Effects of phase change material on the performance of solar dryer used for Eruca Sativa

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Abstract: This work presents experimental investigations of the performance of a solar dryer with and without phase change material (PCM) used to dry Eruca Sativa foodstuffs. This dryer consists of a solar collector with dimensions of (1000 mm as width by 1000 mm depth and by 1000 mm highest) which includes dryer chamber and the heat storage container inside it. The experimental work included the design and fabrication of the solar dryer, and the outdoor tests of the system. The experimental tests were performed under real outdoor weather conditions at the Technical College of Al-Mussaib located in Babylon, Iraq (32.5°N 44.3°E) during December 2019. Three modes of drying (natural drying, solar drying, and solar drying with PCMs) were applied. The results showed that the moisture recorded lowest rating for using the solar dryer with PCMs by 17.3% with that of using the solar dryer without PCMs and 40% with using of natural solar drying. The maximum temperature in the drying chamber with PCMs was reached 45 °C and while it was 40 °C without PCMs and it was 20 °C for sun drying. It found reducing of drying time with using of PCMs comparing with using others methods as: 5.3 hr, 7.3 hr, and 24 hr for solar dryer with PCMs, without PCMs, and sun drying respectively.

Key words: solar, dryer, phase change material, eruca sativa

1. Introduction

Eruca sativa Mill is known locally as Jarjeer in the Arabic region which employed as vegetable and spice. The plant was used at all civilization as food sources due to their important nutritious value, physiological influence, and as materials of pharmaceutical, also it considered as corresponding and alternative medicine [1, 2]. Medicinal and aromatic plants have a moisture high level and micro-organisms. Consequently, instantaneous drying represents the most significant operation in post-produce processes for avoiding losses of the valued [3]. Medicinal plants set up the main source of the new medications and healthcare harvests [4]. The postharvest processes feature is important to effective operation of the leaves; the quality of the leaves could be conserved with improved shelf life [5].

One preservation possibility is drying processes which included decreasing the water contented for minimizing the biochemical, chemical and microbiological deterioration. The dehydration indicated a useful method for preservative the leaves through which the spoilage could be disallowed [6]. The drying presented important processes in the conservation of agricultural foodstuffs. Food products have need of hot air at 45–60 °C temperature for the safe drying process. The drying in controlled conditions for temperature and humidity assistances the agricultural food production for drying...
sensibly quickly for safe moisture contented and for ensuring a greater quality of the production [7]. The literature searches were undertaken on the effects of various methods of the drying processes on necessary oil contents and the chemical compositions of the important oil plants [8, 9]. Solar energy contents great potentials like an alternative energy source, but differences in solar radiation need the using of supplementary energy sources for maintaining continuous drying processes [10]. The solar energy display a particularly promising energy sources, its daily and seasonal fluctuations necessitate the employing of supplemental energy sources like biomass, hydrocarbons, and electric energies and/or solar energy collectors using phase change materials (PCMs). These systems allow the solar dryers for continue their operation through the periods at lower or definitely not radiation [11]. The solar energy is free cost, environmentally clean, consequently acknowledged as one of the best promising alternative energy recourses selections [12]. Phase change materials presented the Latent heat storage materials. PCMs are using chemical bonds for store heat. The thermal energy transfer happens via the chemical bonds the PCMs [13, 14]. A great number of phase change materials (PCMs) are available in at all required temperature range from 0 °C to 150 °C which is motivating for solar applications [15]. El Khadraoui et al. designed and tested an indirect forced-convection solar dryer by using PCMs, the temperature of the drying chamber keep on higher than the ambient temperature via 4–16°C for all night [16]. Nasir et al. 2018 [17] investigated the melting developments of 12 kg of black pure paraffin in the shell and tube heat exchanger numerically and empirically, employing solar thermal energy. Experimental consequences presented that accumulative heliacal radiance and ambient temperature reduced the melt timing of black pure paraffin; the entrance line, and ambient temperatures had a large influence on the fusion method competition with the water circulation volume flow rates. The numerical consequences displayed that the distribution of temperature for black pure paraffin provided perfect effectiveness. The object of this investigation is studied the influence of using solar energy with and without using of PCMs on the drying processes of eruca sativa plant under Iraqi weather conditions. There is one type of PCM used in this work, the type is black Iraqi origin pure Paraffin with amount of 3 kg. Heat transfer modes that employed in this work included radiation, conduction, and convections modes.

2. Methodology
The experimental tests are applied at Al-Mussaib Technical College in Al-Mussaib city at Iraq, positioned at 32°5′ North as latitude and 44°3′ East as longitude, this location taking as position for explanation in measuring of intensity of the solar at the title angle of 42.5° which represented latitude plus 10 ° [21] and weather conditions. Intensity of solar radiation (I), ambient temperature (Ta), collector temperatures, and moisture measured with half hourly time. These parameters are inconstant with time and it gotten every 30 minutes from the recorder measured devices. The proposed solar dryer is shown in Figure 1. which is be made of a structure measuring 1000 mm x 1000 mm x 1000 mm, it has the hot air outlet, it is situated at the top part of the dryer. This delivery lets moist air evaporated from the food for escape addicted to the surrounding because of using front glass. The drawing of complete sketch system is exposed in figure. 2. For measuring the solar radiation, a Kipp and Zonen of class one Pyranometer for model of CMP22 was employed as shown in figure. 3. The Studied Parameters included: (1) Leaved dry weight (g / plant); the leaves of the plant were dried in the electric oven at a temperature of 75 °C. After constant weight, they were weighed by the delicate scale. 100 g of leaves were taken fresh and 100 g of dried leaves dried and weighed by the delicate balance for comparison. (2) Extraction of essential oils; essential oil ratios of wet and dry Eruca Sativa samples were determined using the Neo Clevenger apparatus. While determining the essential oil ratios of wet samples, Analysis was made by passing water vapor through them. In these analyzes, 200 ml of water was placed in the tubes heated at the bottom. 50 g wet Eruca Sativa samples were placed in the upper tubes. In order to reduce heat loss, insulation was made to the top tube. The samples were distilled for 3 hours after the pure water reached the boiling point. Dried Eruca Sativa samples were placed in pure water and boiled. Boiling was carried out by placing 200 ml of distilled water and 20 g of dried sample in the tube. Dry products and pure water were processed in the tube for 3 hours and 15 minutes on the stove. The time required for boiling of pure water was 15 minutes. The essential oil
ratio is calculated in terms of the volume of essential oil obtained from the amount of 100 g dry matter (ml essential oil / 100 g dry matter). The end oil extraction processes were performed in triplicate.

Figure 1. Solar dryer system  
Figure 2. Sketch of solar dryer system

Figure 3. Pyranometer model CMP22

3. Calculation of Solar Radiation
The valuation of the total solar radiation on exposed surfaces is involved the determination for the beam, reflected, and diffuse solar radiation, which are computed depending on the solar time and position. Solar intensity values A, the full of atmosphere extinction coefficient B, and sky diffuse factor C were determined for any day of the month as [18]:

\[ A = 1158 \left[ 1 + 0.066 \cos \left( \frac{360 \text{ ND}}{370} \right) \right] \]  
\[ B = 0.175 \left[ 1 - 0.2 \cos \left( 0.93 \text{ ND} \right) \right] - 0.0045 \left[ 1 - \cos \left( 1.86 \text{ ND} \right) \right] \]  
\[ C = 0.0956 \left[ 1 - 0.42 \cos \left( \frac{360 \text{ ND}}{370} \right) \right] - 0.0075 \left[ 1 - \cos \left( 1.95 \text{ ND} \right) \right] \]

The declination angle \( \delta \) and sun altitude angle \( \alpha \) are given by as [19]:

\[ \delta = 23.45 \left( \frac{360(ND - 60)}{370} \right) \]  
\[ \sin \alpha = \cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi \]

Where:
\( \phi \) is the latitude angle which equals 32.5° for Al-Mussaib city and \( \omega \) is the hour angle [19]:

\[ \omega = 15(AST - 12) \]
Where:
AST is the apparent solar time.

$$\text{AST} = \text{LCT} - \frac{\text{STM} - \text{LONG}}{15}$$  \hspace{1cm} (7)

Where:
LCT is the locally time as hours.
STM is the standard meridian of local time zone which equals 45 °E for Iraq.
LONG is the longitude of the location concerned and equals 44.3°E for Al-Mussaib city.
EQT is the equation of time given as [20]:

$$\text{EQT} = \sum_{k=0}^{5} \left( A_k \cos \left( \frac{2\pi N_n}{365.25} \right) + B_k \sin \left( \frac{2\pi N_n}{365.25} \right) \right)$$  \hspace{1cm} (8)

Where:
$N_n$ is the number of days in the four year.
$A_k, B_k$ are constant.

Duffie and Beckman [21] introduced a general definition of incident angle for any surface orientation as:

$$\cos \theta = \sin \delta \sin \Theta \cos \beta + \sin \delta \cos \Theta \sin \beta \cos \gamma + \cos \delta \cos \Theta \cos \omega + \cos \delta \sin \Theta \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega$$  \hspace{1cm} (9)

Where:
$\gamma$ is the surface azimuth angle which values 0 ° for south facing, west is positive and east is negative (-180° ≤ $\gamma$ ≤ 180°).

For a collector due south $\gamma = 0^o$ and the incident angle calculation reduced to:

$$\cos \theta = \cos (\Theta - \beta) \cos \delta \cos \omega + \sin (\Theta - \beta) \sin \delta.$$  \hspace{1cm} (10)

The direct normal irradiance is calculated as [19]:

$$I_{DN} = A \exp \left( \frac{-P_L}{P_0} \frac{B}{\sin \alpha} \right)$$  \hspace{1cm} (11)

Where
$$\frac{-P_L}{P_0}$$ presented the pressure in the altitude concerned relative to the standard atmospheric pressure at sea level and is given as [19]:

$$\frac{-P_L}{P_0} = \exp (0.0001148 H_{alt})$$  \hspace{1cm} (12)

Where:
$H_{alt}$ is the altitude in meters above sea level.
The beam irradiance can be computed as:

$$I_b = I_{DN} \cos \theta$$  \hspace{1cm} (13)

The diffuse and the ground-reflected components of radiation are computed as:

$$I_d = I_{DN} C \left( \frac{1 + \cos \beta}{2} \right),$$  \hspace{1cm} (14)

$$I_r = \rho_g \left( C + \sin \alpha \right) \left( \frac{1 + \cos \beta}{2} \right).$$  \hspace{1cm} (15)
Where $\rho_g$ is the ground reflectivity, which equals (0.2) for ordinary ground or vegetation, (0.8) for snow cover, and (0.15) for gravel surface [21]. For the present work the value was taken at (0.2).

The total incident radiation on a surface is then:

$$I_T = I_b + I_d + I_r$$  \hspace{1cm} (16)

The energy per unit area ($q_u$) of the collector is given as [22]:

$$q_u = (\alpha \tau)I_T - U_L(T_c - T_a)$$  \hspace{1cm} (17)

The overall heat loss coefficient ($U_L$) calculated as [23]:

$$U_L = \left[ \frac{A_r}{A_g(h_{c,g-a}+h_{r,g-a})} + \frac{1}{h_{r,r-g}} \right]^{-1}$$  \hspace{1cm} (18)

Where:

- $A_r$ is the area of the receiver
- $A_g$ is the area of the glass cover.

$h_{c,g-a}$ presented convection heat transfer coefficient between the glass and the ambient air due to wind [23].

$$h_{c,g-a} = h_w = \frac{Nu_a k_a}{\rho_g}$$  \hspace{1cm} (19)

The thermal efficiency of solar dryer is defined as the ratio of useful energy $Q_u$ delivered per unit area ($A_a$), to the incident solar radiation ($I$) on the aperture area ($A_a$). The thermal efficiency is given as [22]:

$$\eta_c = \frac{q_u}{I_T}$$  \hspace{1cm} (20)

Where $q_u$ and $I_T$ are presented in the equations [17] and [18].

4. **Solar Dryer Working Principle**

This dryer is insulated and consists of a solar collector with dimensions of (1000 mm as width by 1000 mm depth and by 1000 mm highest) which includes dryer chamber and the heat storage container inside it. After directing the equipment towards the sun ray, the plants was located in the dryer chamber and the door was completely closed. It was noticed that after the sun ray reached the glass cover of the drying chamber, it had been penetrated to the black roof of the drying chamber; it was heated due to sun ray absorption and it will result in heat emission, where the glass prevented the leaking of rays to the outer environment. The heat was transferred via the surface to the inside of the drying chamber by connection and ray, which resulted in the vaporization of the contained moisture. The Eruca Sativa was dried by locating it in plates horizontally and it was directly exposed to the sun ray until it reach drying phase.

5. **Temperature and Moisture Measurement**

5.1 **Temperature measurements**

Three thermocouples types (K) with 0.5 mm diameter are employed in existing work. These thermocouples are connected to Digital data logger type of 12 channels temperature recorder with SD card data logger model BTM-4208SD manufactured by Lutron company of Taiwan to read and record the magnitude of temperature with an accuracy of (±4%) as shown in figure 4. The temperature measurements range of (-50 to 999.9 °C) and resolution of 0.1 °C.
Figure 4. Digital data logger type (12 channels temperature recorder Lutron, model BTM-4208SD.

5.2 Moisture Measurement
The moisture percentage was measured according to AOAC,1984 by drying 100 gm of Eruca Sativa using electric drying oven on 105 °C until the weight stabilization.

5.3 Measuring drying required time
The practical drying time was recorded starting from locating the sample in the solar dryer and natural drying until the weight level stabilization depending on the day hours and natural solar drying.

5.4 Drying average calculation
The drying average was calculated by dividing the delate in dry moisture content on the delta of drying period [23].

\[ R_D = \frac{\Delta M}{\Delta t} \]  

R_D : Drying rate (kg H2O / hour)  
\( \Delta M \) : Change in moisture content (g H2O)  
\( \Delta t \) : Change in drying time (hour).

6. Phase Change Materials
There is one type of PCM used in this work, the type is black Iraqi origin pure Paraffin with amount of 3 kg. The physical specifications of PCM are exposed in Table 1.

| Paraffin (C_{21} H_{44}) | Sold                  |
|--------------------------|-----------------------|
| Density                  | 912 kg/m³              |
| Melting Temperature      | 44.0 °C ± 0.5          |
| Heat Capacities          | 2.4 kJ/kg·K ± 3 %      |
| Thermal Conductivities   | 0.21 W/m·K             |
| Heat of fusion           | 189 kJ/kg              |

7. Error analysis
In the present work, Kline and McClintock [30] procedure is used to evaluate the percentage error of the experimental work. The root mean square error in a measured quantity is calculated by the following formula:

\[ \delta R = \sqrt{\sum_{m=1}^{n} (\frac{\delta R}{\delta X_m})^2 \delta X_m^2} \]  

where:
R is the calculated quantity and X is the measured variable.
\( \delta R \) is the error of the calculated quantity.
δX is the error of the measured variable

8. Results and Discussions

Table 2 shows a sample of ambient conditions on the several test days. Figures 5 to 7 show the intensity of solar radiation, ambient temperature, and wind speed for nominated clear days. The comparison between the measuring intensity of solar radiation and theoretical incident solar radiation is shown in figures 8. 9 indicated the influence of solar intensity on useful energy and system efficiency; it can show that the increasing of solar intensity lead to improve the useful energy and system efficiency due to energy gain via solar system, also the maximum thermal efficiency of the collector is found to be 35%.

Table 2. Claimed condition for many days of test.

| Time (hr) | I (W/m²) | T_a (ºC) | Wind speed (m/s) | I (W/m²) | T_a (ºC) | Wind speed (m/s) | I (W/m²) | T_a (ºC) | Wind speed (m/s) |
|-----------|----------|----------|------------------|----------|----------|------------------|----------|----------|------------------|
| 8         | 234      | 5        | 0.1              | 332      | 7        | 2.5              | 283      | 12       | 1.3              |
| 8.5       | 300      | 6        | 0.2              | 434      | 7.9      | 0.5              | 333      | 14       | 0.9              |
| 9         | 355      | 7        | 0.3              | 593      | 15.5     | 1.6              | 383      | 16       | 1.7              |
| 9.5       | 411      | 9        | 0.3              | 654      | 16.8     | 0.6              | 438      | 18.5     | 2.6              |
| 10        | 468      | 9        | 0.3              | 700      | 17.7     | 0.4              | 535      | 20.3     | 2.2              |
| 10.5      | 532      | 10       | 0.7              | 894      | 18.8     | 0.5              | 727      | 22.4     | 2.6              |
| 11        | 600      | 12       | 1                | 943      | 20.1     | 2                | 790      | 23.4     | 2.5              |
| 11.5      | 678      | 14       | 0.7              | 978      | 21.1     | 1.8              | 891      | 24.3     | 1.8              |
| 12        | 700      | 15       | 0.4              | 948      | 21.9     | 1                | 868      | 24.5     | 2.7              |
| 12.5      | 770      | 16       | 0.5              | 900      | 22.3     | 2.8              | 864      | 25       | 2.1              |
| 13        | 763      | 17       | 1.3              | 891      | 22       | 0.2              | 845      | 24.9     | 1.5              |
| 13.5      | 719      | 18       | 1.5              | 826      | 21.7     | 0.7              | 813      | 24.8     | 1.8              |
| 14        | 655      | 16       | 2.1              | 700      | 21.7     | 2.9              | 755      | 24.5     | 2.1              |
| 14.5      | 584      | 13       | 0.7              | 655      | 19.2     | 3.7              | 702      | 24.1     | 2.3              |
| 15        | 489      | 11       | 0.7              | 553      | 19.3     | 1.8              | 613      | 22.2     | 2.5              |
| 15.5      | 392      | 9        | 1.7              | 424      | 20.6     | 0.5              | 453      | 20       | 2.1              |
| 16        | 280      | 7        | 2.2              | 282      | 21.5     | 0.2              | 348      | 18       | 1.8              |

Figure 5. Incident radiation with time
Figure 6. Ambient temperature with time

Figure 7. Wind speed with time

Figure 8. Comparison of measuring and theoretical Incident radiation with time
9. Drying process

The drying operation was conducted during winter (December 2019), and all tests started at 8:00 am with the drying air presented drying chamber in the dryer. Regarding the temperature, it is observed in the solar drying that the temperature in the drying room has increased with the increase in daylight hours and reached its maximum value at two o'clock in the afternoon and then decreased after midday because there are no PCMs that maintain the heat inside the drying room. The temperature in the drying chamber was higher when supplied with PCMs than when it was not used. When using PCMs, hot air will circulate inside the dryer and contribute to raising its temperature and the plant will lose its moisture. The rate of drying curve is of great benefit in determining the time required to dry large quantities under the same drying conditions [24] [25]. It is observed from 10 that shows the relationship between the drying rate (kg of water / hour) with the drying time using natural solar drying and the solar dryer and solar dryer with PCMs, the rate of drying increased with the decrease in the number of drying hours in relation to the solar dryer with the use of PCMs, where the drying rate was (1.21 kg of water / h) while the lowest rate of drying at the solar drying was due to the increase in the drying time. In drying food, after a time period of drying process at a constant rate, it was establish that the water detachable more slowly. The comprehensive drying curve is shown in figure 8. The drying temperature was low and this accounts for the long drying time [26].

It is observed from figure 11 that shows the relationship between the drying time and the moisture ratio (%) of Eruca Sativa dried with natural solar drying and the solar dryer and solar dryer with PCMs, The moisture in Eruca Sativa plant has decreased significantly (p < 0.05) with an increase in drying time by all drying methods. This is due to the evaporation of water from the plant due to its high temperature down to 50 °C with the drying time obsolescence as a result of increased solar radiation energy with the aging of daylight hours, this led to an increase in the energy absorbed and extracted energy that positively affects the increase in the thermal energy inside the solar dryer. In addition, the process of deflating the pressure inside the solar dryer or accelerating the evaporation process because the water evaporates at low temperatures. This is consistent with [25, 26], it showed that moisture decreases with increasing drying time by solar energy and natural solar drying. The
moisture indicated lowest rating for using the solar dryer with PCMs by 17.3% with that of the solar dryer without PCMs and 40% with natural solar drying.

![Figure 10. Variation of drying rate with the drying time of *Eruca Sativa* dryer at various drying levels](image)

The results showed in figure 12 that the temperature in the drying chamber with PCMs increased with the increase in daylight hours and reached its maximum value of 45 and was 40 in the drying chamber without PCMs while the maximum temperature in the outside was 20 degrees, this is due to the increase in the energy of solar radiation, and then its decrease after midday. The temperature in the drying chamber was higher when supplied with PCMs than not, when using PCMs, the hot air and sunlight contribute to raising the temperature of the air, the plant loses its moisture, and by rotating it inside the drying room again, its moisture decreases and the cycle is almost closed [27].

Essential oil analysis results are given in Table 3. Symbols a, b, c, d and e indices given in the table are grouped according to the Duncan test performed in the SPSS program used for the purpose.

**Table 3. Essential oil rates**

| Essential oil analysis       | Volatile Oil for Dried and Fresh Samples Values (ml / 100g dry matter) |
|-----------------------------|-------------------------------------------------------------------------|
| Fresh plant                 | 0.74±0.07a                                                              |
| Natural solar drying        | 0.41±0.001c                                                             |
| Solar dryer                 | 0.70±0.001b                                                             |
| Drying with PCMs            | 0.69±0.06ab                                                             |
In previous studies, significant volatile oil losses were found in *Eruca Sativa* samples dried at room temperature, while in the current study, essential oil ratio value was found very close to fresh sample, especially in drying solar dryer at 45 °C. Therefore, the solar dryer –drying method are recommended for fast drying and similar components compared to the fresh plant material [28]. The drying rate in the drying with PCMs and a decrease in the proportion of essential oil of 0.69 ml / 100 g of dry matter are observed. This difference corresponded to a decrease of 17.6%, but it was insignificant due to uncontrollable errors. Drying in the sun has caused a great loss of essential oil, in the drying under the sun; it may be possible that the sun rays coming directly on the plant will break down into the essential oils stored on the leaf surface by photocatalytic effect [29].

10. Conclusions
In this work a solar dryer including with PCMs thermal storage system was urbanized and its performance estimated. The solar dryer was tested with and without of using PCMs and compared with sun drying. The maximum temperature in the drying chamber with PCMs was reached 45 °C and while it was 40 °C without PCMs and it was 20 °C for sun drying. It found reducing of drying time with using of PCMs comparing with using others methods as: 5.3 hr, 7.3 hr, and 24 hr for solar dryer with PCMs, without PCMs, and sun drying respectively.

11. Data Statement
The data that supports this study is available from the corresponding author upon reasonable request.

**NOMENCLATURE**

- **A**: Area, apparent m²
- **Ag**: Area of glass cover m²
- **Ar**: Area of the receiver m²
- **Cp**: Specific heat J/kg.k
- **Dg**: Cover effective length. m
- **d**: Diameter of the tube m
- **fc**: Friction Factor
- **h_(c.g-a)**: convection heat transfer coefficient between glass and ambient air W/m² K
- **h_(r.g-a)**: Radiation heat transfer coefficient between glass cover and the ambient W/m² K
- **h_(r,r-g)**: Radiation heat transfer coefficient between receiver tube and glass cover. W/m² K
- **I**: Incident solar radiation W/m²
- **K**: Thermal conductivity W/m K
Nu Nusselt number
Q Heat transfer rate W
Qu Useful energy gained from collector W
T Temperature °C
V Velocim/s

Subscripts
a Air, ambient, aperture
g glass
i Inlet
o Outlet
r receiver
w wind

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