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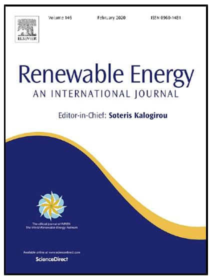

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Impact of solar drying process on drying kinetics, and on bioactive profile of Moroccan sweet cherry

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Abstract

Indirect solar convective drying is less energy intensive, and affordable. Thus, the study was carried out to investigate the efficiency of indirect solar convective dryer system by determination of the different characteristics of the dryer and to evaluate the effects of both drying and storage period on fruit quality. Sweet cherry of "*Burlat"* cultivar were dried at 60, 70 and 80 °C, then stored for one year and analyzed for total phenolics, antioxidant activity, total flavonoids and total anthocyanins. Experimental results showed that the effective moisture diffusivity determined by Fick's second law varied from 2.85×10^{-9} to 6.51×10^{-9} m^2/s, and the activation energy value was 2388.67 kJ/kg. Total energy consumption and the specific electrical energy of dried cherry showed a downward trend with increasing temperature. The Midilli–Kucuk model was the best fitted model for drying cherry. In addition, evaluation of 12-months stored dried cherry showed highest retention of total phenolics and antioxidant activity, while total flavonoids and anthocyanins decreased by 24 and 33 %, respectively.

Keywords: Solar drying; Effective moisture diffusivity; Activation energy; Storage; Bioactive compounds.

1. Introduction

Sweet cherries (*Prunus avium* L.), are seasonal and very popular fruits widely consumed worldwide, in particular in fresh form. The fruit is well known for its high antioxidant levels and for the richness and diversity of its anthocyanins [1,2,3]. They are highly perishable with a short shelf-life of 7 to 10 days under conventional cold storage conditions [4]. Generally the fruits are sold quickly at low prices to expedite movement and reduce post harvest loses once the fruit quality drops further below market standards, such practice is not economically beneficial to farmers. A potential solution to this issue is the adoption of processing technologies that enable cherries to be available all year around. Technologies for processing pulp into juice and nectars do exist, as well as making jams and jellies. However, they are embraced by few cooperatives, require heavy investment, and are less preferred by consumer compared to fresh or dried fruits.

Postharvest losses of sweet cherry fruits in Morocco are alarming. Practically, in addition to the fruit short life spam, the high cost of adopting proper postharvest handling techniques such as rapid cooling, proper refrigeration and packaging, which impact the shelf-life, freshness of flavor, appearance, nutritional quality, and consumer acceptability of the fruit are major challenges to small farmers. However, several authors showed that solar drying of sweet cherry fruits is a cheap and practical alternative to prevent post harvest losses and extend shelf life while maintaining the fruit quality [5,6]. In the Maghreb countries, particularly in Morocco, solar energy is clean and less expensive source . Morocco experiences 3000 hours per year of annual sunshine equivalent to 5.3 kWh/m²/day [7]. This makes solar thermal application a promising and low cost alternative to be adopted.

Local and small farmers practice sun drying as conventional drying system to preserve fruits because of abundant solar irradiation during the year, such is a free and renewable source of energy. However, there are various known limitations of sun drying such as damage to the fruits by animals, birds and rodents, degradation in fruit quality due to direct exposure to solar radiation, dew or rain, contamination by dirt, dust or debris. Also this system is labor intensive and time consuming, as fruits must be covered at night and during bad weather, and protected from attacks by domestic animals. Also, insect infestation and growth of microorganisms due to non-uniform drying do occur on regular basis.

Therefore, substantial efforts are needed to implement efficient, low-cost, indigenous technology that reduces postharvest loss of sweet cherry fruits. Thus, the introduction of low cost and locally manufactured solar dryer provides a promising alternative to prevent post-harvest losses, produce high quality marketable products, and to improve the economic situation of the farmers.. The use of solar dryer helps to control temperature, reduce drying time and preserve the quality of the dried product in comparison to the sun drying. In recent years, several attempts have been made to develop and optimize solar dryers mainly for preserving foods. Solar drying systems must be properly designed in order to meet particular drying requirements of specific crops and to give satisfactory performance with respect to energy requirements [8]. Drying characteristics of the particular materials being dried and simulation models are necessary to understand the fundamental transport mechanism and a prerequisite to successfully simulate or scale up the whole process for optimization or control of the operating conditions. Several researchers have developed simulation models for natural and forced convection solar drying systems [10,11,12,13].

High drying temperatures may impact fruit quality parameters such as coloring, vitamins, texture and sensory properties [13]. They may have negative effect on the bioactive compounds [14]. Degradation of bioactive compounds in fruits and vegetables depends on the type of food, processing time, processing temperature and storage conditions [15]. The final quality of dried fruits should be safe for consumers and possess high quality. Thus, the evaluation of fruit quality after drying is important.

Although, there is well established literature on drying behavior of various vegetables and fruits such as grape [16], potatoes [17], onion [19,20], green pepper, green bean and squash [20] and rice [21]. There is no detailed study on the solar drying kinetics of sweet cherry.

In this context and in order to valorize Moroccan sweet cherry, this study investigates the possibility of adopting forced convection solar drying to reduce post-harvest losses of sweet cherry by converting these perishable sweet cherries into more stabilized and of good quality dried fruits that can be stored under a minimal controlled environment for longer period, therefore helping local farmers economically.

The overall objectives of this study are:

- Estimate the effective moisture diffusivity at different temperatures and the corresponding energy of activation for sweet cherry;
- Calculate the total energy consumption and the energy efficiency of the solar drying process;
- Find the precisely thin-layer drying model for describing the solar drying system;
- Investigate the effects of solar convective drying at 60, 70 and 80 °C and storage time (12 months) on the bioactive compounds of "*Burlat*" cherry cultivar.

2. Materials and methods

2.1. Drying of cherry samples

Mature sweet cherry fruits of "*Burlat*" cultivar were carefully harvested during July of 2017.This cultivar is the most cultivated in Morocco. The fresh cherries were pitted and cut manually into two halves with a average diameter of 19.69 ± 0.85 mm and a thickness of 7.8 ± 0.93 mm. The initial moisture content of fruit samples was 82.12 ± 1.44 % on wet basis, as determined by vacuum drying at 105°C for 24 h. Three kg of cherries were placed on the drying trays and dried at constant temperatures of 60, 70 and 80 °C during 8, 6 and 4 h, respectively with a volume flow rate of 0,1845 m^3/s. Drying time of the same cultivar under the same conditions was determined previously by Ouaabou et al,. [5].Air temperature and relative humidity values were recorded using a thermo-hygrometer (HANNA HI9565). The ambient air temperature varied between 21 and 32 °C and the relatively air humidity ranged between 17–27 % during the drying period. Dried cherry slices with final moisture content of 23 ± 3 % were vacuum packaged using polyethylene bags (PE). Packaged samples (200g per each treatment) were stored at ambient temperature and were sampled for analysis after 3, 6, 9 and 12 months of storage.

2.2. Experimental system

An indirect solar dryer system with forced convection was used to study the kinetics of drying of cherry fruits (Fig.1). This is a system without storage and with partial or total recycling of air [23, 24,25]. The basic components of the experimental apparatus are solar air collector coupled with an auxiliary electric heater, drying cabinet consisting of ten trays and a ventilator. Specifications of various components of the solar dryer are presented below:

- The solar air collector is oriented south under the collector latitude angle of 31° with dimensions of 1 m by 2.5 m. This orientation maximizes the incident solar radiation that falls on the solar collector. A corrugated galvanised iron sheet painted black is used as an absorber plate for absorbing the incident solar radiation. A glass and plastic sheet was used as a transparent cover for the air heater to prevent the top heat losses;

- The centrifugal fan (0.083 m^3s^{-1}; 80 mm EC; 220 V, 0.1 kW), mounted towards the north side of the drying cabinet, allows a theoretical velocity of 1.7 ms^{-1}, with a regulator which allows to vary the air flow rate from 0.028 to 0.083 m^3s^{-1};
- The thermo-regulator that has range between 0–100 °C with a precision of 0.1 °C, connected to a PT100 platinum probe acting on the electric auxiliary heater used to set the desired temperature at the inlet of the drying chamber;
- The drying cabinet was constructed with insulted walls formed as a rectangular tunnel in 42×46×100 m^3 dimensions and has 10 trays. The hot air enters the drying cabinet below the trays and is distributed uniformly into the cabinet;
- The ventilator with a power of 0.1 kW to supply fresh air;
- The auxiliary heater connected to the inlet of control box and presented a power of 4 kW.

Fig. 1.Schematic of the experimental setup.

(1) Solar collector, (2) ventilator, (3) fan, (4) air flow direction, (5) control box, (6) auxiliary heating , (7) floors, (8) drying cabinet, (9) air valve, (10) air inlet, (11) air outlet, (12) humidity sensor, (13) thermocouple, (14) sample holder.

2.3. Theoretical principal

2.3.1. Determination of effective moisture diffusivity

Fruits and vegetables products have high moisture content; generally no constant rate period is seen in the drying processes. The dominant physical mechanism governing moisture movement in the material during the falling rate period is effective moisture diffusion phenomenon. During drying, it can be assumed that diffusivity, explained with Fick's diffusion equation is the only physical mechanism to transfer the water to surface [25]. Effective moisture diffusivity which is affected by composition, moisture content, temperature and porosity of the material, is used because of the limited information on the mechanism of moisture movement during the drying process and complexity of the process [26]. The effective moisture diffusivity D_{eff} at any given moisture content can be determined using 'method of slopes' technique [28,29,30]. Fick's second law of diffusion shown as Eq. (1):

$$\frac{\partial MR}{\partial t} = Deff\nabla^2 MR \quad (1)$$

The analytical solution of (Eq. 1) is given below for infinite slab geometry with the subsequent assumptions: the particle is homogenous and isotropic, temperature distribution and initially moisture distribution are uniform, the shrinkage is neglected [30].

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

For sufficiently long drying periods (n=1) the above equation takes the following form [31,32]:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \tag{3}$$

Equation 3 indicates that the variation of ln(MR) values versus t is linear and the effective moisture diffusivity is determined from the slope of Eq. (3).

$$D_{eff} = -\frac{B4L^2}{\pi^2} \tag{4}$$

2.3.2. Computation of activation energy

The temperature, one of the strongest factors, affects D_{eff}, this effect can generally be described by an Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{5}$$

where D_0 is Arrhenius factor in m^2/s. E_a is the activation energy in kJ/kg, R is the universal gas constant in kJ/moL.K and T is temperature in K [33].

The activation energy was calculated by plotting the $\ln(D_{eff})$ as a function of the reciprocal of the temperature $(\frac{1}{T})$.

2.3.3.Energy aspects of solar drying

The total energy consumed (kWh) of convective solar dryer was obtained using Eq. 6 [34]:

$$E_t = (A.v.\rho_a.C_a.\Delta T.D_t) + E_{mec} \tag{6}$$

Where E_t is the total energy consumption (kWh) of drying system, A is the sectional area of the tray where sample is placed (m^2), v is the air velocity (m/s), ρ_a is the air density (kg/m^2), C_a is the specific heat of air (kJ/kg °C), ΔT is the temperature difference (°C), D_t is the total drying time (h) and ρ_a is the microwave power (kW).

Specific heat capacity of the inlet air [35] and microwave power [36] were calculated using Eqs. (7) and (8):

$$\rho_a = \frac{101.325}{0.287 \times T} \quad (7)$$

$$C_a = 1.04841 - \frac{3.83719 \times T}{10^4} + \frac{9.45378 \times T^2}{10^7} - \frac{5.49031 \times T^3}{10^{10}} + \frac{7.92981 \times T^4}{10^{14}} \quad (8)$$

E_{mec} is the mechanical energy consumed during each experiment and can be defined as the electrical energy consumed by the fan and the auxiliary heater, it was measured by an electric energy meter with an accuracy of 0.01 kWh.

The specific thermal energy (kWh/kg) needed to remove 1 kg water from the sample was calculated using Eq. 9 [37]:

$$SEC = \frac{E_t}{m_w} \quad (9)$$

Where: m_w is the mass of removed water (kg) and was calculated using Eq. 10 [38]:

$$m_w = \frac{W_0(Y_0 - Y_f)}{100 - Y_f} \quad (10)$$

Where: W_0 is initial weight of sample (kg) , Y_0 is initial moisture content (% d.b) at time (t=0) and Y_f is final moisture content (% d.b).

2.3.4. Mathematical models

The most popular thin layer drying models cited in literature and used at industrial scale were tested to describe the drying curves of cherry slices. The moisture ratio ($MR=((M-M_e)/(M_0-M_e))$ where M, M_0 , M_e are the moisture content at any time, the initial moisture content and the equilibrium moisture content of the sample, respectively, was calculated from the moisture data and then the drying kinetics of the cherry was tested by curve fit tool. Table 1 represents the model equations used. CurveExpert 1.4 software was used to fit the drying curves and to calculate the goodness of each approach fit. Three parameters were determined: Adjusted R-square R^2, root mean square error (RMSE) and reduced chi-square (χ^2).

Table 1. Mathematical models used.

Models	Equations	References
Newton	MR=exp(-kt)	[39]
Page	MR=exp(-kt^n)	[40]
Logarithmic	MR=aexp(-kt)+c	[41]
Wang and Singh	MR=1+at+bt^2	[42]
Diffusion approach	MR=aexp(-kt)+(1-a)exp(-kbt)	[43]
Midilli-Kucuk	MR=aexp(-kt^n)+bt	[39]
Handerson & Pabis	MR=aexp(-kt)	[44]
Modified Handerson & Pabis	MR=aexp(-kt)+bexp(-gt)+cexp(-ht)	[45]
Two term	MR=aexp(-k_1t)+bexp(-k_2t)	[46]
Verma & al	MR=aexp(-kt)+(1-a)exp(-k_0t)	[47]

K,n,a,b,c,k_0,k_1,k_2,g,h :models constant

2.4. Quality analysis

Bioactive compounds of fresh, dried and dried stored cherries after 3, 6, 9 and 12 months of storage were evaluated. All measurements were conducted in triplicate.

2.4.1. Extraction procedure

Sweet cherry fruits (2 g) were powdered using a mixer grinder and introduced into a flask then 20 mL of methanol was added. After 30 minutes of stirring, the mixture was centrifuged and filtered through a whatman filter paper no.1 (What man International. Ltd.). The extracts of dried fruits were prepared directly before analysis.

2.4.2. Determination of total phenolics content (TPC)

Phenolics content of cherry extracts were determined according to Singleton and Slinkard method [48]. A volume of 0.25 mL of the sample extract was added into a tube test, along with 0.25 mL of Folin-Ciocalteu reagent (2 N) and 2 mL of distilled water and stirred by vortex for 3 min, then 0.25 mL of sodium carbonate (20 % w/v) was added.

The extracts were mixed and allowed to stand in the dark for 30 min before measuring the absorbance at 750 nm using a UV spectrophotometric (J.P.SELECTA). The results were expressed as mg gallic acid equivalent in 100 g dry weight (mg GAE/100g dw).

2.4.3. Determination of antioxidant activity

The antioxidant activity was measured by the free radical 2,2 diphenyl-1-picrylhydrazyl (DPPH) [49]. A volume of 0.1 mL of the extract was mixed with 3.9 mL of DPPH solution (0.1 mM). The absorbance of samples was measured at 515 nm after 1 h of incubation in the dark. Methanol solvent was used as blank. The inhibition activity was calculated:

$$\% \text{ of radical scavenging activity} = ((\text{abs control-abs sample}) / (\text{abs control})) \times 100 \quad (11)$$

The results obtained were reported as DPPH% per 100 g of dry weight.

2.4.4. Determination of total flavonoids content (TFC)

The total flavonoids of cherry extracts was determined according to the colorimetric method [50]. Briefly, 1 mL of sample was mixed with 1 mL of 2 % aluminium chloride methanolic solution. The mixture was allowed to stand for 15 min, and absorbance was measured at 430 nm. Rutin was used as the standard to quantify total flavonoids. The results were expressed as mg of rutin equivalent/100 g of dry weight (mg RE/100g dw).

2.4.5. Determination of total anthocyanins content (TAC)

The total anthocyanins content (TAC) was evaluated by applying the method described by Rodriguez and Wrolstad. [51] using two buffer systems: sodium acetate buffer pH 4.5 (0.4 M) and potassium chloride buffer pH 1.0 (25 mM). The reaction was performed with 0.4 mL of extract and 3.6 mL of corresponding buffers. The absorbance of TAC was recorded at 510 and 700 nm. The water was used as a control. The Absorbance (Abs) was expressed as follows:

$$\text{Abs} = (A_{510}\,\text{nm} - A_{700}\,\text{nm})\text{pH}_{1.0} - (A_{510}\,\text{nm} - A_{700}\,\text{nm})\text{pH}_{4.5} \quad (12)$$

TAC of cherry was conducted in triplicate and presented as mg cyanidin-3-glucoside per 100 g of dry weight (mg cya-3-glu/100g dw) and was determinate using equation below:

$$TAC= [Abs\times MW\times DF\times 100]\times 1/MA \quad (13)$$

With: Abs: absorbance; MW: molecular weight (449.2 g/moL); DF: dilution factor (10); MA: molar absorptivity of cyanidin-3-glucoside (26.900).

2.4.5. Statistics

Statistical analyses were performed using one-factor analysis of variance. Differences between sample means were analyzed by Tukey test. Differences at $p < 0.05$ were considered significant. The experimental data was analyzed by using "XLSTAT Addinsoft TM" software (XLSTAT, 2016).

3. Results and discussion

3.1. Calculation of effective moisture diffusivity and activation energy

The effective moisture diffusivity is a useful tool in explaining the drying kinetics, and activation energy is important in describing the sensibility of D_{eff} with temperature. The moisture diffusivity depends mainly on the product's temperature, the moisture content, and the structure. The D_{eff}, is generally determined graphically by representing the logarithm of the reduced moisture content X* as a function of the drying time. The numerical values of diffusion coefficients computed for all the drying air temperatures are given in Table 2. The Fig. 2 shows the variation of effective diffusivity coefficient as function of drying time at different drying conditions. The values of D_{eff} for dried cherry were 2.85×10^{-9}, 3.18×10^{-9} and 6.51×10^{-9} m^2/s at 60, 70 and 80 °C, respectively. The diffusion coefficients for the drying of sweet cherry increased with the temperature. Diffusion is a characteristic behavior of slow-drying materials where drying or water vapor transfer rates inside the material are controlled by diffusion towards the outer surface. Then, the water vapor concentration on the outer surface of the material becomes at equilibrium or very close to equilibrium values. The D_{eff} increases as a result of increasing equilibrium concentration of the water vapor on the material surface at higher temperatures. This increases resistance to transport by preventing water vapor concentration to reach equilibrium.

Typical moisture diffusivity for fruits and vegetables is in the range of 10^{-11}–10^{-9} m^2/s. Numerous studies carried out on fruits and vegetables under similar temperature conditions showed D_{eff} values to lie between 2.4 and 12.1×10–^{9} m^2/s for strawberry leathers in the temperature range of 50–80 °C [53], (6.76–12.6)×10^{-10} m^2/s for apricot at 55 °C [54], (3.32–90)×10^{-10} m^2/s for blueberries at 50–70 °C [55], (2.4–6.22)×10^{-10} m^2/s for grapes at 50–70°C [56].

Table 2. Effective moisture diffusivity and activation energy values of the sweet cherry.

Temperature of drying (°C)	D_{eff} (m^2/s)	r	E_a (kJ/kg)	r
60	2.85×10^{-9}	0.9895	2388.67	0.9992
70	3.18×10^{-9}	0.9908		
80	6.51×10^{-9}	0.9823		

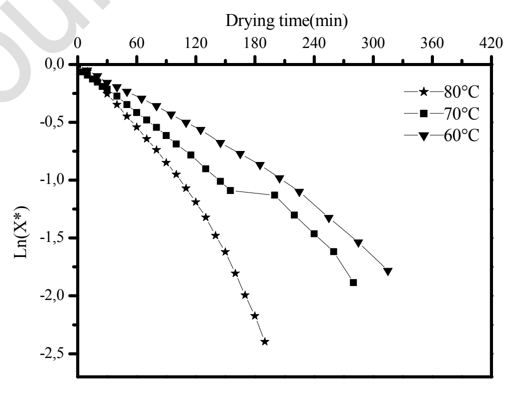

Fig. 2. Simultaneous effects of temperature and air flow on the effective diffusion coefficient.

The activation energy was calculated by plotting ln(D_{eff}) versus the reciprocal of the temperature (1/T) (Fig.3).

The fruit higher activation energy value is most likely related to its tissue and to the fruit higher moisture content (82.12 % (w.b)), the activation energy value recorded was 2388.67 kJ/kg, which is higher than those reported by [6].

$$D_{eff} = 4.9962 \times 10^{-3} \exp\left(-\frac{287.3070}{T}\right) \quad (14)$$

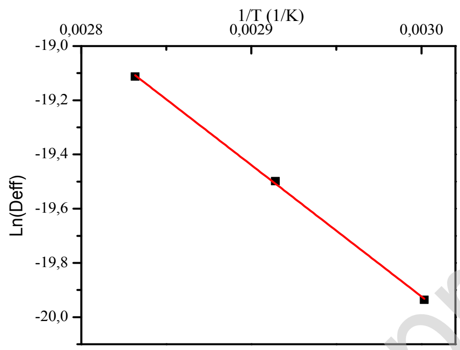

Fig. 3. Arrhenius-type relationship between effective diffusivity and reciprocal absolute temperature.

3.2. Energy aspects of drying system

The changes in total energy consumption and the electrical energy consumption of dried sweet cherry fruits at different drying temperatures are presented in Fig. 4. It is observed that total energy consumption and electrical energy consumption decreased as air-drying temperature increased. By increasing the temperature, drying time has been reduced. Therefore, the energy consumption of the drying system also was reduced. The decrease in energy consumption at higher temperatures is reported for agri-foods products [57, 58,59]. The total energy consumption was 27.82, 19.63 and 11.49 kWh at 60, 70 and 80°C, respectively. The increase in drying temperature from 60 to 80 °C decreased the total energy consumption by 58.70 %. The electrical energy consumption of dried sweet cherry at different aero-thermal conditions can be defined as the amount of the energy consumption of the fan and the auxiliary heater. It was measured by an electric energy meter with an accuracy of 0.01 kWh. The electrical energy values were low because drying processes was fully conducted in summer. As shown in Fig. 4, the electrical energy consumption decreased simultaneously with the increase in air drying temperature. High drying temperatures resulted in reduction of both drying time and the electrical energy. The electrical energy consumption recorded was 1.94, 2.31 and 5.13 kWh at 60, 70 and 80 °C, respectively. At high drying temperatures only the pump was running while the auxiliary heater rarely intervened. During all the experiments, the intervention of the electrical energy did not exceed 5%.This corroborates that the convective solar drying is low cost to free, renewable and non-polluting source of energy. Solar dryer is a suitable alternative to reduce crop losses and to improve the quality of the dried products compared to traditional drying methods. Also, solar drying may become a more convenient alternative especially for small farmers in rural areas where electricity is scarce and supplied irregularly.

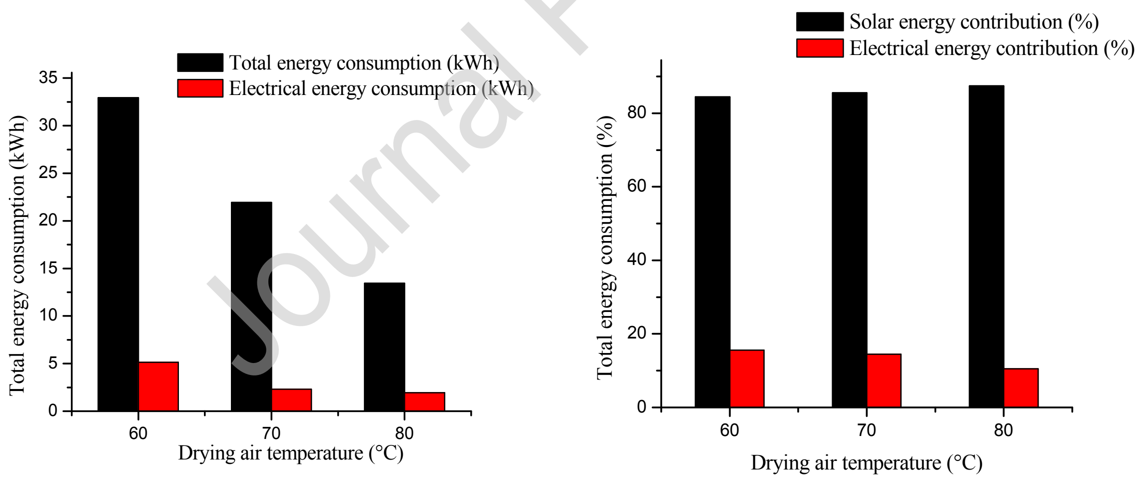

Fig. 4. Total energy consumption at different drying air temperatures.

Specific energy consumption (SEC) values during all drying experiments of sweet cherry are presented in Fig. 5. It is defined as the energy required for drying 1 kg of sweet cherry. The SEC decreased when the drying air temperature increased. The increase of temperature from 60 to 80 °C resulted in a decrease of the specific energy requirement by 71.04 %. Minimum and maximum values of specific energy were 5.91 (MWh/kg) and 20.41 (MWh/kg) observed at 80 °C and 60 °C, respectively. The specific electrical energy was not significant compared to the total energy consumption at each drying temperature.

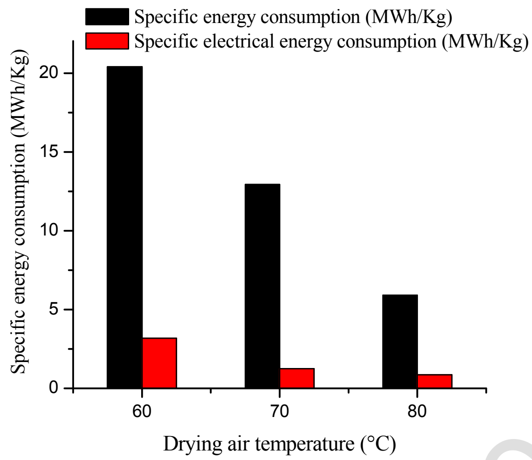

Fig. 5. Specific energy consumption at different drying air temperatures.

3.3. Mathematical modeling of drying curves

To describe solar drying kinetics of sweet cherries, ten thin-layer drying models were evaluated and compared using statistical measures. The quality of the fitted models was assessed with the following statistical parameters: coefficient of determination (R^2), low chi-square (χ^2) and root mean square (RMSE). The model with the higher value for R^2 and low χ^2 and RMSE was selected to describe the drying curves. The statistical measures are presented in Table 3. All tested models had high R^2, χ^2 and RMSE values ranging between 0.9931 to 0.9991, 0.0001 to 0.0033 and 1.5 10^{-5} to 0.0132, respectively. Therefore among those models examined, Midilli-kucuk model was the best one to describe drying experimental data of the sweet cherry. The established model was validated by comparing the experimental and the predicted moisture ratios by Midilli-kucuk model at different air drying temperatures. The performance of the model at different drying temperatures was illustrated in Fig. 6 and Fig. 7. The experimental data are generally banded around the straight line representing computational data, which indicates the suitability of the Midilli-kucuk model in describing drying behaviour of sweet cherry.

Table 3. List of statistical results of mathematical modeling used for studying the solar drying process of sweet cherry.

Temperature (°C)	Parameters				Statistical parameters		
					R^2	χ^2	RMSE
Newton	k						
60	0.01				0.9934	0.0072	0.0325
70	0.01				0.9958	0.0008	0.0048
80	-0.01				0.9900	0.0019	0.0023
Average					0.9931	0.0033	0.0132
Page	k	n					
60	$2.21\ 10^{-3}$	1.16			0.9969	0.0006	0.0066
70	$7.87\ 10^{-3}$	0.97			0.9959	0.0008	0.0037
80	$3.12\ 10^{-3}$	1.25			0.9980	0.0004	0.0047
Average					0.9969	0.0006	0.0050
Wang and Singh	a	b					
60	$-3.89\ 10^{-3}$	$3.85\ 10^{-6}$			0.9989	0.0003	0.0018
70	$-5.53\ 10^{-3}$	$8.60\ 10^{-6}$			0.9895	0.0065	0.0010
80	$-7.61\ 10^{-3}$	$1.47\ 10^{-6}$			0.9996	0.0001	0.0007
Average					0.9960	0.0023	$1.17\ 10^{-3}$
Logarithmic	a	k	c				
60	1.27	$3.23\ 10^{-3}$	-0.29		0.9998	0.0002	$1.30\ 10^{-5}$
70	1.04	$5.72\ 10^{-3}$	-0.07		0.9967	0.0006	$2.80\ 10^{-5}$
80	1.23	$7.24\ 10^{-3}$	-0.22		0.9998	0.0004	$4.00\ 10^{-6}$
Average					0.9988	0.0004	$1.50\ 10^{-5}$
Diffusion approximation	a	k	b				
60	4.90	$7.88\ 10^{-3}$	1.14		0.9975	0.0005	0.0056
70	0.96	$6.68\ 10^{-3}$	1.00		0.9957	0.0019	0.0132
80	10.30	$1.75\ 10^{-2}$	1.07		0.9980	0.0004	0.0043
Average					0.9971	0.0009	0.0077
Midilli-Kucuk	a	k	n	b			
60	0.99	$4.39\ 10^{-3}$	0.97	$-3.9\ 10^{-4}$	0.9998	0.0001	$2.17\ 10^{-5}$
70	1.01	$1.50\ 10^{-2}$	0.79	$-4.8\ 10^{-4}$	0.9978	0.0004	$6.80\ 10^{-5}$
80	1.00	$5.94\ 10^{-3}$	1.08	$-4.3\ 10^{-4}$	0.9998	0.0001	$4.00\ 10^{-5}$
Average					0.9991	0.0002	$4.32\ 10^{-5}$
Handerson & Pabis	a	k					
60	1.02	$5.21\ 10^{-3}$			0.9940	0.0011	0.0054

70	0.98	$6.58\ 10^{-3}$					0.9962	0.0007	0.0015
80	1.07	0.01					0.9928	0.0014	0.0082
Average							0.9943	0.0011	0.0050
Modified Handerson & Pabis	a	k	b	g	c	h			
60	0.45	$5.22\ 10^{-3}$	0.13	$5.18\ 10^{-3}$	0.45	$5.22\ 10^{-3}$	0.9940	0.0014	0.0054
70	0.43	$6.58\ 10^{-3}$	0.12	$6.62\ 10^{-3}$	0.43	$6.58\ 10^{-3}$	0.9963	0.0009	0.0015
80	0.50	$1.10\ 10^{-2}$	0.07	$1.11\ 10^{-2}$	0.50	$1.10\ 10^{-2}$	0.9928	0.0017	0.0082
Average							0.9944	0.0013	0.0050
Two term	a	k_0	b	k_1					
60	0.51	$5.22\ 10^{-3}$	$5.12\ 10^{-1}$	$5.22\ 10^{-3}$			0.9940	0.0013	0.0054
70	0.49	$6.64\ 10^{-3}$	$4.91\ 10^{-1}$	$6.54\ 10^{-3}$			0.9962	0.0007	0.0014
80	0.53	$1.10\ 10^{-4}$	$5.33\ 10^{-1}$	$1.10\ 10^{-2}$			0.9928	0.0015	0.0082
Average							0.9943	0.0012	0.0050
Verma	a	k	k_0						
60	-12.76	$8.07\ 10^{-3}$	$7.61\ 10^{-3}$				0.9952	0.0005	0.0055
70	-1.48	$6.55\ 10^{-3}$	$6.64\ 10^{-3}$				0.9958	0.0025	0.0280
80	-3.53	$3.71\ 10^{-3}$	$4.73\ 10^{-3}$				0.9998	0.0001	0.0013
Average							0.9969	0.0010	0.0116

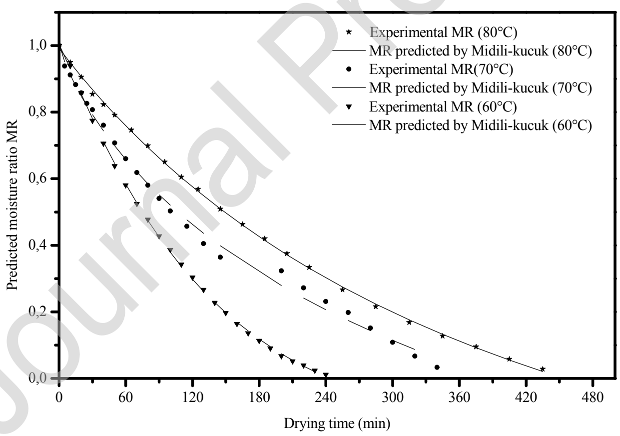

Fig. 6. Experimental data of moisture ratio versus drying time fitted with Midilli-Kucuk model.

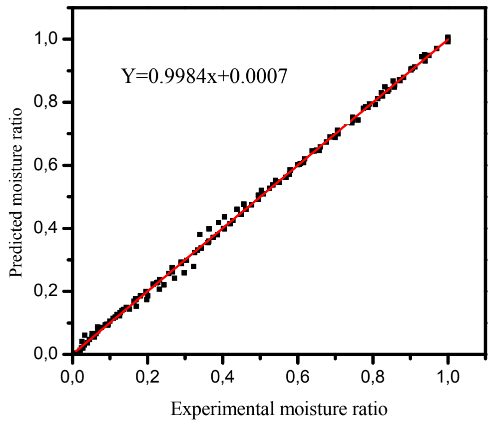

Fig. 7. Comparison of predicted moisture ratio from Midilli-Kucuk model and observed moisture ratio of cherry at different temperatures of drying ($R^2 = 0.9986$).

The temperature dependency of Midilli Kucuk parameters for the convective solar drying of sweet cherry was determined for a temperature Ɵ in °C. The values of a, b, k and n can be used to estimate the moisture content of sweet cherry at any time during the drying process with a good accuracy.

$a = 0.5787+0.0116\ \Theta - 7.895\ 10^{-5}\ \Theta^2$ $k = -0.4739+0.0139\ \Theta - 9.868\ 10^{-5}\ \Theta^2$

$n = 12.0905-0.3283\ \Theta+0.0024\ \Theta^2$ $b = 0.0029-9.41\ 10^{-5}\ \Theta+6.61\ 10^{-7}\ \Theta^2$

3.4. Quality evaluation of dried cherry

The results of bioactive indices (total phenolics content (TPC), antioxidant activity (AA), total flavonoids content (TFC) and total anthocyanins content (TAC)), in fresh and dried cherry fruits at 60, 70 and 80 °C , and after 12 months of storage are summarized in Table 4, changes in bioactive compounds levels at different drying air temperatures and storage periods are shown in Fig. 8.

Table 4. Changes in the levels of bioactive compounds in sweet cherry.

		Storage period in months					
		0			12		
Item	Fresh cherry	60 °C	70 °C	80 °C	60 °C	70 °C	80 °C

TPC (mg /100g)	306.17 [a]	307.49[ab]	307.56 [ab]	307.61 [a]	306.44 [bc]	306.15 [c]	306.56 [bc]
AA (% DPPH)	18.32 [a]	37.20 [a]	37.36 [a]	37.64 [a]	27.19 [b]	28.56 [bc]	28.87 [c]
TFC (mg /100g)	395.43 [a]	292.72 [ab]	300.83 [b]	279.22 [c]	279.91 [a]	299.27 [ab]	302.80 [c]
TAC (mg /100g)	490.11 [a]	377.4 [a]	374.25 [a]	373.43 [ab]	331.03 [b]	330.73 [b]	330.11 [b]

TPC(expressed as mg of gallic acid equivalents/100 g dw);AA (expressed as % of DPPH); TFC (expressed as mg of rutin equivalents/100 g dw); TAC (expressed as mg of cyanidin-3-glucoside equivalents/100 g dw).

The same letter (a–c) indicates no significant difference at the 95% confidence level.

3.4.1. Effect of drying on total phenolics content

The changes of the total phenolics content of fresh, dried and stored cherry extracts are shown in Table 4 and Fig. 8. The TPC of fresh cherry recorded an average of 306.17 mg GAE/100 g dry solids. The TPC of dried and stored cherry varied from 307.49 to 307.61, and from 306.15 to 306. 56 mg/100 g dw, respectively. TPC was not affected by either drying or storage conditions. TPC of fresh, dried and stored cherries were nearly the same and there was no distinct differences between each other. The observed stability in total phenols in this study was not related to polyphenoloxidase (PPO) enzymatic activity. In fact, during the dehydration processes, PPO activity remains high for longer periods around a drying temperatures of 55-60 °C, whereas only a shorter exposure period is needed to inactivate the enzyme at temperatures of 75-80 °C [59,60]. Furthermore, the probable higher residual activity of PPO at the lower drying temperature went on longer, due to the higher processing time. In our case, the processing time for dried cherry was 8, 6 and 4 h at 60, 70 and 80 °C, respectively. A good preservation of sweet cherries phenolic compounds under shorter dyring condition has been found in cherry due to the shorter drying time. Currently, limited data about the variation of phenolics content of thermally processed fruits exist. Howard and Griffen. [61] reported an increase in total phenols of minimally processed carrot sticks and associated this with a wound-induced increase in phenylalanine-ammonia-lyase. Rocha and

Morais.[62] reported also a significant increase in phenolics content of processed apple after storage.

3.4.2. Effect of drying on antioxidant activity

The DPPH scavenging activity method was used in order to determine antioxidant activity of fresh and dried cherry. There was no significant effect of the drying temperature on the % of DPPH ($p < 0.05$). The DPPH scavenging activity of fresh cherry was 18.32 %. A positive effect of drying process on antioxidant activity was observed. Drying treatments resulted in higher AA, twice the initial value, for the three drying temperatures tested. Antioxidant activity of stored dried cherry ranged from 27.19 to 37.64 %. The increase of antioxidant activity observed may be explained by the shorter time of drying and formation of new compounds with antioxidant activity, such as Maillard reaction products, which continue to be formed later during storage time [63,64]. This observation is in accordance with results obtained by Piga et al.[65] in dried plums. They reported a significant increase in AA as a results of an increase of drying temperatures. Furthermore, the anthocyanins breakdown as a result of drying temperature can generate new products, which might act as antioxidants without being affected by the thermal process comparatively to fresh sweet cherry.

3.4.3. Effect of drying on total flavonoids content

The total flavonoids content of fresh cherry was 395.43 mg/100 g dry solids (Table 4). Total flavonoids content of dried and stored cherry was less compared to fresh ones. There was no significant difference between drying temperatures ($p < 0.05$) on degradation of TFC. The flavonoids decreased by 24 % after drying and decreased slowly during storage (Fig. 8). The reduction of TFC was 30 % after 12 months of storage. It is clear that flavonoids are sensitive to drying temperatures. The observed results are in agreement with other reports [67,68] who found strong reduction on color of fruits and vegetables during processing and storage. Those studies were carried out at a temperature below 100 °C and at high-moisture conditions. Julkunen-Tiito et al. [68] showed that air drying at an elevated temperature (60-90 °C) was deleterious to leaves flavonoids content in purple willow as compared with those found in the fresh leaves. They reported also, in addition to drying temperatures, that the degradation of the flavonoids was significantly accelerated by various glycosidase activities and severe pH in the samples.

3.4.4. Effect of drying on total anthocyanins content

The anthocyanins content of fresh, dried and stored cherry are summarized in Table 4. Anthocyanins content of fresh cherry was 490.11 mg /100 g of dw. TAC ranged from 373.43 to 377.4 and from 330.11 to 331.03 mg/100 g dry solids for dried and stored cherry, respectively. Degradation of anthocyanins of dried fruits varied from 24 % just after drying to 33 % after 12 months of storage, respectively. Similar observations were reported by Lohachoompol et al. [69] who found a degradation of anthocyanins of more than 49 % in dried blueberry. Del Caro et al.[70] reported a rapid degradation of anthocyanins in dried prunes under high temperature and high oxygen concentration treatments. Anthocyanin degradation is primarily caused by the presence of native enzymes which has been reported to be very active in cherry [71]. Native enzymes can accelerate anthocyanin degradation in the presence of polyphenolics, particularly chlorogenic acid, which is one of the major phenolic compounds in cherry [71,72]. These native enzymes, particularly polyphenoloxidase with glycosidase, who are present in blueberries, are the major enzymes responsible for anthocyanin degradation in this fruit [73,74]. This degradation may come to the copigmentation of anthocyanins could affect the increase in both, hypochromic effects and bathochromic shifts [75].

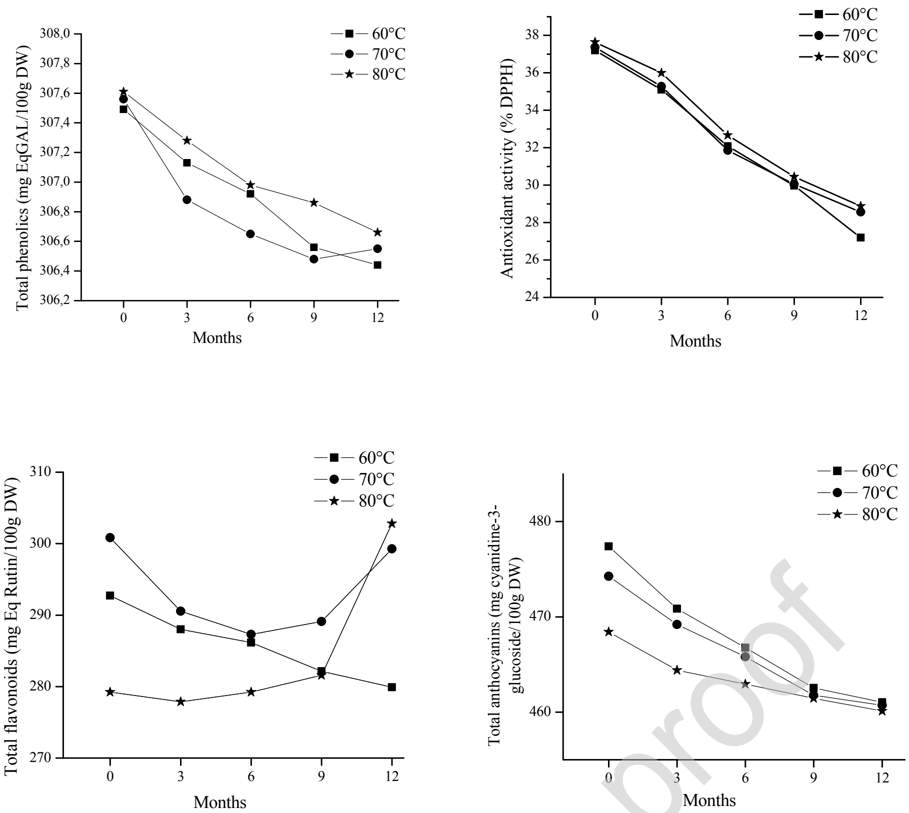

Fig. 8. Changes in the levels of bioactive compounds in dried cherry depending on the temperature of drying and period of storage.

4. Conclusion

This study investigated, for the first time, the potential use of indirect forced convection solar dryer in drying Moroccan sweet cherry as a drying technique to be adopted by small farmers in rural areas. The study examined the characteristics of proposed drying process such as effective moisture diffusivity, activation energy, total energy consumed and the effect of both the proposed drying technique and storage period on bioactive compounds of dried sweet cherry. The results obtained are as follow:

The effective moisture diffusivity varied between 2.85×10^{-9} and 6.51×10^{-9} m^2/s in the temperature range of 60–80 °C. The effective moisture diffusivity increased proportionally with the increase in air drying temperature. Additionally, the recorded activation energy for moisture diffusion was 2388.67 kJ/kg.

The electrical heating in this study did not exceed 5 %. This corroborate that solar drying process is an efficient and attractive alternative to open sun drying.

Midilli-kucuk drying model could adequately describe the one layer solar drying behavior of sweet cherry.

The indirect forced convection solar dryer had no impact on the total phenolic contents and their associated antioxidant capacity even after long storage period. However, flavonoids and anthocyanins were affected negatively by air drying temperatures. The decrease is being 24 and 33 % for flavonoids and anthocyanins, respectively.

In general, the indirect forced convection solar dryer process had no major impact on sweet cherry fruit quality. This results will help farmers to valorize their sweet cherry fruits by drying them eco-friendly, at low cost and generate more income by introducing their dried product later on the market.

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Declarations of interest

None.

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Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

- Reducing sweet cherry post harvest losses;
- Maintaining the nutritional value of sweet cherry by optimization of drying kinetics;
- Solar dryer are a practical solution under semi-arid climate.