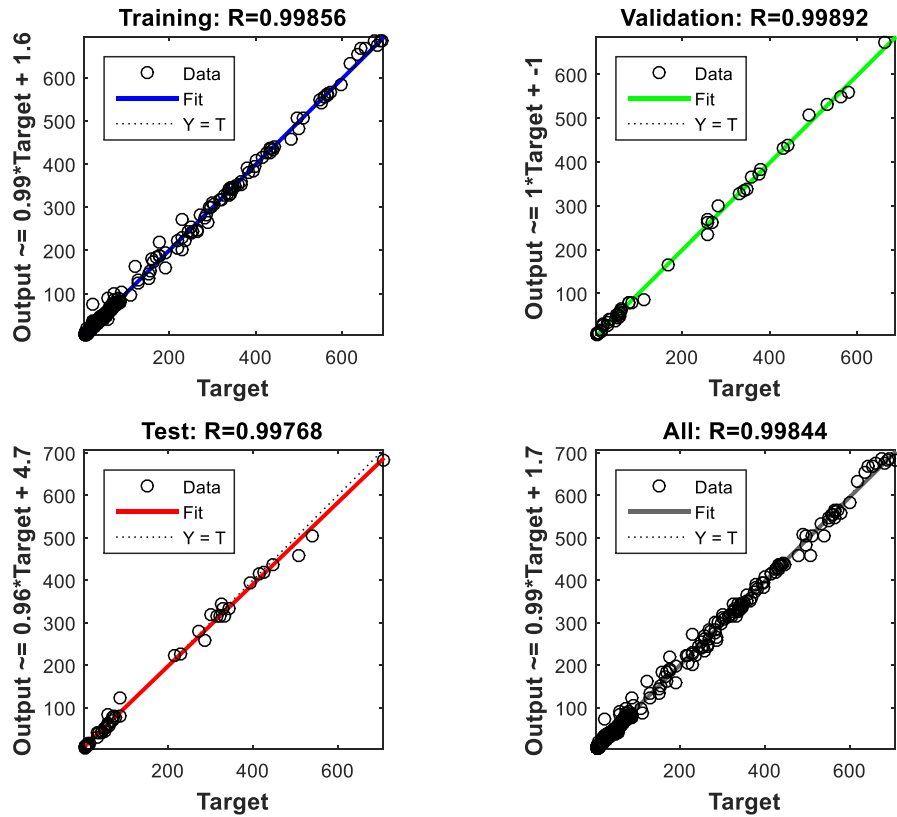


Figure 4. Regression curves of drying parameters.

Table 1. Real and estimated values depending on drying parameters.

Parameters			Real (Experimental) Values					Estimated Values				
t(min)	I(Wm ⁻²)	$\dot{m}$ (kg s ⁻¹)	Q _{col}	Q _{dc}	EUR	ExL	Hex	Q _{col}	Q _{dc}	EUR	ExL	Hex
45	545	0.012	275.805	258.404	35	9.6	75.97	265.447	255.346	29.208	7.652	75.780
120	650	0.012	364.283	357.807	57	11.9	53.72	362.950	344.455	62.939	12.00	51.801
195	720	0.012	420.560	406.412	81	15.5	38.95	421.416	390.673	76.263	14.228	42.713
270	710	0.012	435.450	422.7346	83	15.99	34.67	432.077	406.138	79.392	14.386	40.853
345	625	0.012	414.948	390.869	67	11.23	47.334	403.679	374.892	66.410	12.203	48.072
420	490	0.012	290.379	283.854	35	5.6	68.665	315.485	311.892	31.450	6.715	69.348
0	450	0.026	260.919	217.004	9.9	3.1	71.22	304.260	246.243	11.472	4.415	76.620
75	600	0.026	417.079	407.653	34.23	5.123	65.22	415.554	358.566	33.519	5.166	68.209
150	690	0.026	501.909	508.978	57.5	7.1	55.46	525.912	490.124	54.550	6.215	53.382
225	725	0.026	565.531	549.035	65.44	7.99	49.44	562.521	530.164	65.093	7.364	50.048
300	700	0.026	539.611	523.116	61.5	6.86	54.65	539.504	500.142	63.245	8.425	52.879

375	570	0.026	398.228	360.526	36.45	4.55	74.77	412.574	349.453	34.465	6.826	73.661
45	545	0.033	470.154	443.174	15.77	4.3	55.33	470.542	432.188	13.630	5.022	50.116
120	650	0.033	617.931	526.655	23.33	5.8	47.25	610.100	517.236	35.169	5.769	49.602
195	720	0.033	680.864	629.903	30.33	7.28	44.66	681.358	620.455	29.849	6.329	46.770
270	710	0.033	693.863	663.955	32.22	7.28	46.26	680.155	631.348	32.236	8.149	42.855

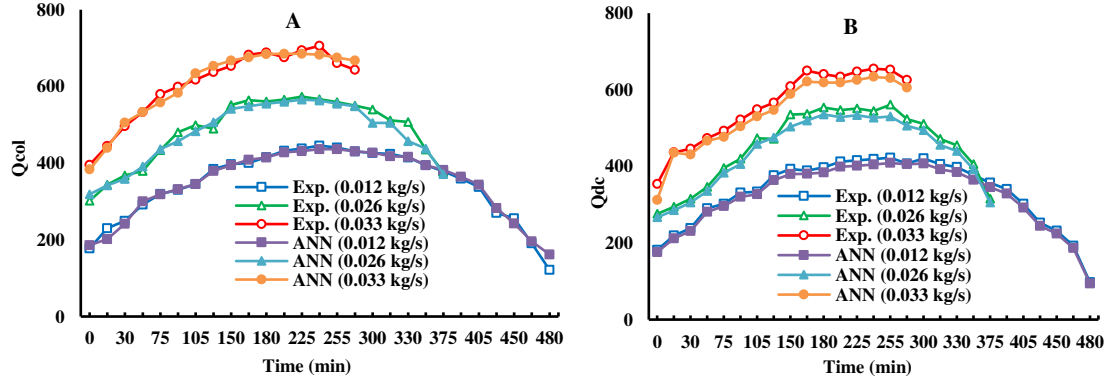
1

2 4.1. Analysis of energy

3 The results of energy analysis is shown in “Fig. 5.”. The maximum experimental value of the Q_{col} was
4 445.6 W for a flow rate of 0.012 kg/s during the 480 min experiment procedure (“Eq. 8”). Under the same
5 conditions for ANN, the highest value of the Q_{col} was 436.2 W which was shown in “Fig. 5A”. Also, at a
6 flow rate of 0.026 kg/s, the experimental and ANN values of Q_{col} were 573.5, and 565.4 W, respectively
7 during 390 min experiments. Increased in the flow rate increased the Q_{col} values and at the flow rate of
8 0.033 kg/s, the highest experimental and ANN values were obtained as 705.8 and 682.8 W, respectively
9 during 300 min experiments (“Fig. 5A”). As the mas flow rate increased, the energy provided by the solar
10 collector increased, and a reduction was observed also in the experiment duration. Our results are in
11 consistency with Akbulut [9] study which reported that in the solar drying of mulberry as the air flow rate
12 increased, the Q_{col} increased. However, in our investigation, Q_{col} at a mass flow rate of 0.033 kg/s was
13 705.8W which was higher than their results (Q_{col} =525.62 W at a flow rate of 0.036 kg/s), which may be
14 related to the difference in the magnitude of solar radiation.

15 The energy analysis of the drying chamber was shown in “Fig. 5B”. At the flow rate of 0.012 kg/s the
16 maximum Q_{dc} values from experimental and ANN modeling were 422.6, and 408.7 W, respectively (480-
17 min). While Q_{dc} increased to 560.8 and 530.1 W, for experimental and ANN, respectively (0.026 kg/s, 390
18 min) and further increased to the 655.0 and 633.5 W, for experimental and ANN, respectively at the flow
19 rate of 0.033 kg/s at the 300 min. “Figure 5B” exhibited that as the flow rate increased, the Q_{dc} increased
20 which agrees with another study [9].

21



22

23

Figure 5. Energy values against drying time in the A) solar collector, B) drying chamber.

24 “Fig. 6.” showed the alterations in the EUR during the drying process. The EUR was varied from 10.4 to
25 87.1% (at 0.012 kg/s), 13.66 to 66.75% (at 0.026 kg/s), and 7.45 to 33.66% (at 0.033 kg/s). It is revealed
26 that as the flow rate decreased, the EUR increased. The EUR of the solar dryer reached a maximum in the
27 low mass flow rate and in contrast it was at the minimum level when air with a high flow rate was applied
28 to dry the mint leaves. The EUR as an important parameter in the energy analysis is also related to the
29 microstructure and moisture content of mint.

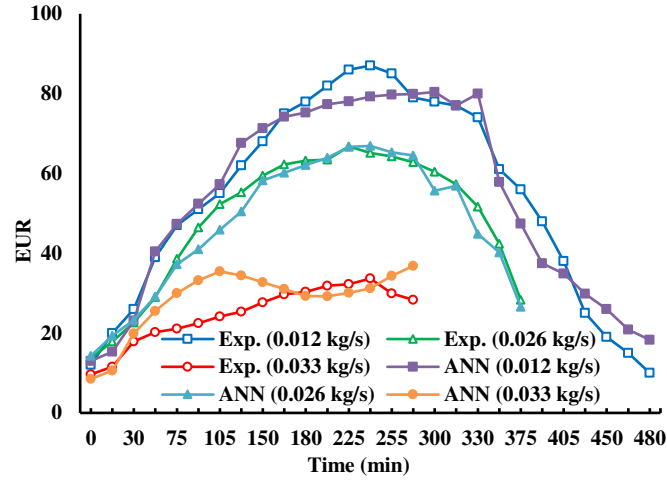


Figure 6. The energy utilization ratio of solar dryer.

4.2. Analysis of exergy

The results of analysis of the exergy production during the drying were shown in “Figure 7.”. The results revealed that for all flow rates exergy losses increased during the first 300 min, and after that it was decreased which can be related to the variation in the solar radiation (“Fig. 7A”). The averages of the exergy loss for the air with flow rates of 0.012, 0.026 and 0.033 kg/s were calculated as 16.2 W, 8.2 W, 6.88 W, respectively. Under the same conditions for ANN, the averages of the exergy loss for the flow rates of 0.012, 0.026 and 0.033 kg/s were 14.5 W, 8.5 W, 7.7 W, respectively (“Fig. 7A”). The maximum and minimum exergy losses were determined at the time that the flow rates were 0.012 kg/s and 0.033 kg/s, respectively. The results revealed that as the flow rate increased, the exergy losses decreased. Also, the amount of the change in the radiation has influenced the exergy loss.

The exergy efficiency values of the drying chamber for all mass flow rates were shown in “Fig. 7B”. The η_{Ex} values ranged from 33.99 to 85.76 % for the flow rate of 0.012 kg/s, 46.44 to 78.88% for the flow rate of 0.026 kg/s, and 40.1to 58% for the flow rate of 0.033 kg/s. Under the same conditions for ANN, the η_{Ex} values were determined to be between 40.33 to 84.10% (at 0.012 kg/s), 49.17 to 76.65% (at 0.026 kg/s), and 41.38 to 60.73 % (at 0.033 kg/s).As, the difference between the temperatures of air that entered the drying chamber and the air which existed from the chamber decreased (means when inlet and outlet temperature was near together), the η_{Ex} increased. The results revealed that the η_{Ex} of the drying chamber reduced while the energy gained from the solar collector was productively used. Also, our results showed the ANN modeling is suitable for estimating the energy and exergy parameters in the drying operations. This agrees with the study conducted by different authors such as Özdemir et al. [32] on the drying of kiwi fruits in the convective-infrared drying, and Azadbakht et al. [36] on the fluidized bed drying of potato cubes.

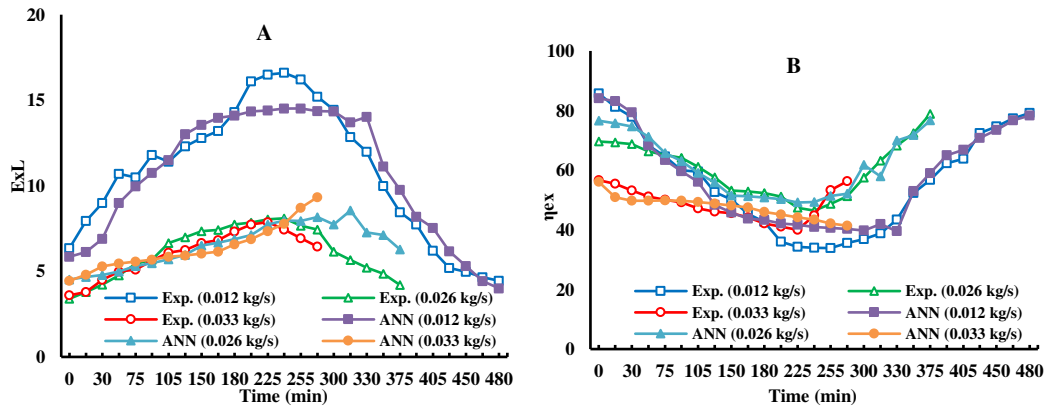


Figure 7. A) Exergy loss, B) Exergy efficiency.

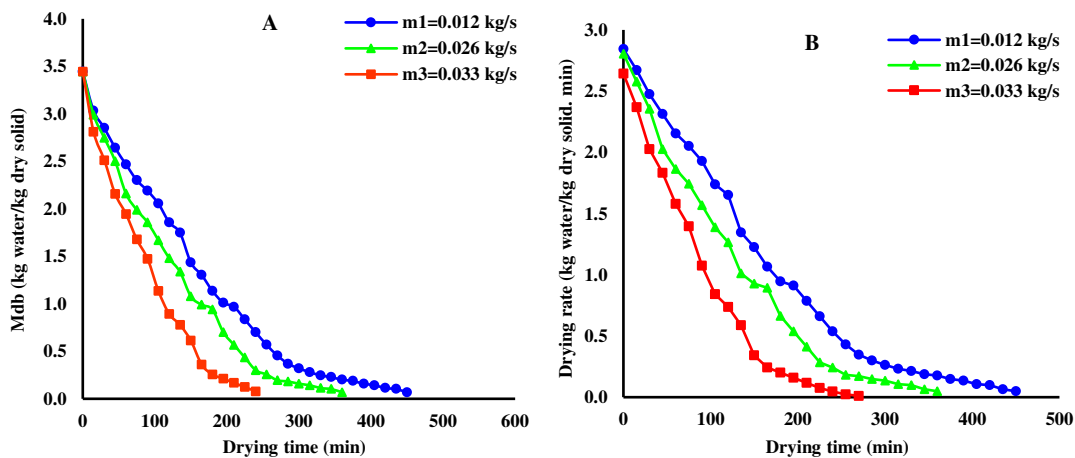
4.3. Drying kinetics

Since the main purpose of the drying process is to remove the moisture in the agricultural product, it is necessary to know the amount of moisture in the mint leaf, which is the agricultural product to be dried. Considering previous studies, the equilibrium moisture in mint leaves was determined to be approximately 11% using the ETUV method [44]. In our experimental study, the moisture content of mint leaves was calculated by looking at the dry mass of the dried samples at the moment when their mass changes almost stopped. As a result of our calculations, it was determined that the humidity rate we obtained was compatible with the humidity amounts in the literature.

Before starting drying process with the help of solar air collectors, drying was done in a natural environment to determine the equilibrium moisture of the mint. Mint dries in a natural environment in approximately 2 days. During the natural drying process, the mint was left inside the conditioning room by closing its entrance and exit channels during hours when there was no solar radiation. Thus, the next day, the initial values were approximately the same as the values of the previous day. It has been determined that the mass change of mint dried in a natural environment approaches zero after approximately the 930th minute. As it is known, the amount of water in the product is never zero at the end of the drying process. Depending on the internal structure and physical properties of each product, this moisture content is reduced to a "reasonable rate" during the drying process. This "reasonable rate" has a different value for each product. That is, at the end of the drying process, a certain amount of water remains in the product. In the study, it was determined that this reasonable rate for mint was between 10-12%.

By drying 200 grams of mint, 45 grams of dry product is obtained. In other words, approximately 77% water content of mint is eliminated from the product in 300-480 minutes, depending on the mass flow rate of the air. The change in moisture content according to drying time, obtained from the drying experiments for mint, is given in "Figure 7A". Here, for the moisture content of the product; The maximum moisture content for mint is 3.55. In other words; Fresh mint contains 3.55 times more water than dried mint.

The drying kinetics of mint samples dried by air with different flow rates (0.012, 0.026, and 0.033 kg/s) were shown in "Fig. 8.". For all samples as drying time increased, the moisture content exponentially decreased. Furthermore, increases in the flow rate of air caused a significant reduction in the drying time ("Fig. 8A"). The constant rate period was not observed, and drying rates of all samples were started from the falling rate period ("Fig. 8B"). As the flow rate of air increased, the drying rate increased, and faster drying decreased the drying time of samples. Also, a reduction in the moisture ratio during drying was observed ("Fig.8C"). The slope of $\ln MR$ vs. drying time ("Fig. 8D") was used for calculation of diffusion coefficient ($Deff$) which was found to be 0.65×10^{-9} , 0.84×10^{-9} , and $1.15 \times 10^{-9} \text{ m}^2/\text{s}$ for flow rates of 0.012, 0.026, and 0.033 kg/s, respectively, which was in the normal range of 10^{-12} to 10^{-8} for foodstuff [43]. An increase in the flow rate increased the removal of moisture from the surface of mint, therefore it can help to increase the driving force (due to differences in the concentration of moisture in the surface and inside the sample) for removal of moisture, resulting in an increase in the diffusion coefficient.



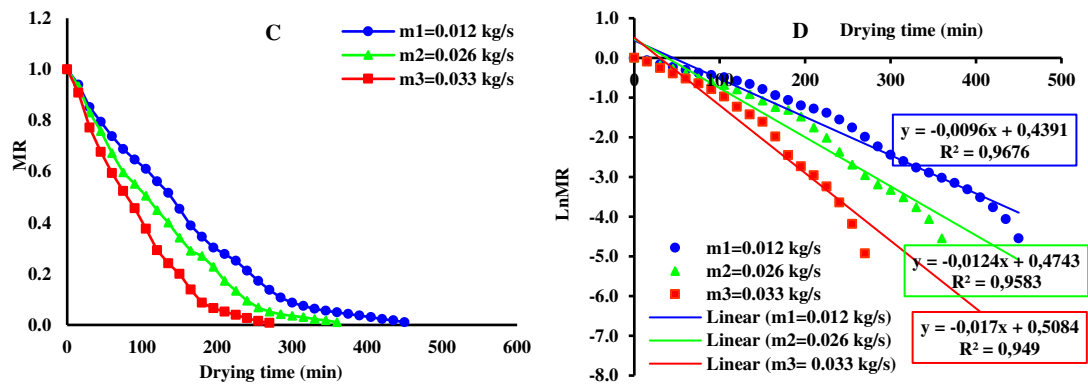


Figure 8. Changes in the different parameters during drying of mint samples by air at different flow rates
A) Moisture content, B) Drying rate, C) Moisture ratio, D) LnMR.

5. Conclusions

The solar dryer under 125 W/m^2 - 750 W/m^2 solar radiation and 0.012 to 0.033 kg/s flow rates was successfully used for drying of mint leaves. As flow rates of air increased, the drying time and exergy loss decreased while the moisture diffusion coefficients and energy obtained from the collector increased. The necessary drying time to reach the final moisture content was 480 , 390 , and 300 min for air with flow rates of 0.012 , 0.026 , and 0.033 kg/s , respectively. The provided energy by the collector was used efficiently for the drying chamber at the time that the EUR was accelerated. The EUR is an important factor to analysis the usage of energy in the drying of mint. Moreover, the amount of radiation influenced the loss of the exergy. The highest exergy loss was observed at 0.012 kg/s flow rate. To improve the energy utilization using a different barrier in the airflow duct should be taken into consideration to increase the heat transfer area. The results of ANN were consistent with the experimental outcomes which showed that ANN can be used as a quick and practiced way for modeling drying processes.

Author contribution Fevzi Gülçimen: design and perform the experiments, conceptualization, investigation, methodology, formal analysis. Hakan Karakaya: conceptualization, methodology, software, data curation, investigation, formal analysis, and writing — original draft. Aydın Durmuş: review and editing, investigation, supervision, and resources.

Funding This work was supported by the Fırat University Research Foundation (FUNAF-1038).

Declarations

Competing interests The authors declare no competing interests.

References

- [1] Ozer A (2010) Drying of some medical plants using hot air dryer and effects of different drying temperatures on product quality. Dissertation (MSc. Thesis), Graduate School of Natural and Applied Sciences Main Science Division of Agricultural Machinery Namık Kemal University, Tekirdağ.
- [2] Zhang J, Li M, Zhang H, and Pang X (2022) Comparative investigation on aroma profiles of five different mint (*Mentha*) species using a combined sensory, spectroscopic and chemometric study. Food Chemistry 371:131104.
- [3] Ye L, EL-Mesery HS, Ashfaq MM, Shi Y, Zicheng H, and Alshaer WG (2021) Analysis of energy and specific energy requirements in various drying process of mint leaves. Case Studies in Thermal Engineering 26:101113.
- [4] Kian-Pour N, and Karatas S (2019) Impact of different geometric shapes on drying kinetics and textural characteristics of apples at temperatures above 100°C . Heat and Mass Transfer 55:3721-3732.
- [5] Pochont NR, Mohammad MN, Pradeep BT, and Kumar PV (2020) A comparative study of drying kinetics and quality of Indian red chilli in solar hybrid greenhouse drying and open sun drying. Materials Today: Proceedings 21:286–290.
- [6] Ahmadi A, Das B, Ehyaei MA, Esmailion V, Assad MEH, Jamali DH, Koohshekan O, Kumar R, Rosen MA, Negi S, Bhogilla SS, and Safari S (2021) Energy, exergy, and techno-economic performance analyses of solar dryers for agro products: A comprehensive review. Solar Energy 228:349-373.

- [7] Pacifico I, De Gara L, Stellari A, Marinoni L, and Cattaneo TMP (2022) The application of solar drying process for the valorisation of papaya fruit. *European Food Research and Technology* 248:857–867.
- [8] Devan PK, Bibin C, Shabrin IA, Gokulnath R, and Karthick D (2020) Solar drying of fruits – A comprehensive review. *Materials Today: Proceedings* 33(1):253-260.
- [9] Akbulut A, and Durmuş A (2010) Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer. *Energy* 35:1754–1763.
- [10] Murugavelh S, Anand B, Prasad KM, Nagarajan R, and Kumar SAP (2023) Exergy analysis and kinetic study of tomato waste drying in a mixed mode solar tunnel dryer. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 45(3):8978-8994.
- [11] Seerangurayar T, Al-Ismaili AM, and Jeewantha LJ (2019) Experimental investigation of shrinkage and microstructural properties of date fruits at three solar drying methods. *Solar Energy* 180:445–455.
- [12] Şevik S, Aktaş M, Dolgun EC, Arslan E, Tuncer AD (2019) Performance analysis of solar and solar-infrared dryer of mint and apple slices using energy-exergy methodology. *Solar Energy* 180:537-549.
- [13] Lingayat A, Chandramohan VP & Raju VRK (2020) Energy and Exergy Analysis on Drying of Banana Using Indirect Type Natural Convection Solar Dryer. *Heat Transfer Engineering* 41:551-561.
- [14] Rani P, Tripathy PP (2023) Drying characteristics and performance acceleration of a mixed-mode solar dryer using finned collector for pineapple slice drying. *Biomass Conv. Bioref.* <https://doi.org/10.1007/s13399-023-05107-7>.
- [15] Gopinath GR, Muthuvel S, Muthukannan M, Sudhakarapandian R, Kumar BP, Kumar CS, and Thanikanti SB (2022) Design, development, and performance testing of thermal energy storage based solar dryer system for seeded grapes. *Sustainable Energy Technologies and Assessments* 251:101923.
- [16] Seerangurayar T, Al-Ismaili AM, Jeewantha LHJ. et al. (2023) Experimental investigation and modeling of date drying under forced convection solar dryers. *Biomass Conv. Bioref.* <https://doi.org/10.1007/s13399-023-04450-z>.
- [17] Kumar D, Mahanta P, and Kalita P (2020) Energy and exergy analysis of a natural convection dryer with and without sensible heat storage medium. *Journal of Energy Storage* 29:101481.
- [18] Aghbashlo M, Mobli H, Rafiee S, Madadlou, A (2013) A review on exergy analysis of drying processes and systems. *Renewable and Sustainable Energy Reviews* 22:1–22.
- [19] Lemoubou EL, Aghogue Donchi CP, Tchinda R, and Bogning JR (2022) Thermal Analysis of the Effect of Absorber Plate Geometric Parameters on the Dynamic of an Indirect Type Solar Dryer. *ASME. J. Thermal Sci. Eng. Appl.* 14(12): 121003.
- [20] Dincer I (2002) On energetic, exergetic and environmental aspects of drying systems. *International Journal of Energy Research* 26:717-727.
- [21] Midilli A, and Kucuk H (2003) Energy and exergy analyses of solar drying process of pistachio. *Energy* 28:539–556.
- [22] Aydoğmuş E, Demirpolat AB & Arslanoğlu H, (2022) Isothermal and non-isothermal drying behavior for grape (*Vitis vinifera*) by new improved system: exergy analysis, RSM, and modeling. *Biomass Conv. Bioref.* 12, 527–536. <https://doi.org/10.1007/s13399-021-02034-3>.
- [23] Rabha D, Muthukumar P, and Somayaji C (2017) Energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger. *Renewable Energy* 105:764-773.
- [24] Karthikeyan A , and Murugavelh S (2018) Thin layer drying kinetics and exergy analysis of turmeric (*Curcuma longa*) in a mixed mode forced convection solar tunnel dryer. *Renewable Energy* 128:305-312.
- [25] Silva GMD, Ferreira AG, Coutinho RM, and Maia CB (2021) Energy and exergy analysis of the drying of corn grains. *Renewable Energy* 163:1942-1950.
- [26] Beigi M, Torki-Harchegani M, Tohidi M (2017) Experimental and ANN modeling investigations of energy traits for rough rice drying. *Energy* 141:2196-2205.
- [27] Omid M, Mahmoudi A, Omid MH (2009) An Intelligent System for Sorting Pistachio Nut Varieties. *Expert Syst. App.* 36(9):11528–11535.
- [28] Kurtulmuş F, Polat A, İzli N (2020) Modeling of Drying Rate and Moisture Ratio Parameters in Drying Apricot with Different Drying Methods Using Artificial Neural Networks Abstract. *COMU J. Agric. Fac.* 8(2):261-269. <https://doi.org/10.33202/comuagri.733166>.
- [29] Kurtulmuş E, Kurtulmuş F, Kuşçu H, Arslan B et al (2023) Determination of Pipe Diameters for Pressurized Irrigation Systems Using Linear Programming and Artificial Neural Networks. *Journal of Agricultural Sciences* 29(1):89-102. <https://doi.org/10.15832/ankutbd.936335>.
- [30] Guiné RPF (2019) The Use of Artificial Neural Networks (ANN) in Food Process Engineering. *International Journal of Food Engineering* 5:15-21.

- [31] Tripathy P, and Kumar S (2009) Neural network approach for food temperature prediction during solar drying. *International Journal of Thermal Sciences* 48:1452–1459.
- [32] Özdemir MB, Aktaş M, Şevik S, and Khanlari A (2017) Modeling of a convective-infrared kiwifruit drying process. *International Journal of Hydrogen Energy* 42:18005 -18013.
- [33] Winiczenko R, Górnicki K, Kaleta A, Martynenko A, Janaszek-Mańkowska M, and Trajer J (2018) Multi-objective optimization of convective drying of apple cubes. *Computers and Electronics in Agriculture* 145:341-348.
- [34] Azadbakht M, Torshizi MV, Noshad F, and Rokhbin A (2018) Application of artificial neural network method for prediction of osmotic pretreatment based on the energy and exergy analyses in microwave drying of orange slices. *Energy* 165:836-845.
- [35] Kılıç F (2021) Effects of three drying methods on kinetics and energy consumption of carrot drying process and modeling with artificial neural networks. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 43:1468–1485.
- [36] Azadbakht M, Aghili H, Ziaratban A, and Torshizi MV (2017) Application of artificial neural network method to exergy and energy analyses of fluidized bed dryer for potato cubes. *Energy* 120:947-958.
- [37] Akpınar EK (2010) Drying of mint leaves in a solar dryer and under open sun: Modelling, performance analyses. *Energy Conversion and Management* 51:2407–2418.
- [38] Boulemtafes-Boukadoum A, and Benzaoui A (2011) Energy and exergy analysis of solar drying process of Mint. *Energy Procedia* 6:583–591.
- [39] Bhardwaj AK, Kumar R, Kumar S, Goel B, and Chauhan R (2021) Energy and exergy analyses of drying medicinal herb in a novel forced convection solar dryer integrated with SHSM and PCM. *Sustain Energy Technol Assess.* 45:101119.
- [40] Akpınar EK (2019) The effects of some exergetic indicators on the performance of thin layer drying process of long green pepper in a solar dryer. *Heat and Mass Transfer* 55:299–308.
- [41] Kilickap E, Yardımeden A, and Çelik YH (2017) Mathematical Modelling and Optimization of Cutting Force, Tool Wear and Surface Roughness by Using Artificial Neural Network and Response Surface Methodology in Milling of Ti-6242S. *Applied Science* 7:1064.
- [42] Özek C, Çelik YH (2012) Calculating Molding Parameters in Plastic Injection Molds with ANN and Developing Software. *Materials and Manufacturing Processes* 27:160–168.
- [43] Kian-Pour N, Akdeniz E, and Toker O (2022) Influence of coating-blanching in starch solutions, on the drying kinetics, transport properties, quality parameters, and microstructure of celery root chips. *LWT - Food Science and Technology* 160:113262.
- [44] www.kurutma.net
- [45] Gulcimen F, Karakaya H, Durmus A (2016) Drying of sweet basil with solar air collectors. *Renewable Energy* 93:77-86.

Figure captions:

- Figure 1.** A. Experimental set up (schematic)
 B. Experimental set up (photo)[9,45]
 C. Collector stream line [45].
- Figure 2.** A) Model of a neuron cell [42], B) The structure of ANN Model.
- Figure 3.** Change of efficiency, solar radiation and temperature values over time
 (for $\alpha = 30^\circ$ and $\dot{m} = 0.033 \text{ kg/s}$).
- Figure 4.** Regression curves of drying parameters.
- Figure 5.** Energy values against drying time in the A) solar collector, B) drying chamber.
- Figure 6.** The energy utilization ratio of solar dryer.
- Figure 7.** A) Exergy loss, B) Exergy efficiency.
- Figure 8.** Changes in the different parameters during drying of mint samples by air at different flow rates
 A) Moisture content, B) Drying rate, C) Moisture ratio, D) LnMR.

Table captions

- Table 1.** Real and estimated values depending on drying parameters.