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Improving the performance of an indirect solar dryer using moisture adsorbent materials

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Abstract

This article presents a Modified Indirect Solar Dryer (MISD) with the integration of polyvinyl chloride tube (PVC) for recycling the hot air in a close circulation system. Meanwhile, a Silica gel beds (SGB) were used between trays of drying chamber at the air outlet to adsorb moisture. In addition, the basil leaves were dried in MISD, Unmodified Indirect Solar Dryer (UMISD) and Direct Solar Dryer (DSD) as well as the drying parameters were investigated. The indirect solar dryers were a forced convection of hot air by an electric fan operated by a photovoltaic panel and installed on top of them to maximize the utilization of solar energy at any remote area. Results revealed that the drying times for DSD, UMISD and MISD were 12 h, 9 h, and 7 h, respectively. While, the Specific energy consumptions for MISD, and UMISD were 0.35 kWh/kg, and 0.48 kWh/kg, respectively. Furthermore, the internal air temperature inside the MISD was higher than that in the UMISD by 2 °C. Meanwhile, the average relative humidity during the day time in MISD was higher than that of the UMISD by 3 %. The moisture content (wet basis) of basil leaves reduced from 87% (w.b.) to be 14% in MISD, 20% in UMISD, and 25% in DSD. Moreover, the MISD dryer increased the thermal performance efficiency by 51.4 % comparing to the DSD. In conclusion, the indirect solar dryer integrated with PVC tube and silica gel as an absorbent material for reusing the waste heat energy of hot air and absorbing its moisture, could reduce the drying time by 41.6% with a high quality of dried basil leaves which significantly higher in total volatile oils comparing to the direct solar dryer.

Keywords: drying rate, indirect solar dryer, silica gel, moisture content, thermal efficiency.

1. Introduction

Drying agricultural products is an important post-harvest technique that extends the shelf life of product by inhibiting fungal and bacterial development. Moreover, it extends the shelf life of product by, reduces volume and weight, lowering losses, and transportation costs due to it could remove 80% -90% of the initial moisture content [1, 2]. Solar dryers can be classified in to three types; direct solar dryers, indirect solar dryers and hybrid solar dryers according to the way of exposing the product to solar radiations. The traditional direct sun drying under sunlight is the simplest and cheapest drying method has been discovered and widely used for drying agricultural products in villages and rural areas for centuries. Nevertheless, the product could be affected by the environmental conditions and it takes time to dehydrate the moisture due to the fluctuated temperatures during the day and night [3].Moreover, the vital ingredients such as vitamins begin to deplete when the crop is exposed directly to sunlight as well as its effects on the actual taste, color, and texture of the product and significantly reduces its quality [4]. Meanwhile, the Post-harvest losses could be increased as a result of poor drying technology, poor transportation, and a variety of other factors such as insects, birds, bad weather, wind, dust and rain [5]. The indirect solar dryers have a separate solar collector and a drying unit. However, to improve the efficiency of indirect active solar dryer the air flow rate across the solar collector and in the drying chamber should be controlled by using a fan or a blower to maintain a desired air flow rate in the drying unit which results in a uniform drying.[4, 6]. The drying air temperature for most agricultural products should be ranged from 45 to 60 ºC to safely preserve the product. Due to drying under controlled temperature and humidity could speed up the drying prosses and improve the quality of dried product [7]. Thus, numerous studies have been conducted to improve the efficiency of the indirect solar dryers by designing new structures, adding heat storage materials, using solar collectors and air recycling system [8-13]. However, the active solar dryers with

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a forced convection remained unpopular, due to the need of fans for conventional electricity, which is not available everywhere especially in rural areas. Andharia et al. [14] used the black pebble stones as sensible heat storage material while paraffin wax (melting temperature 58-60 ºC) was used as a latent heat storage material in a small-scale mixed-mode solar thermal dryer. They found that the dryer with paraffin wax could sustain drying for 3 more hours and the maximum drying air temperatures were 86.51 ºC, and 86.42 ºC for sensible heat, and latent heat stored units, respectively. On the other hand, a novel active-mode indirect solar dryer consisted of evacuated tube solar collector, a DC fan and a drying chamber was investigated to dry fenugreek leaves and turmeric [15]. Results showed that the overall thermal efficiency was found to be 34.1% and the quality of dried fenugreek leaves and turmeric was better than those in the open sun drying. Rezaei et al. [9] investigated the performance of a new forced convection solar dryer with a phase change materials (PCM). Results illustrated that using bobbin absorber plate and PCM in the dryer improved the average collector efficiency by 28.5% and the average dryer efficiency by 52.1%. Nabnean et al. [16] studied the performance of a new designed indirect solar dryer consisted of drying cabinet, heat exchanger, water type solar collector, and water type heat storage unit for drying cherry tomatoes. They reported that the efficiencies of the solar collector were 21% - 69% and the pay-back period of the dryer was estimated to be 1.37 years. Basil (Ocimum basilicum L.) is an herb which has a number of volatile aroma compound, such as glandular trichomes, and accumulating terpenoid oils. Thus, basil leaves need a low temperature to be dried [17]. Moreover, basil has many minerals, micronutrients, and pharmacological activities. It helps in getting rid of forgetfulness and strengthening memory. It can be used against bacteria in the body and contains vitamin A and vitamin C and antioxidants [18]. The adult basil plants length is a proximately 20 to 60 cm and its leaves length is varying from 1-5 cm and the leaves width is about 1-3 cm [19]. Shalaby et al. [20] reported that using the indirect solar drying integrated with phase change material could provide a drying temperature of 34-40 °C with 5-11 °C more than ambient temperature. Thus, it was better than the direct solar drying, due to it saves most of volatile organic compounds, meanwhile it saves 48.33% of the total drying time. In addition, using of sorption materials in solar dryers needs more attention for its toxicity due to the drying air will be in contact with the agricultural product. Therefore, the transfer of toxic particle to the products should be avoided [21]. Silica Gel Beds (SGB) is the most popular and used sorption material for physical adsorption of water vapor due to its hydrophilic properties. Therefore, the white silica gel has been considered for dehumidification in solar dryers, both in direct and indirect forced convection solar dryers due to the standard white silica gel is non-toxic and inert [22-25]. All the previous studies which used SGB as a dehumidifier unit based on sorption material indicated that the performances in a solar dryer could be ranged from 15 to 30% reduction in drying time compared to operation without the sorption material integrated into the dryer [21, 22, 24, 26]. Thus, in this study an innovative indirect solar dryer was designed to reuse the waste heat in drying prosses by recycling the hot air after the absorption of moisture by silica gel beds in a close circle. In addition, the drying performance of the proposed dryer and the drying characteristics of basil leaves were investigated

2. Materials and methods

The experiment was conducted at Agricultural Engineering Department, Faculty of Agriculture. Cairo University, Giza (longitude of 31.13º N and latitude 30.03º E). During the period of late November 2021. Subsequently, the experiments were repeated in July 2022.

2.1. The description of solar dryers

In this experiment two indirect solar dryers were designed, namely Modified Indirect Solar Dryer (MISD) with a forced convection and Unmodified Indirect Solar Dryer (UMISD), with the same dimensions and materials. The differences in the modified solar dryer were the attached PVC pipe to recycle the hot air in a closed circuit and the silica gel beds which used in the drying chamber between the drying trays to absorb the extracted moisture of the dried product, as well as the number of holes for air inlet at the bottom of solar collectors was two holes and five holes in the MISD and UMISD, respectively the diameter of each hole in UMISD was 5 cm at a distance of 15 cm. The main and same components of each solar dryer were a solar collector, drying chamber and a small circulation fan to circulate the hot air. The circulation fans for both dryers were operated by small solar panels attached on top of each solar dryers as a standalone system without any auxiliary electric, as shown in Figures (1-3).

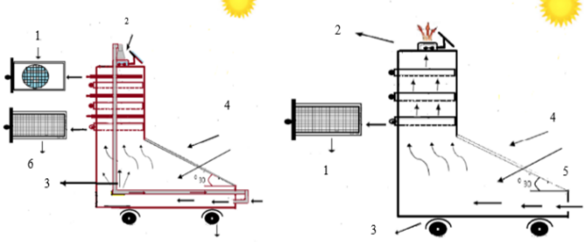

Fig.1Schematic diagram of two types of indirect solar dryer: (A) MISD (B) UMISD with forced convection

(A) The MISD: 1- Silica gel bed;2-Fan;3-Pvc tube;4-Glazing; 5-Air inlet hole; 6-Tray of drying

(B) The UMISD: 1-Tray of drying ;2-Fan;3- Scroll wheel ;4-Glazing;5-Air inlet hole

The solar air collector for each solar dryer was made of a glass with surface area of 0.48 m^2 (80 cm × 60 cm) and with a tilt angle of 30 °C exposed to the south direction throughout the drying period. In addition, the internal surface of the wood solar air collector painted black for a better heat absorption. The drying chamber dimensions were (50 cm length × 50 cm width × 88 cm height) and it had three shelves of three trays, each try was (40 cm × 40 cm) and the base of each tray was made of stainless-steel mesh to allow air to pass during the drying period as shown in Table.1.and Fig.2. (A). The air velocity of both fans was adjusted to be the same at 1.8 m/s in the UMISD and MISD respectively. The PVC tube in the MISD was installed on the fan nozzle of 12 cm in diameter at the top of the dryer and extended to the holes at the bottom of the dryer to circulate the air inside the dryer in a closed circuit. The tube was painted black to absorb and retain more heat. Meanwhile, the silica gel beds (SGB) in the MISD was used in two net beds of 200 grams for each bed and installed between the trays of drying in the drying chamber as shown in Fig.2. (B).

Table 1 Dimensions of solar dryers and solar collector

Parameters	Dimensions
Collector	
Length (L_C), m	0.80
Width (W), m	0.60
Collector Area (A_C), m^2	0.48
Drying chamber	
Length (L), m	0.50
Width (B), m	0.50
Height (H), m	0.88

The experiments were conducted parallelly in the three solar dryers and repeated three times, the Modified indirect Solar Dryer (MISD) and Unmodified indirect Solar Dryer (UMISD) with a forced convection, and the Direct Solar Dryer DSD), as shown in Fig.3. The main purpose of choosing these types of indirect dryers is that they are simple in design, low cost of maintenance and operation, as well as suitable for drying different products according to the seasons.

2.2. Pre-treatment of basil leaves

The fresh basil leaves were collected from basil grown in the agricultural farm. The initial moisture content of basil leaves was 87 % (wet base). The original moisture content of 100 grams of basil leaves was assessed by oven drying at 105 °C for 24 h, and the total volatile oils was determined as specified by the Association of official Analytical Chemist (AOAC) [27].

The Silica gel material was spread between the drying trays in the drying chamber and near the outlet of exhaust air. The thickness of the silica gel bed was 1.5 cm.

Fig.2. (A). The side view photo of the MISD solar dryer.

Fig.2. (B) The side view photo of the UMISD solar dryer.

Fig.3 Front view photo for the three dryers (UMISD, MISD and DSD)

2.3. Properties of Silica Gel (SG)

The bulk density of silica gel (g/cm^3) was estimated by dividing a certain mass of silica to the same volume and the porosity of silica gel **(**P_S**)** (%) was estimated by the following equation:

$$P = \frac{V1-V2}{V1} \times 100 \qquad (1)$$

Where

V_1: The apparent volume of silica (m^3)

V_2: The true size of silica(m^3).

The degree of saturation (D_S of silica gel (%) was estimated by passing water vapor over a specific weight of silica (200 g) and determining the saturation degree of silica from water vapor (g $_{water}$/kg $_{silica}$).while, the degree of dehumidification of silica after saturation (DD_S) was estimated by divided the quantity of moisture (g) that could be removed from 1 kg of saturated silica with water vapor (g $_{water}$/kg $_{saturated\ silica}$).

The solar system along with the dryers were tracked manually during the daytime to face the sun light to maximize the utilization of solar energy. The solar system characteristics are as shown in Table 2.

Table 2 The characteristic of solar system and fan.

Name	Classification
PV Panel	Model ST-P
PV Peak power	20 W &12 V
Battery (lead-acid)	12 AH & 12V
Charge controller	20 A
Inverter	300 W & 12 V
Exhaust or circulation Fan	3.6 W& 12 Volt

2.4. Measurements and instruments

The mass was measured by electric digital balance (Model HG-5000-Range 0 - 500 g ± g, Japan) daily for the direct solar dryer and hourly for indirect solar dryers. Air temperature and relative humidity were measured every 30 min by a NOMAD data logger at accuracy of ±0.5°C ℃± 3, measuring range (-40 to 80°C), 0 to 95% RH made in USA. The solar radiation was measured by SMP21-V Pyranometer, KIPP &ZONEN company, serial number 200193, made in Germany at accuracy of 0.1 W/m^2, and analogue output range of 0 -1600 W/m^2

2.5. Drying calculations

2.5.1. Drying behavior

The moisture content [28] was calculated by Eq.(1)

$$M(\%) = \frac{Wi - Wf}{Wi} \times 100 \quad (2)$$

Where:

M: The moisture content of leaves

W_i: The initial mass of basil leaves (g)

W_f: The final mass of basil leaves (g)

The moisture content dry base [29]was calculated by Eq. (2)

$$M_{(d.b)} = \frac{W_w}{100 - W_w} \quad (3)$$

Where:

$M_{(d.b)}$: The moisture content of leaves (dry base) (g_{water}/g_{solid})

W_w : The moisture content of leaves (wet base) (%)

The average drying rate of basil leaves [29] were calculated by Eq. (3)

$$Dr = \frac{W_f}{W_i} \times 100\ \% \quad (4)$$

Where:

Dr: The drying ratio

W_f : The final mass of leaves (g)

W_i: The initial mass of leaves (g)

2.5.2. The thermal efficiency for dryers

The thermal efficiency (η_d) of solar dryer system, η_d, is an indicator of a drying system's overall efficiency. It is the ratio of the amount of energy required to evaporate the moisture from the product to the amount of energy provided to the solar drier [30, 31]

The system drying efficiency was calculated by Eq. (5)

$$\eta_d(\%) = \frac{m_w h_l}{A_c I\ t} \times 100 \quad (5)$$

Where:

m_w: Mass of evaporated water from basil leaves (K_g)

h_l: Latent heat energy of vaporization of water, (2256k_j/k_g)

I: Direct solar radiation (W/m^2)

A_c: Area of solar air collector (m^2)

t: The drying time (s)

2.5.3. The Specific Moisture Extraction Rate (SMER) which is usually mentioned in kg/kWh [32]

$$SMER = \frac{\text{mass of water removed (kg)}}{\text{total energy consumption (kWh)}}$$

The Specific Energy Consumption (SEC)[33]

$$SEC = \frac{\text{total energy consumption (kWh)}}{\text{mass of water removed (kg)}}$$

Mass of water removed (W_m) can be calculated as

$$W_m = \frac{W_i\ (\text{initial moisture content} - \text{final moisture content})}{100 - \text{final moisture content}}$$

3. Results and discussions

3.1. The thermal performance of solar dryers for drying basil leaves

Figure 4 illustrates the differences in air temperature between the solar dryers and the ambient temperatures. It was observed that the average air temperature in drying chamber of MISD was higher than that of the ambient temperatures by 5 ºC. The maximum air temperature in drying chamber of MISD and UMISD were 51 ºC and 50 ºC respectively, while the maximum ambient air temperature was 44ºC. Thus, the hourly ambient air temperature during the day time on 21th of July, 2022 was varied from 28 ºC to 44 ºC with an average of 38 ºC and the hourly air temperature in the center of drying chamber was varied in the UMISD from 28 ºC to 50 ºC with an average of 41 ºC. While, in the MISD was varied from 28 ºC to 51 ºC with an average of 43 ºC.

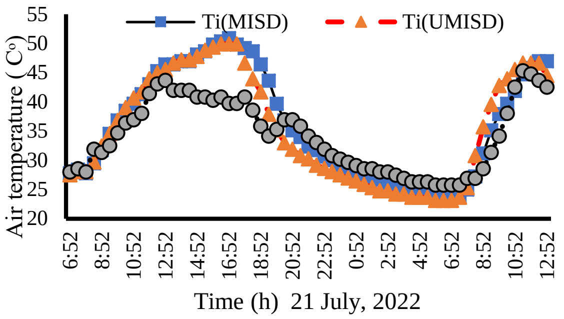

Fig.4 Air temperature inside and outside the three dryers on 21th of July, 2022 with full load.

On the other hand, the hourly relative humidity during the day time was varied from 13 to 41% with an average of 17.5% and the hourly relative humidity in the center of drying chamber was varied in the UMISD from 13 to 55% with an average of 27%. While, in the MISD was varied from 13 to 60% with an average of 30% as shown in Fig.5.

These results due to during the day time, as the hot air flows into the drying chamber, Silica Gel Beds (SGB) will be heated up and lose their moisture along with the drying products, silica gel can be regenerated by using only solar radiation[23]. subsequently, during the off-sunshine hours, when the circulation fan switched off, the SGB adsorbs the remaining moisture from the basil leaves and thus keep them dry even during the night. Thus, the average relative humidity in MISD was slightly higher than that of UMISD during the day time and decreased at night. These results are in agreement with the previous studies [34].

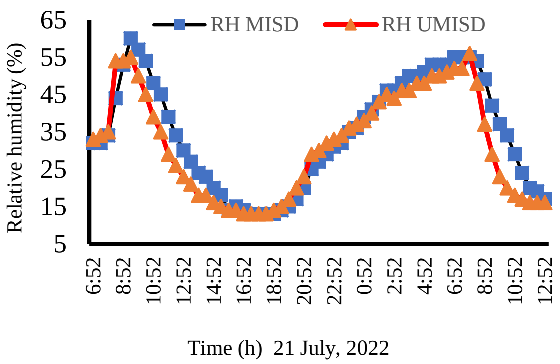

Fig.5 Relative humidity inside solar dryers on 21th of July, 2022 with full load.

It was found that the maximum air temperature in the MISD at the lower tray (T_{3max} 53 ºC) and it was higher than that of the upper tray (T_{1max} 48 ºC) due to the hot air which was coming from the solar collector. Then pass through the first and second trays to dry basil leaves and easily flow up to be recycled. Meanwhile, the average air temperature of lower tray was 46 ºC and the average air temperature of upper tray was 42ºC. Thus, the air temperature decreased gradually from down to top of the drying chamber as shown in Fig.6.

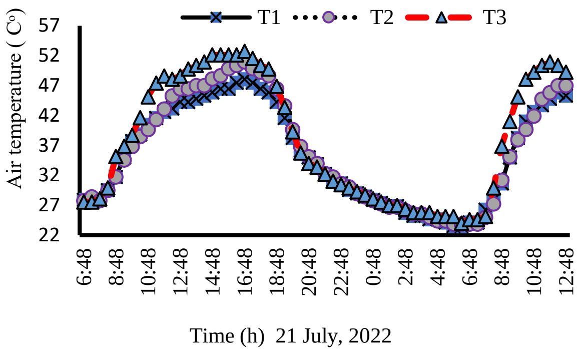

Fig.6 Air temperatures inside MISD in different trays on 21th of July, 2022 with load.

In the contrast, the relative humidity of the upper tray was higher than that of the lower tray. The maximum relative humidity of the upper tray was 66% and the maximum relative humidity of the lower tray was 61%. The average relative humidity of the upper tray was 38% and the average relative humidity of lower tray was 30% as shown in Fig.7. Thus, the relative humidity increased gradually from down to top of the drying chamber because of the moisture extracted from the basil leaves during the drying prosses and the air flow carried up the moisture to be recycled in the drying system.

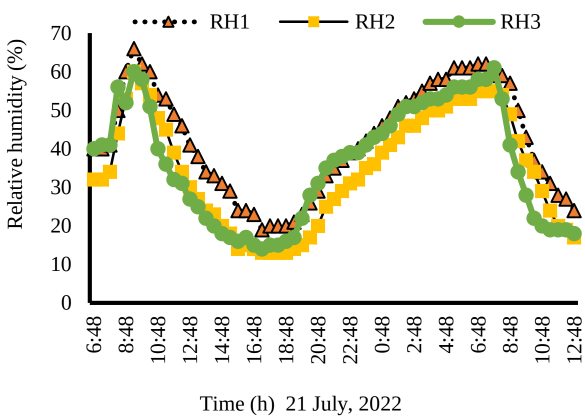

Fig.7 Relative humidity inside MISD in different trays on 21th of July, 2022 with full load.

Results found that air temperatures at the inlet and middle of UMISD was varied and the highest air temperature was at the inlet in the solar collector at

56 ºC. Therefore, the average air temperature at the inlet was 46 ºC and the average air temperature at the middle of UMISD was 42ºC as shown in Fig.8.

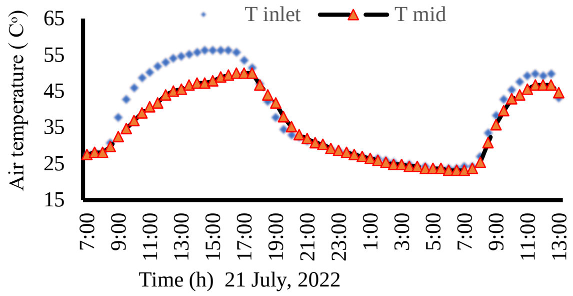

Fig.8 Air temperatures at the inlet and middle of UMISD on 21th of July, 2022

It is clear that solar radiation could influence the thermal performance of solar dryers in sunny days. The maximum Solar radiation on the experimental area was 950 W/m^2 which recorded at 12:15 p.m.

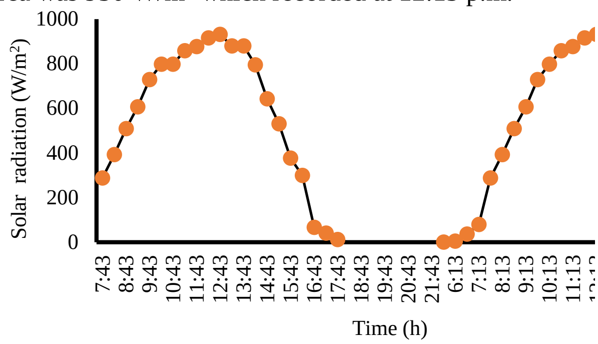

Fig.9 Solar radiation in the experimental site.

3.3. Thermal performance of solar dryers during solar drying process of basil leaves

Figure 10 shows a decrease in moisture content over the time of the drying process, dropping from 87% (6.69 g $_{water}$/g $_{solid}$) to 14% (0.176 g $_{water}$/g $_{solid}$) in7 h for MISD dryers of silica gel as an adsorbent material. While, moisture content for the UMISD without adsorbent materials decreased from 87% (6.69 g $_{water}$/g $_{solid}$) to 20% (0.25 g $_{water}$/g $_{solid}$) in 9 h, and for the direct solar dryer DSD, moisture contents decreased from 87% (6.69 g $_{water}$/g $_{solid}$) to 25% (0.33 g $_{water}$/g $_{solid}$) in 12 h. It was noted also that with the increase in the drying period, the moisture content of basil leaves reaches the balanced point of moisture.

Regarding the drying rate, it has been observed that this rate initially decreased and then stabilized (during the time of the constant rate and before declining in regression phase) and there was a clear decrease after that in the regression stage as shown in Fig.11. The reduction of the drying rate at the end of drying for the three dryers may be due to the reduction in moisture contents

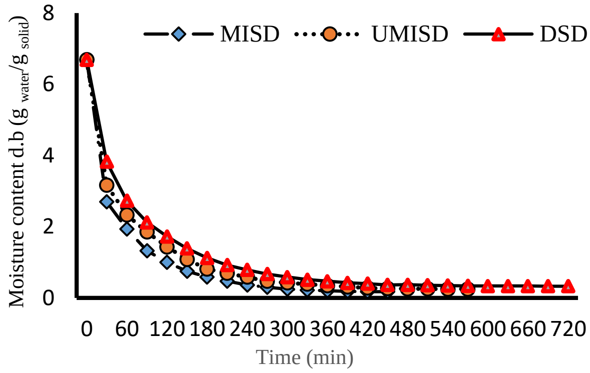

Fig.10 Effect of drying time on moisture content (d.b.) of the three dryers

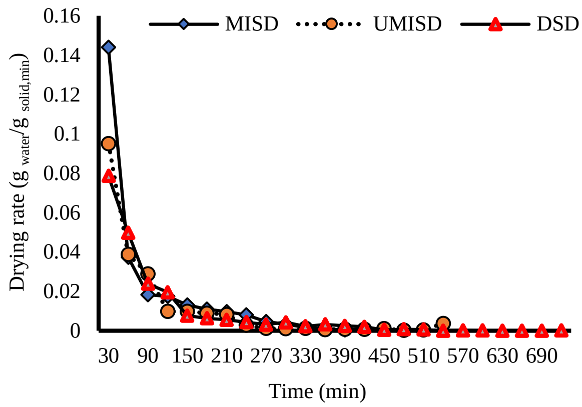

Fig.11 Effect of drying time on the drying rate (g $_{water}$/g $_{solid,\ min}$) of the three dryers

3.4 Drying characteristics and the thermal efficiency of dryers

Using the MISD in drying basil leaves increased the thermal performance efficiency by 51.4 % comparing to the DSD and increased the thermal performance efficiency by 43% comparing to UMISD, these results are in agreement with Shalaby et al. [20]. Results also revealed that the MISD reduced the moisture content of basil leaves from 87% to 14% in a short time of 7 h while using UMISD reduced the moisture content to 20% in 9 h. So, the dryer with adsorbent material (Silica gel) achieves a shorter drying time while, DSD reduced the moisture content to 25% in a period of time equal to 12 h. Meanwhile, the final mass of basil leaves was reduced in the first experiment from the initial weight of 100g to be 38, 33, and 27g for DSD, UMISD, and MISD respectively. Therefore, using the MISD could reduce the drying time by approximately 41.6% comparing to the DSD and by 22.2% comparing to the UMISD as shown in Table 3.

Table 3: Results of drying 100 g of basil leaves using different types of dryers.

Types of dryers	Initial moisture content (%)	Final moisture content (%)	Final mass of basil leaves (g)	Drying time, (h)	Drying ratio
MISD	87	14	27	7	3.7
UMISD	87	20	33	9	3.03
DSD	87	25	38	12	2.63

The calculated results showed that the specific moisture extraction rate (SMER) for MISD was 2.9 kg/kwh, which is higher than that of UMISD 2.1 kg/kwh. In contrast, the specific energy consumption (SEC) for the MISD was 0.35 kWh/kg, which is lower than that of UMISD 0.48 kWh/kg. Due to the MISD shorten the drying time comparing to the UMISD.

3.5 The total volatile oils (TVO) of dried basil leaves.

Results found that the mean of total volatile oils in dried basil leaves at MISD was significantly higher than those of UMISD and DSD. where it was 0.71, 0.46, and 0.39 mg/l, for, MISD, MISD and DSD, respectively (Fig.12). These results indicated that the silica gel could maintain the volatile oils and improve the quality of dried basil leaves more than the direct solar dryers.

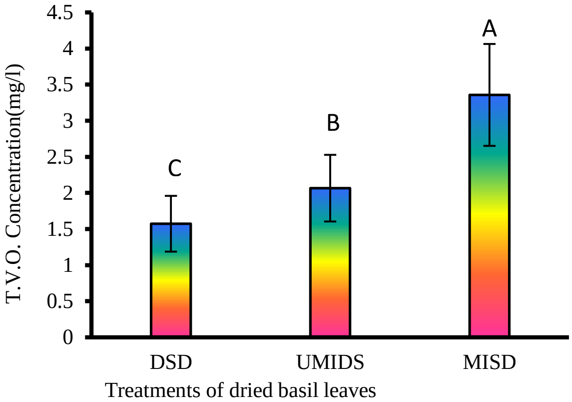

Fig. 12 The concentration of total volatile oils (mg/l) in different treatments

3.6 Silica gel properties after drying process

Figure 13 shows a photo for the variation of silica gel beds (SGB) at 8:00 a.m. before drying in the morning and at 3 p.m. after drying. SGB was white before drying without absorbing any moisture from the basil leaves and then it turned into light brown. As the circulation fan was turned on at 8.00 a.m. and the drying chamber gets heated up. The moisture from basil leaves was removed and then the SGB absorbed it in the close system. The results also revealed that the silica gel saturation percentage of moisture was 25% and the degree of dehydration was 10% after its first saturation as shown in Table 4. Therefore, drying basil leaves using the MISD, the silica gel beds should be changed after 2.3 h for each 100 g of silica gel.

Table 4 Properties of silica gel.

Bulk density (g/m^3)	0.98
The porosity of silica gel (%)	46.66
Degree of saturation with water vapor, ($g_{water}/kg_{silica\ gel}$)	250 (25%)
Degree of dehydration of silica gel after the saturation, ($g_{water}/kg_{silica\ gels}$)	100(10%)

Fig.13. Silica gel before drying at 8 a.m.(A), Silica gel after drying at 3 p.m. (B).

4. Conclusion

The use of moisture adsorbent materials such as, silica gel beds along with reusing the waste heat of hot air from the drying process and recycling it in a closed circuit for developing indirect solar dryers was investigated. Results revealed that the modified solar dryer MISD could increase the air temperature inside the drying chamber and shorten the drying time comparing to the UMISD and DSD. Results showed that the closed drying system using SGB along with recycling the hot air in MISD could increase the internal air temperature inside the solar dryer by an average of 2 °C comparing to the UMISD and 5 °C comparing to the DSD. Meanwhile, the average relative humidity during the day time in MISD was higher than that of the UMISD by 3 % and higher than the DSD by an average of 12.5%. The drying time for basil leaves decreased in the MISD comparing to the direct solar dryer. In addition, the specific energy consumption (SEC) for the MISD was lower than that of UMISD.

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Conflicts of interest
The authors declare that they have no conflict of interest

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