Investigating the Performance of Dryers Equipped with MOF and Closed Air Circulation

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ABSTRACT: *One of the most common methods of drying is the use of heat. Therefore, high energy consumption has always been of concern in the drying process, and various methods have been tried to reduce high energy consumption. This research evaluated the performance of a thermal dryer with a closed air circulation system using porous Metal-Organic Framework (MOF) nano sorbents. Dryer sections consisted of a crop drying chamber, connecting air pipes, air blowers, a chamber containing MOF nano sorbents, an electric air heater, and measurement and control systems. The performance of the dryer on the mint plant was compared at three temperature levels (40, 50, and 60 °C) and in two open and closed-air circulation methods. Finally, the energy consumption and efficiency were measured and evaluated for the dryer. The results showed that the closed air circulation system reduced energy consumption by 35% and therefore increased dryer efficiency, significantly affecting dryer efficiency and energy consumption. There was no obvious difference in the total color index between the two methods of use and without using nano sorbents. Antioxidant activity increased with increasing temperature. The study results indicated that a closed air circulation system significantly affects the dryer's energy consumption and output. The highest output of the dryer was achieved at 50 °C when the dryer had been equipped with a closed air circulation system. No significant difference was evidenced in the total color index between the two applied methods when not using nano absorbents. The antioxidant activity was found to increase with the increase in temperature.*

KEYWORDS: *MOF nano absorbent; Closed air circulation; Consumed energy; Dryer's output; Quality properties.*

INTRODUCTION

Drying is one of the most important post-harvest processes that turn perishable crops into resistant ones, increasing the storage period and maintaining food quality. On the other hand, the processing method significantly affects volatile compounds in the essential oils of medicinal plants. Therefore, the appropriate processing method is particularly important for these crops [1].

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1021-9986/2023/8/2735-2746 12/$/6.02

Drying operations involve heat transfer, mass, and motion size with high energy consumption. Choosing the appropriate drying method can improve the quality of the crop, in addition to economic savings. Hot air drying is the most common method of drying agricultural products so that quality products can be produced in a short time by using this method [2].

Mint leaves were used in this study. The mint plant (*Mentha spicata*) from the Lamiaceae family is one of the important medicinal plants used since ancient times. Mint is a perennial, herbaceous plant with square stems, broad, dark green, and opposite leaves. This plant has a pleasant aroma and is therefore used in essential oil extraction, commercially known as spearmint oil [2].

Due to the low thermal conductivity of agricultural products, heat transfer to the interior of these materials is very slow; therefore, they require high energy consumption for drying [3]. The energy required for drying is typically provided by fossil fuels. Due to the rising global prices of fossil fuels and their environmental pollution, much attention has now been paid to using renewable energy as an alternative or supplement to fossil fuels. Energy recovery methods have also been of interest to several researchers who have used the closed air circulation system in the dryer to increase energy efficiency in solar dryers [4-6].

In Iran, a large body of research on dryers with dry air circulation. For example, *Zare et al*. [7] investigated the effect of mass flow rate and discharge time on paddy drying rate in a semi-continuous solar dryer. Moreover, a solar dryer with forced airflow was designed and evaluated for leafy vegetables [8]. The energy and kinetics of drying mint leaves with a vibrating floating bed equipped with a heat pump were investigated *by Ataei et al*. [9].

In dryers equipped with a closed air circulation system, hot air is not circulated to the outside environment after passing through the crop and absorbing the moisture from the drying chamber. In this type of dryer, the relative humidity of the air passing through the crop increases after a while due to the moisture absorption of the crop, and the moisture absorbability of the air decreases inside the dryer. In most dryers equipped with closed (forced) air circulation systems that have been examined so far, a certain fraction of the crop drying air is usually provided from the closed air circulation system and the rest from the open air, and this process has been fixed from the beginning to the end of crop drying.

In this type of dryer, hygroscopic are used to reduce the humidity of the air inside the dryer. In this situation, the moist air inside the dryer chamber exits the crop chamber. It is circulated by the connecting pipes to the water-absorbent chamber to be passed through by exposure to hygroscopic and reduce the relative humidity of the system air. After moisture absorption of the passing air by hygroscopic, the hot and dry air is recirculated to the crop drying chamber to re-enter the drying cycle of the system. This method reuses the hot air of the system. The advantages of using a dryer equipped with a closed-air circulation system include the reduction of microbial contamination in the crop due to the reduced use of ambient air [10].

The use of the moisture absorbents in the driers lowers the energy consumption and, simultaneously, enables constant drying during non-sunny hours in addition to increasing the drying rate due to the creating contact with the hot and dry air, enhancing the very uniform drying and preserving the quality of the products, especially for the products that are sensitive to heat.

The advantages of water-absorbent dryers include: 1) a saturated absorbent can be regenerated by hot air flow, 2) the system design is easy and does not require maintenance for many years, 3) using the absorbent with other drying methods reduces energy consumption, and 4) easy replacement of absorbents after working cycles [11].

The adsorption separation process requires an adsorbent that can selectively adsorb a component of the basal mixture. Nowadays, porous materials have many applications in adsorption processes. According to the International Union of Pure and Applied Chemistry (IUPAC) classification, porous materials are divided into three groups based on pore size: macroporous (pore diameter of about 50 nm), mesoporous (pore diameter of 2-50 nm), and microporous (pore diameter < 2 nm) [12].

Metal-Organic Frameworks (MOFs) and micro-and mesoporous materials have unique geometries among the different classes of porous compounds. MOFs, or more generally porous coordination polymers, have been known since late 1950 and were developed by scientists such as Robson, Kitagawa, etc. [13]. MOFs result from bonding metal ions and organic binders, the first example of which was synthesized by *Tamik* in 1965 [14].

New types of nanostructured absorbents have been introduced in recent years, which have been of interest to many researchers due to their very high free surface area, high adsorption capacity, and lower energy consumption during the reduction process. Some of these absorbents are recovered at temperatures below 80 °C, resulting in significant energy savings [15].

Due to the properties and characteristics of MOF absorbents, their widespread use and industrial application in various adsorption processes, such as water absorption and separation, are not far from expectation shortly. In this regard, to help the selection of appropriate adsorbent(s), the relationship between adsorbent properties and its adsorption capacity has been evaluated in 60 types of MOFs [16].

Since MOFs have the highest porosity among porous absorbents, their pore size, shape, dimensions, and chemical environment are desirable parameters. Unlike other porous solids, which do not have much diversity and are composed of a limited number of structural units, many MOFs with a surface area > 1000 m^2/g have been reported so far, while some of them, such as 101-MIL and 1- UMCM, possess areas > 5000 m^2/g [13]. MOF nano sorbents with water vapor absorbability from a subgroup of the MIL family, known as MOF-199, were used in this research. The highest water absorption capacity belongs to Cr-MIL-101, with measured water absorption of 1.4 cm^3/g [16].

MOFs with permanent porosity are widespread compared to other groups in terms of the variety of porous materials and arrangements. These advantages make MOFs ideal for absorbing and storing moisture, gases, and catalysis. The production of nanocomposites by adding metal oxide nanoparticles to the polymer increases the barrier properties to oxygen and water vapor with mechanical strength; moreover, it has light-blocking properties and antimicrobial activities [17].

The high absorption capacity of MOF nano-adsorbent materials has led to their various applications. Absorption of water vapor is one of the characteristics of these nano adsorbents which is widely used. MOFs are a new class of crystalline materials with a porous structure that can absorb water vapor due to their high surface area, porosity, pore volume, and low framework density [18]. In the literature by *Xiaoxia et al*. and (*Menghao Qin et al.*, 2021)[19], MOFs have been reported as a moisture-absorbent material for internal humidity control and energy saving, while so far, no research has been written on the use of these nano adsorbents in dryers.

Although progress has been made with the development of new MOFs, MOFs are expected to play a vital role in the modern age compared to other conventional moisture absorbents (such as silica gel and activated alumina) to increase the dryers' efficiency and better preservation of the food products' quality.

The purpose of this research is to investigate the effect of different temperatures in two states (with MOF nano adsorbent and without MOF nano adsorbent) on energy consumption and dryer efficiency and to investigate the qualitative changes of mint leaves in drying mint leaves.

EXPERIMENTAL SECTION

Fig. 1 displays a dryer and the chamber where the nano-absorbent sheets are situated. The various sections of this system are a dryer device that incorporates a sample of the given product to be dried, an electric heater, fans, and a dryer’s control system; the system’s moisture-absorbing components are the chamber wherein the nano absorbent sheets are situated, MOF nano absorbent sheets, a reductive (revitalizing) electric heater, reductive fan, temperature and moisture sensors and the control system. At the beginning of the experiment, to get the system equilibrated with the laboratory’s ambient temperature, the dryer machine was allowed to work for an hour under the constant 25 °C temperature conditions of the laboratory. The system can reach stability continuously. The experiments were conducted for three temperature ranges, namely (40, 50, and 60 °C), with and without nano adsorbent sheets. The experiments were carried out to determine the amount of energy consumed and the output of the dryer in three iterations under identical conditions. The information about the time, environment’s temperature, the dryer’s temperatures before and after nano absorbents, moisture rates before and after applying the nano adsorbent sheets, and the total and instantaneous energy consumption rates were recorded. The energy consumed by the dryer equipment and components, including the nano adsorbent sheets’ reductive chamber, was measured using a wattmeter. Moreover, all the nano adsorbent sheets’ chamber components, connective pipes, and tubes were insulated.

Fig. 1: The photo of the chamber wherein the nano absorbent sheets and other equipment are installed and the method of their connections to the dryer

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After the system's temperature reached a balance, the mint leaf sample was placed inside the dryer's chamber. The increase in the temperature of the dryer's chamber caused the sample's texture to give off moisture to the air inside the chamber. The moisture emitted from the sample caused an increase in the moisture level inside the dryer's chamber. Connecting the dryer's air stream to the nano adsorbent sheets' chamber enabled the dryer's fan to transfer the moist air inside the dryer's fan through the pipes and tubes into the nano adsorbent sheets' installation chamber. Fig. 2 demonstrates the schematic view of the nano adsorbent sheets' installation chamber and its components.

Measurement and control systems

the components of the nano sorbent chamber were designed so that the temperature and humidity sensor B issued an on/off command to the electric dryer heater. Temperature and humidity sensor B measured the percentage of humidity in the dryer environment before entering the nano sorbent sheets, and temperature and humidity sensor C controlled the moisture percentage in the air leaving the absorber chamber. Planning for temperature and humidity sensor C operation was such that in a certain range and after absorbing 70% of the moisture by the nano-absorbent sheets, it issued the on/off command to the electric heater and the recovery fan of nano sorbent sheets to perform the recovery of nano-absorbent sheets. The information obtained from these sensors was transferred to a data logger. To be controlled and programmed with software designed for this purpose. The required command is issued after delivering the data by the sensors. This cycle includes the continuous sending of the system's data by the moisture and temperature sensors to the control system and the subsequent issuing of a command by the control system for opening or closing the valve on the nano adsorbent sheets' chamber as well as for turning the electric heater on or off during the nano adsorbent sheets' revitalization stage. A load cell was used to measure the changes in the sample's weight during the experiments. The consumed energy of the dryer's electric heater and nano adsorbent sheets' revitalization chamber is measured using a wattmeter device (Model TM1 5010 with a 0.5% precision rate for the maximum output, made by Lutron Company, Taiwan). When the nano adsorbent sheets are not used, the dryer's air is replaced by fresh air to reduce the amount of moisture inside the dryer and prevent the dryer's air from getting mixed with the saturated moisture,

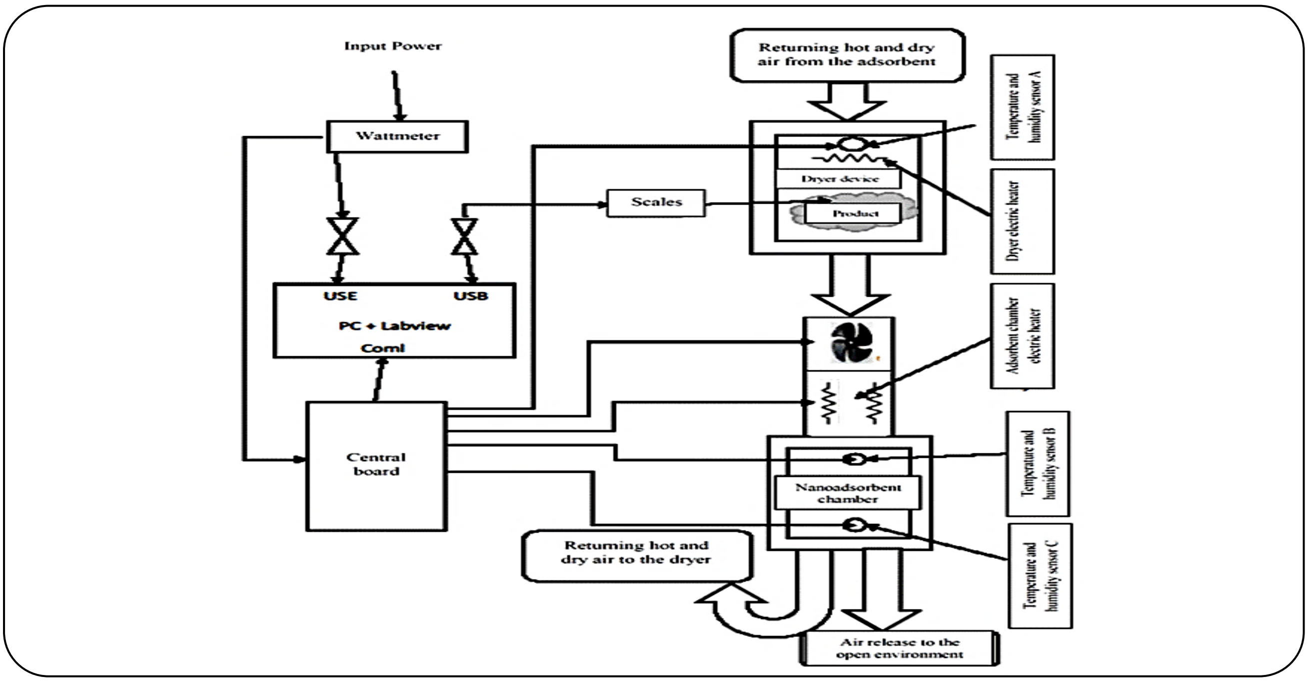

Fig.2: Schematic of the nano adsorbent sheets chamber and the used equipment

which causes the wastage of part of the energy for increasing the temperature of the fresh air inflowing to the dryer. Nevertheless, when using the nano adsorbent sheets, the moist air inside the dryer is allowed to pass over the nano adsorbent sheets to be dried, with a large amount of the dry and hot air being again returned to the dryer and a small part thereof being transferred to the open air at the time of the nano adsorbent sheets' revitalization. This cycle is continued during the drying operation and prevents the wastage of energy. The experiments have been conducted with the fixed 0.05 kg/s mass flow rate.

The moisture adsorption happens in several consecutive stages in drying by the nano adsorbent sheets. The constant circulation of air inside the dryer causes the product's moisture to be absorbed into the air inside the dryer. Air passes over the surfaces on which MOF nano adsorbent sheets are installed, enabling the adsorption of moisture by these sheets with the dried hot air being returned to the drying cycle. At the same time, the dryer's temperature is kept constant.

Fig. 2 displays the dryer and chamber (where the nano adsorbent sheets are situated) used in this research. The various sections of this system are a dryer device including a product chamber, an electric heater, fans, a dryer's control system, and the system's moisture-absorbing components including the chamber (where the nano adsorbent sheets are situated), nano adsorbent sheets, a revitalizing electric heater, a revitalizing fan, temperature, and moisture sensors, and the control system. A Batch dryer device was used for the experiment. All the equipment and connective pipes were installed and the chamber (where the nano adsorbent sheets are situated) was connected to the device to convey the continuous flow of dryer air. All connective pipes and the nano adsorbent chamber were insulated to prevent the system's energy wastage.

The variables of this test are the temperature and humidity of the air inside the dryer, which is recorded by temperature and humidity sensor A. The temperature and humidity of the air entering the nano adsorbent chamber are measured by the temperature and humidity sensor B, and the temperature and humidity of the air coming out of the nano adsorbent chamber are controlled by the temperature and humidity sensor C. The information obtained from these sensors is transferred to the data logger, controlled, and programmed by Labview software. After sending the information by the sensors, the necessary command for opening or closing the valves is issued by the software.

Considering that the airflow inside the dryer is affected by the decrease or increase in the heat after passing through the nano adsorbent chamber, the control system issues the command to turn on/off the electric heater of the dryer. Programming is done by a control system, that after absorbing 70% of moisture by the nano adsorbent sheets, issues the command to turn on/off the electric heater and nano adsorbent sheets revitalization fan so that the nano adsorbent sheets can be now revitalized.

The consumption power for revitalizing nano adsorbent sheets, done by an electric heater and fan, is measured by a wattmeter. Their total consumption power was measured as 317 W/h. This cycle is continuously performed by transmitting the system data to the control system by humidity and temperature sensors, sending a command by the control system for opening or closing the valve of the nano adsorbent sheets chamber, turning on/off the electric heater, and the nano adsorbent revitalization stage. The energy consumed by the dryer electric heater and the revitalization of the nano adsorbent sheets was measured by a wattmeter.

In the case without nano adsorbent sheets, to reduce the humidity of the dryer air and prevent the air inside the dryer from reaching saturated humidity, the dryer air is replaced with free air, and this condition causes the loss of part of the energy used to increase the temperature of the fresh air entering the dryer. But when using nano adsorbent sheets, the humid air of the dryer is dried after passing over the nano adsorbent sheets, a large part of the dry and hot air returns to the dryer, and only a small part of the hot air of the system is transferred to the free environment during the revitalization of the nano adsorbent sheets. This cycle continues continuously during the drying process to avoid energy loss.

To determine the amount of the initial moisture in the mint leaves, 10 g of the fresh mint leaves separated from the stems was weighed using a digital scale (Model KERN, 572-57 with a 0.1g precision rate) and placed inside an oven; the samples were brought out of the device after 72 hours and were immediately transferred to desiccators so that, meanwhile preventing moisture adsorption, the sample could be cooled down. Then, the sample's secondary weight was measured using the digital scale, and the required calculations were made. The experiment was conducted in three iterations and matched with the standards of the Association of Official Agricultural Chemists (Association of Official Agricultural Chemists Association of Official Agricultural Chemists (AOAC).

After the system's temperature reached a balance, the experiments were conducted at (40, 50, and 60 °C). In all of the experiments, fresh mint leaves were utilized. The mint leaves were separated from the stems, and 100g of fresh mint leaves were weighed for every experiment. The samples were immediately put inside the dryer's chamber. In three iterations, the experiments were carried out in two states with and without nano adsorbent sheets under identical conditions. In the experiments and determined times (at first, within 10-minute and then within one-hour intervals), since the samples' moisture reduction process had slackened, the weighing was done in 20-minute intervals.

The energy required for drying the products is calculated based on the Relation (1), and the output of the dryer is computed using Relation (2) [20].

$$Q_{drying} = m_{wd} \cdot h_{fg} \quad (1)$$

In the above relation, Q_{drying} is the energy required to be consumed for drying the product; m_{wd} is the mass of the moisture lost during the drying process in grams, and h_{fg} is the latent evaporation heat in kJ/kg.

$$\eta_{dryer} = \frac{q_{drying}}{q_{drying} + q_{heater} + q_{fan}} \quad (2)$$

In Relations (1) and (2), a wattmeter device has been used for calculating the energy required for operating the electric heater and dryer device's blower and the nano adsorbent sheets' chamber.

Quality variations

Quality changes are important and assessable parameters in drying food and agricultural products. The effects of the drying process should be in such a way that the minimum changes are brought about in the quality parameters of the materials. Quality parameters include physical and chemical changes in such physical properties of the materials as dimensions, form, shape, shrinking, texture hardness, and so forth as well as in such chemical properties of the materials as color change, change in the number of fats, changes in vitamins, and so on. This research examines color variations and antioxidant content changes in two methods, with and without nano adsorbent sheets.

Color change

In the drying process, chemical changes occur in the dried product's chlorophyll pigments in such a way that the longer the drying period and the higher the temperature,

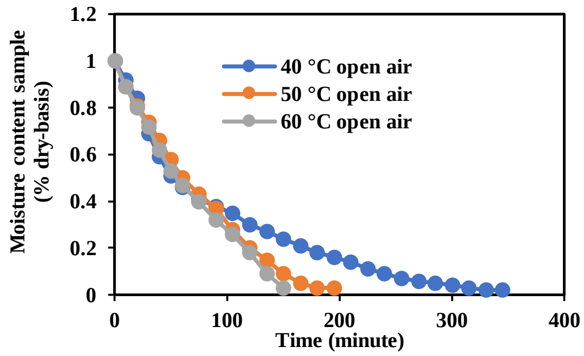

Fig. 3: The moisture-to-drying time ratio in the method without using nano adsorbent sheets

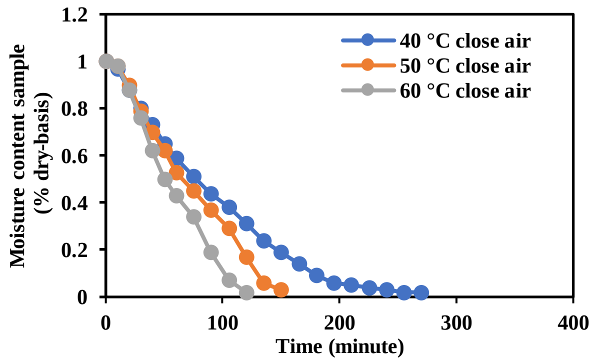

Fig. 4: The moisture-to-drying time ratio in the method using nano adsorbent sheets

the more intense the loss of the pigments would color changes. Thus, the increase in temperature causes the color preservation capacity to be reduced. To determine the number of color changes in the dried product and compare it with the fresh product sample, total color index variations were the measurement method designed by Commission International De L* 'Eclairage (Commission International de L'Eclairage (CIE)) and used herein. In this model, a*, b*, and L* are color indices. L* index indicates the contrast, and the a* and b* indices fall between +60 and -60, with the positive values reflecting redness and yellowness and negative values expressing greenness and blueness. The other parameters can also be formed by combining these three indices [21].

Before any experiment, some samples of fresh mint leaves were ground to be transformed into tiny segments. The samples' color indices were immediately measured using Spectrophotometer Model RT 100-200. Furthermore, after the mint leaves were dried in every experiment, the dry mint leaves were turned into powder using an electric milling device. Then, the color indices of the dry leaves were measured using a spectrophotometer for various temperatures in two methods with and without the use of nano adsorbent sheets. The results obtained in three iterations from the examined samples were compared with those of the fresh mint leaves in the evidence group. After the color indices and parameters' amounts were determined and presented in a table, the total color index's rate (ΔE) was calculated using relation (3).

$$\Delta E = \sqrt{(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^* - b^*_0)^2} \qquad (3)$$

Where a*, b*, and L* are the amounts of the dried samples' parameters, and a^*_0, b^*_0, and L^*_0 are the initial amounts of these parameters (fresh samples before drying).

Antioxidant activity

To determine and measure the antioxidant activity of plant extracts, the 2,2-Diphenyl-1-picrylhydrazyl (DPPH) method was used. Free radicals are trapped using the DPPH method [22]. At first, various concentrations of mint plants' extracts, namely 50, 100, 300, and 500 parts in a million phenolic compounds) were prepared. Also, various concentrations of synthesized Butylated Hydroxy Toluene (BHT) antioxidants (1 to 100 micrograms per milliliter) were used as the evidence concentrations. Then, 0.1 CC of each sample and evidence materials was prepared and separately mixed with 0.5 CC of DPPH methanol solution (0.1 millimolar) and measured using spectrophotometry in 517 nm wavelength. The total antioxidant activity (Total Antioxidant Activity (TAA)) was calculated using the percentage of DPPH's cleaning of the free radicals, as shown in Relation (4).

$$TAA(\%) = \left(1 - \frac{Abs_{sample}}{Abs_{control}}\right) \times 100 \qquad (4)$$

Abs_{sample} is the sample group's absorption, $Abs_{control}$ is the evidence group's absorption, and TAA is the total antioxidant activity in percentage.

RESULTS AND DISCUSSION

Figs. 3 and 4 present diagrams indicating the products' drying rates. As seen, the products' drying time is reduced by about 45% on average under the conditions of not using nano adsorbent sheets and following the increase in temperature from 40 °C to 50 °C. This reduction in the drying time is the temperature difference between the sample's temperature and the dryer's air temperature. With the increase in the temperature, the moisture transmission

Table 1: The comparison results of temperature and valve' s opening or closing effects' variances on the dryer's consumed energy and output

Mean squares		Degree of freedom	Change source
Consumed energy	Dryer's output		
49118.436*	31517.111*	2	Temperature
80054.676**	5065.916**	1	Valve
1412.853**	12.185**	2	Temperature & valve
0.388	100.154	12	Error

* and **respectively mean significant differences in 5% and 1% probability levels.

from the product to the dryer's air is accelerated, and the product is dried faster. In the method that uses the nano adsorbent sheets, the drying time is reduced by 42% to 50 °C. Since the dryer works with a closed-air circulation system, the speed of the product's drying is increased compared to when it works with an open-air ventilation system. In the former system, the speed of the moisture transmission from the product into the air hence the product's drying, is increased due to the use of the nano adsorbent sheets and the trivial reduction in the vapor pressure of the dried air. This finding is consistent with the results obtained in the other research [6].

In addition, in comparing the drying methods with and without using nano adsorbent sheets, the intermediate drying time reduction has been 21%. Therefore, as expected, using the nano adsorbent sheets along with a closed air circulation system in the drying system influences the latent evaporation heat by increasing the moist air's absorption in the dryer and returning the hot air and dry air into the drying system. In contrast, the air flowing into the drying system is lower in temperature in the open-air ventilation system, which runs the risk of getting a percentage of the environment's humidity entered into the system. It is more tangible in humid regions when drying products using this system.

The energy consumed for drying the product includes the electrical energy consumed by the electric heater and dryer's blower and the chamber in which the nano adsorbent sheets are installed. In each experimental treatment, the total consumed energy and the dryer output were measured using relations (1) and (2) for a fixed 0.05 kg/s mass flow rate. The experimental design's variance analysis results have been given in Table 1. The calculations have been made using (SPSS MINTAB) Software. The results indicated that the effect of the dryer's temperature on consumed energy and the dryer's output is significant in a 95% confidence level. It has also been found that the effect of the dryer's air circulation (open or closed valve) on the dryer's consumed energy and output are also significant in a 99% confidence level.

This means that temperature changes in the dryer have less effect on the energy consumption and efficiency of the dryer than the air circulation of the system (open or closed valve). In both cases (open/closed valve), the dryer's air circulation effect increases the rate of moisture transfer from the inside to the surface of the product during drying.

The use of MOF nano adsorbent in closed air circulation conditions in the dryer will absorb moisture in the dryer air and continuously circulate hot and dry air in the system. It also prevents wasting part of the system's energy. In the open-air circulation without MOF nano adsorbent, it is necessary to transfer the humidity of the dryer air to the outside and replace it with fresh air to reduce the humidity of the dryer air. It increases energy consumption and reduces the efficiency of the dryer.

Fig. 5 demonstrates a diagram showing the results of the mean comparisons for the mutual effects of temperature and valve on the dryer's consumed energy. As seen, temperature and valve significantly affect the consumed energy in a 99% confidence level.

Perhaps one of the reasons for the significant mutual effects of temperature and valve on energy consumption is the significant effect at a 99% confidence level in the closed air circulation of the dryer system, which causes...

Perhaps, the use of the closed air circulation system and the minimization of the peripheral air's entry into the system are the reasons for this reduction in energy consumption. The temperature differences between the interior and exterior environments of the dryer cause increase in the energy consumption for getting the dryer's temperature balanced. In higher temperature gradients between the dryer's internal and external environments, a higher

Table 2: The amounts of the dried leaves' color indices in various temperatures, with and without using the nano absorbents

Treatment	L*	a*	b*	ΔE
MOF; T=40°C	37.9	-3.21	15.52	9.22
NMOF; T=50°C	39.25	-2.64	16.07	8.45
MOF; T=40°C	39.02	-2.72	16.46	8.6
NMOF; T=50°C	38.32	-2.99	16.31	9.03
MOF; T=60°C	35.88	0.39	14.35	12.86
NMOF; T=60°C	34.69	-0.05	14.02	15.02
Fresh mint leaves (evidence)	46.13	-7.36	15.06	0.00

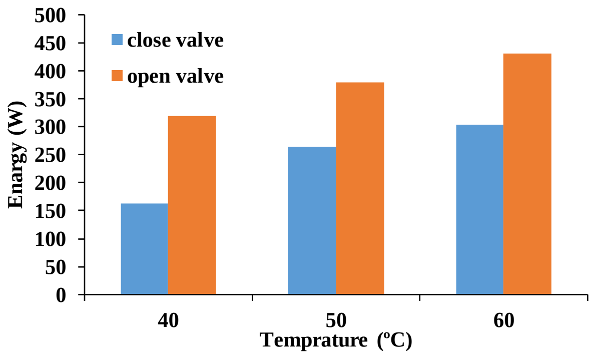

Fig. 5: The diagram showcases the mutual effects of temperature and valve opening or closing on the dryer's energy consumption

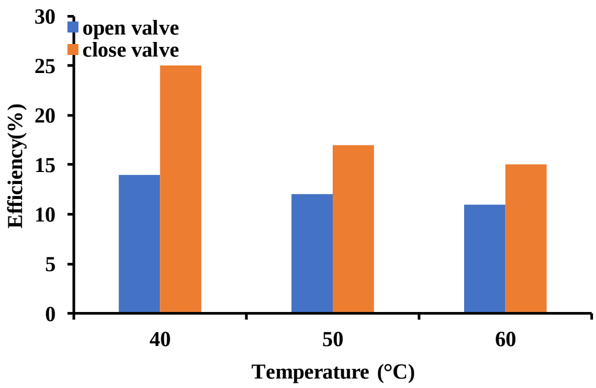

Fig. 6: The diagram showing the mutual effects of the temperature and valve's opening or closing on the dryer's output

energy rate must be consumed to get the environment's fresh air temperature to reach the optimum temperature in the dryer. Another reason for reducing energy consumption in the closed air circulation system is the shortened product drying time. This finding is similar to that of the other studies [5].

Fig. 6 displays the mean comparisons for the mutual effects of temperature and valve opening or closing on the dryer's output. The temperature and the valve being opened or closed significantly influence the dryer's output at a 99% confidence level. The diagram shows that these changes are statistically meaningful between the first and second temperature variations at a 95% confidence level. Still, the temperature variations take a descending trend between the second a nd third levels, probably up to a 95% confidence level. However, the output of the dryer is positively and significantly influenced when a closed air circulation system is applied. The highest dryer's output has been obtained in 50ºC treatment when a closed air circulation system is used.

Perhaps one of the reasons for the significant efficiency of the dryer in the condition of mutual effects of temperature and valve is the effects of air circulation in the dryer system, which has affected the temperature effects.

In research, the highest dryer's output has been attained with a combined method that uses solar energy and silica gel along with a closed air circulation system [7].

Changes in the color index of the dried mint leaves

The color index ΔE is applied to describe the color variations. The low amounts of the total color index differences indicate the lowest differences between the a*, b*, and L* indices amongst the dried and fresh samples. Table 2 presents the results of the total color indices' measurements and experiments.

The increase in temperature from 40 °C to 60 °C brings about an increase in the total color index from (9.22) to (12.86), and the change in temperature from 40 °C to 50 °C does not cause any vivid change in the total color index, which is decreased from (9.22) to (8.6). However, the change in the temperature from 50 °C to 60 °C causes an increase in the total color index, indicating the effect of the temperatures above 50 °C on the differences in the color indices obtained for the dry samples and the fresh ones. Additionally, no significant difference was documented between the two methods of using and not using.

Nanoadsorbent sheets for all three (40, 50, and 60 °C) temperatures. Of course, the increase in the temperature causes the temperature differences to be widened in comparing the two methods for such a possible reason as the differences in the drying times when nano adsorbent sheets are utilized. Fig. 7 exhibits the total color indices' variations for various temperatures with and without using the nano adsorbent sheets.

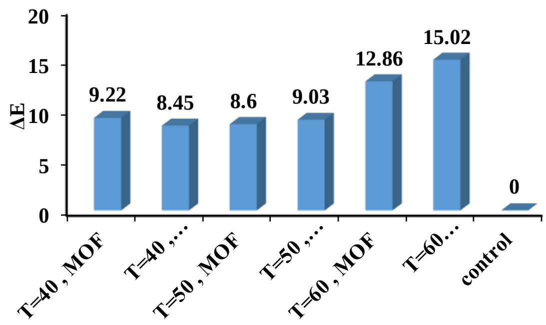

Fig. 7: ***Diagram showing the comparison of the results pertinent to the total color indices ΔE variations between the dried and fresh samples***

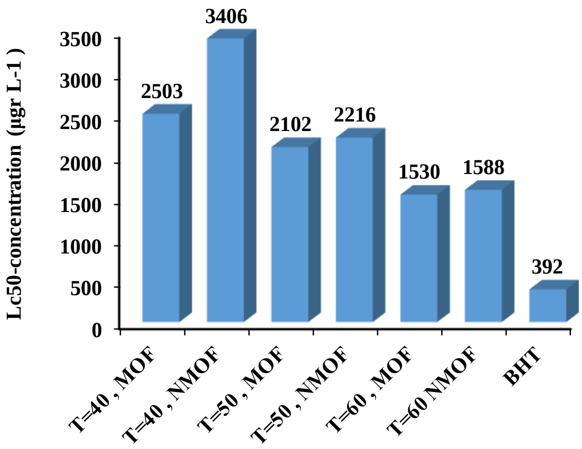

Fig. 8: ***The antioxidant activity rates of the dried mint leaves for various temperatures in the two drying methods***

Antioxidant activity of the dried samples

The amount of antioxidant activity of the prepared extract has been shown as IC_{50} (the concentration of the extract that inhibits free radical capacity by 50%). This amount is measured by the linear analysis of the radical scavenging capacity (Radical Scavenging Capacity (RSC)) for various concentrations of the samples. The obtained results were compared with the IC_{50} of the butylated hydroxytoluene (Butylated Hydroxy Toluene (BHT))'s antioxidant activity as the control.

Fig. 8 shows the results of the mint leaves antioxidant activity examination. As pointed out above, the lower the IC_{50} of a sample, the higher its antioxidant activity would be. Therefore, the lowest amount of IC_{50} (392 µg/L) pertains to the evidence or control (BHT) sample, and it is accordingly reflective of the highest antioxidant activity of the evidence group's plants. On the other hand, disregarding the experimental method, the increase in the temperature brings about a reduction in IC_{50}'s amount in such a way that the antioxidant activity is found to be reduced when not using nano adsorbent sheets from (3406 µg/L) at 40 °C to (1588 µg/L) in 60 °C and this is reflective of the ascending trend of the antioxidant activity in this method. This situation has also been found repeatedly when using nano adsorbent sheets. The amount of antioxidant activity has decreased from (2503 µg/L) to (1530 µg/L) at 60 °C, which reflects the increase in the antioxidant activity in proportion to the temperature increase. The main reason for such a phenomenon can be a reduction in the drying time due to an increase in the temperature. Besides, the comparison of IC_{50} values for an exact temperature and with and without the use of nano adsorbent sheets confirms that the drying time is reduced when using nano adsorbent sheets in contrast to when no nano adsorbent sheet is used. Therefore, it can be concluded that the antioxidant activity is a function of the drying time; the shorter the drying time, the more the antioxidant activity. The two important factors that can influence the antioxidant activity and the active ingredient of the plant species are drying temperature and duration [23].

Of course, an increase in temperature can cause a reduction in antioxidant activity. Still, it was found in this experiment that the increase in temperature adds to the antioxidant activity. Under such conditions, it can be concluded herein that the antioxidant activity is more influenced by the two factors of drying duration and the closed air circulation than by the drying temperature. A similar finding has been reported for apricot drying [24]. In this report, the increase in temperature from 50 °C to 70 °C caused the antioxidant activity to be increased in the samples. Moreover, another research indicated that dill drying by oven and microwave methods reduces the antioxidant activity. In contrast, drying plants like edible mint, peppermint, and thyme under the sunlight and in the shade causes an increase in antioxidant activity [25].

CONCLUSIONS

Aiming to devise a system that optimally dries crops and features such advantages as low volume and high moisture absorption, a thermal dryer was constructed herein using MOF nano adsorbent sheets. This system applies close air circulation to save energy and guarantee the quality of the dried product. The results obtained from numerous experiments on this drying machine showed that the product drying duration had been reduced on average by 50% when it was equipped with an open-air ventilation system without any use of the nano adsorbent sheets for a temperature increase from 40 °C to 50 °C; however, the machine's product drying duration was found reduced by 67% on average when equipped with a close air circulation system with the use of MOF nano adsorbent sheets for a temperature increase from 40 °C to 50 °C. The dryer's temperature on the amounts of the dryer's consumed energy and output were found to be significant in a 95% confidence level. It has also been found that the type of the dryer's air circulation (open or closed valve) significantly affects the dryer's consumed energy and output at a 99% confidence level. Which shows the stronger effect of system air circulation than the dryer's temperature changes.

The total color index was found to increase with the increase in the temperature, but no vivid difference was observed between the two methods with and without the nano adsorbent sheets. The antioxidant activity was found to increase with the increase in temperature. It seems that it is more influenced by the sum of the two factors' effect, i.e., the drying duration and the closed air circulation system, than the drying temperature.

It is suggested that the results be experimentally validated and confirmed in future research.

Received : Dec. 25, 2022 ; Accepted : Mar. 11, 2023

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