Investigation into Solar Drying of Moroccan Strawberry Tree (Arbutus unedo L.) Fruit: Effects on Drying Kinetics and Phenolic Composition

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Abstract: Solar drying is affordable, requiring low energy and an eco-friendly method. Thus, the present paper studies the efficiency and characteristics of the indirect solar convective drying in the fruits of *Arbutus unedo* L. as well as its effects on the fruit phenolic compounds. The fruit samples were dried at 60 °C, 70 °C, and 80 °C. Phenolic compounds were investigated using a Liquid Chromatography platform. Experimental results revealed that the effective moisture diffusivity determined by Fick's second law varied from 1.51×10^{-9} to 4.68×10^{-9} m^2/s, and the activation energy recorded was 2203.62 kJ/kg. Both the total energy consumption and the specific electrical energy of the dried fruits decreased as temperature increased. The Midilli–Kucuk model was selected as the best-fitted model for drying *Arbutus unedo* L. Significant effect of temperature on phenolics was observed. The concentration of the phenolic compounds decreased by 15.54, 39, and 40.63% at 60, 70, and 80 °C, respectively.

Keywords: convective solar drying; *Arbutus unedo* L.; energy efficiency; polyphenols

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1. Introduction

The *arbutus* (*Arbutus unedo* L.), commonly called arbutrus, is an evergreen shrub belonging to the Ericaceae family. It is native to the Mediterranean region. The fruits are consumed as fresh fruits or usually used for the production of jams, jellies and alcoholic beverages [1,2]. Fruits also can be added as pieces to different types of yogurts or as a flavoring agent. Also, used in similar to other berries in confectionery and cereal products, among other applications [3–5].

It is widely known for its higher content in bioactive molecules such as polyphenols, aromatic acids, iridoids, monoterpenoids, phenylpropanoids, sterols, triterpenoids, and flavonoids. Moreover, A. unedo fruits are considred as an important source of antioxidants, in particular the phenolic compounds (such as flavonoids, anthocyanins, tanins, and gallic acid derivatives), vitamins C and E, and carotenoids [1,3,4,6–11]. In addition, *A. unedo* fruits have been extensively used in traditional medicine. It has been reported that its fruits have anti-inflammatory [12], antimicrobial [13], anti cancer effects [14], and antidiabetic [15]. Also, the leaves as a good source of various biochemical compounds with numerous biological properties were reported as anti-diarrheal, astringent, anti-inflammatory, urinary antiseptic, anti-diabetic, and anti-hypertension [1,8,11,16–24].

However, it is still one of the under-exploited species in the Mediterranean region. In Morocco, strawberry tree's fruits are only sold locally when they are harvested. Picked fruits are brought by local farmers to town markets or sold by the side of the roads in small baskets. The development of these strawberry fruits chain value is very limited at the national level [25], which is why the Food and Agriculture Organization (FAO) has been promoting various projects for its development in Morocco since 2010 [26].

The fruit's high-moisture content makes it more sensitive to infection by many microorganisms and thus very perishable. The fruits cannot be cold-stored for along period because of its structure and also, storage conditions and parameters are not well reported.

Because of this, the adoption of one of the different preservation methods, such as refrigeration, freeze or oven drying remains a major challenge for small farmers located in remote rural areas.

While technological drying techniques such as freeze and oven drying have shown potential benefits in drying the strawberry tree fruits [27] especially on the color and sensor properties of the fruits, there are very costly, expensive, especially that the fruits are harvested in clusters with limited quantities. Orak and co-workers (2012) demonstrated that drying methods showed significant effects on the color, antioxidant activity and nutritional characteristics of dried strawberry tree fruits with the freezing technique being more preservative of the antioxidant activities, nutritional composition, and fruits color of fruits when compared to hot-air drying technology [27].

The most commonly used technique to dry the arbutus fruits in the rural areas in Morocco is sun drying. While it is more cost-effective than the other drying methods. However, there are many limitations for open sun drying such as slow drying rate, elevated risk of contamination, inadequacy of drying, and the effect of the surrounding weather conditions [28]. However, hybrid solar drying is becoming the trend in recent decades to overcome the limitations imposed by open traditional sun drying technique. Hybrid solar dyers are economic to produce, more affordable, environmentally friendly, and have lower operational costs than other drying methods.

In most common hybrid dryers, fruits are dried using direct solar radiation energy with auxiliary heating system for energy back-up in case of the absence of sunlight. Bala and Woods (1994) reported that solar hybrid drying resulted in significant microbial reduction in the dried food products [29]. Ferreira and co-workers (2007) showed that the drying time for the banana fruits using a solar hybrid drying was lower compared to open-air or artificial drying [30]. Furthermore, fruits color, aroma, and texture were far better when dried in hybrid dryer system than under open-air sun drying [31]. Similar findings were found by Eltawil et al., (2018) when studying the hybrid-dried peppermint [32]. They also, reported a dryer efficiency of 31% with a net carbon dioxide (CO2) mitigation of 32 tons over the life span of the hybrid dryer. Similar findings were reported on other crops such pineapples [33], mushrooms [34], cashew nuts [35], and sweet cherries [36].

In order to limit these post-harvest losses of arbutus fruits, and in particular, in Morocco, solar drying is considered a viable option as it is a clean and less expensive source of energy for small farmers. This allows local farmers to dry their strawberry fruits by shortening the drying time, and extend their shelf life while preserving their qualities. The application of this method is an alternative and promising method, especially in Morocco where sunshine is abundant (3000 h of sunshine per year, or 5.3 kWh/m^2/day) [37].

To reduce post-harvest losses and properly valorize the Moroccan *Arbutus unedo* L. fruits production, this research aimed to investigate the possibility of adopting forced convection solar drying as an eco-friendly method under Moroccan climate conditions. Also, evaluating its efficiency in converting these highly perishable fruits into more stabilized dried fruits while maintaining their quality and extending their shelf life by storing them under a minimal controlled environment. We hypothesize that results of this study as well of other published data on the use of hybrid solar drying on various crops can persuade local farmers to adopt it over the traditional open sun drying technique

The objectives of this study are:

- Investigate the drying kinetics of *Arbutus unedo* L. fruits in a convective solar dryer;
- Study the effect of both temperature and flow rate of the drying air on the drying kinetics of the *Arbutus unedo* L. fruits;
- Describe the characteristic drying curve (CDC) of *Arbutus unedo* L. fruits;
- Calculate, at different temperatures, the effective moisture diffusivity as well as the corresponding energy of activation;
- Estimate both the energy efficiency and the total energy consumption of the solar drying process;
- Select the best model that could describe the drying characteristics of the *Arbutus unedo* L. fruits;
- Investigate the effects of the three drying temperatures (60 °C, 70 °C, and 80 °C) on phenolic compounds by liquid chromatography analysis.

2. Materials and Methods

2.1. Experimental Procedure

Fruits of *Arbutus unedo* L. were harvested from a mountainous region in Marrakech, Morocco. A fresh fruit mass of 40 ± 0.1 g per tray was used, and the samples uniformly placed on the drying cabinet first shelf were dried at 60 °C, 70 °C, and 80 °C with air drying velocity of 0.18 m/s.

The heated air enters the drying cabinet from below the trays and moves upwards through the sample. The loss of fruit samples mass during the drying process was measured using an electronic balance (±0.001 g). In each experiment, the product weight was measured every 5 min at the beginning of the drying process and every 30 min at the end of drying until the final mass of the fruit sample reached a stable value.

The drying process of *Arbutus unedo* L. fruits was carried out at the fixed three temperatures and the mass loss $M_h(t)$ of the samples was monitored over time by weighting the samples repeatedly until $M_h(t)$ reached stable values (corresponding to the final water content). The total dehydration of the final mass (Mf) was completed in an oven set at 105 °C for 7 h. The dry-based moisture content at a given time (t) M(t) is described as:

$$M(t) = \frac{M_h(t) - M_d}{M_d} \quad (1)$$

2.2. Experimental System

The drying kinetics of *Arbutus unedo* L. fruit were studied using an indirect solar dryer system with forced convection (Figure 1). The system has no storage unit with partial or total air recycling. This system is made of a solar air collector attached to an auxiliary electric heater, a multilayer drying chamber (10 trays), and a ventilator. The equilibrium humidity value of the environment varied between 23 and 33% (Figure 2). Characteristics and detailed specifications of the system were reported in a previous article by Ouaabou et al., (2020) [38].

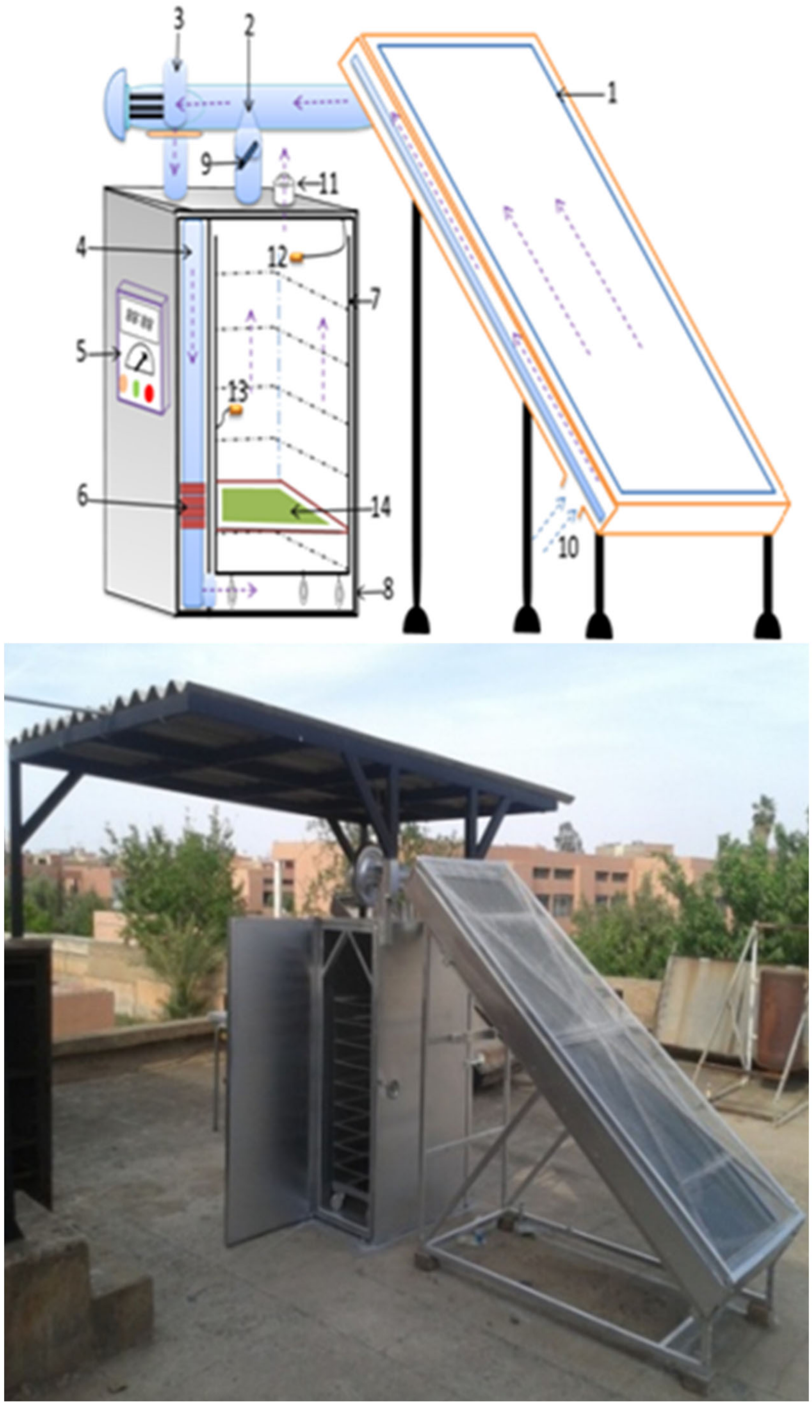


Figure 1. Design of the solar dryer. (1) Solar collector, (2) direction of the fan, (3) fan, (4) air flow direction, (5) control box, (6) auxiliary heating system, (7) floors, (8) drying cabinet, (9) air valve, (10) inlet air, (11) outlet air, (12) humidity probe, (13) thermocouple and (14) drying tray.

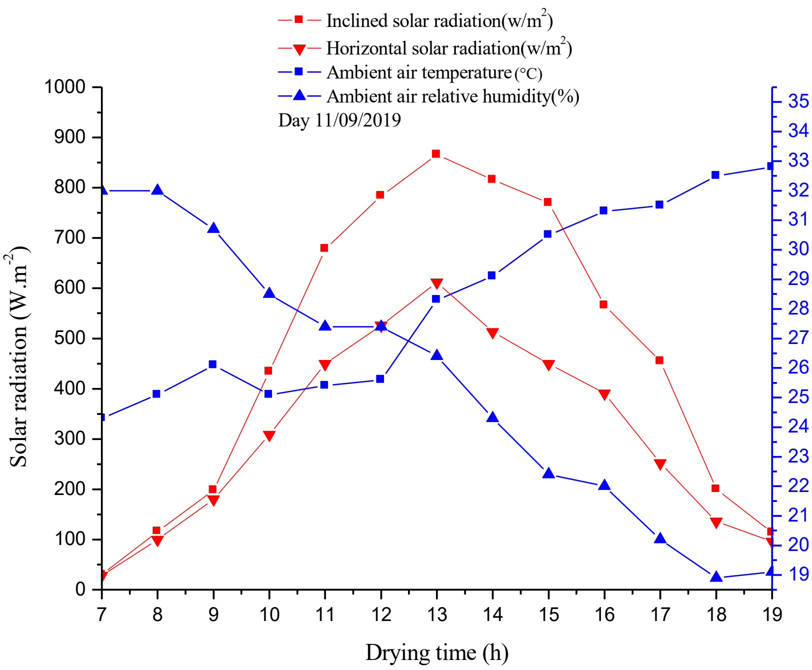


Figure 2. Variation of solar radiation versus daytime during the drying process.

2.3. Theoretical Principal

2.3.1. Moisture Ratio and Dimensionless Drying Rate

The moisture ratio (MR) expression as well as the dimensionless drying of the fruit samples were calculated using the above two equations:

$$MR(t) = \frac{M(t) - M_e}{M_0 - M_e} \tag{2}$$

$$f = \left(-\frac{dM}{dt}\right)_t \Big/ \left(-\frac{dM}{dt}\right)_0 \tag{3}$$

where M (t) is the mass of the sample at time t. M_0 is the initial mass, and M_e is the equilibrium moisture content of the fruit sample. Because the values of M_e are relatively negligeable in comparison to M_t or M_0, thus, the error involved in the simplification process is negated [39].

For each experiment, the program 'Lissage' was selected to calculate precisely the drying rate [40].

2.3.2. Determination of Effective Moisture Diffusivity

The term diffusivity is normally used to describe the drying kinetics of the product. Its driving force is the concentration gradient. This phenomenon is well described by using Fick's diffusion equation; therefore, the moisture transport mechanisms are mathematically described by the Equation (4). Using the slopes' method technique.

$$\frac{\partial MR}{\partial t} = Deff\nabla^2 MR \tag{4}$$

The solution to Equation (4) is illustrated below. For the infinite slab geometry, the proposed solution assumes the following: the particle is both homogenous and isotropic, both temperature and initial moisture distributions are uniform, and the shrinking phenomenon is considered nil [41].

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-(2n+1)^2\pi^2\frac{D_{eff}t}{R^2}) \tag{5}$$

When drying periods are longer (n = 1) the previously stated equation becomes [42,43]:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \quad (6)$$

Because of the linear trend of ln(MR) values against "t", the D_{eff} is derived from the slope of the following equation (Equation (7)).

$$D_{eff} = -\frac{B4L^2}{\pi^2} \quad (7)$$

2.3.3. Empirical Calculation of Activation Energy

Temperatures do strongly impact the activation energy. It is defined using an Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (8)$$

where D_0: pre-exponential factor of the Arrhenius equation (m^2/s). E_a: energy of activation (kJ/kg), R: universal gas constant (8.3143 kJ/mol K), and T: absolute air temperature (K) [44].

The plot of ln D versus 1/Ta gives the activation energy.

2.3.4. Energy Aspects of The Indirect Solar Convective Drying System

The total consumption of energy (kWh) by the drying system was calculated using Equation (9) [45]:

$$E_t = (A.v.\rho_a.C_a.\Delta T.D_t) + E_{mec} \quad (9)$$

where E_t: The total energy consumption (kWh), A:tray surface area (m^2), v: velocity of air (m/s), ρ_a: density of air (kg/m^2), C_a: air specific heat (kJ/kg °C), ΔT: the difference between ambient and hot air temperatures (°C), D_t: total drying time (h), and ρ_a refers to the power (kW).

The specific heat capacity parameters of both the inlet air [46] and the power [47] were computed using Equations (10) and (11):

$$\rho_a = \frac{101.325}{0.287 \times T} \quad (10)$$

$$C_a = 1.04841 - \frac{3.83719 \times T}{10^4} + \frac{9.45378 \times T^2}{10^7} - \frac{5.49031 \times T^3}{10^{10}} + \frac{7.92981 \times T^4}{10^{14}} \quad (11)$$

The mechanical energy (E_{mec}) used per each experiment is measured via an electric energy meter. It is the total energy used by both auxiliary heater and fan.

The specific thermal energy (kWh/kg) required to remove one kilogram of mass of water from the product was calculated by using Equation (12) [48]:

$$SEC = \frac{E_t}{m_w} \quad (12)$$

where: m_w is the quantity of water evaporated (kg). It is computed using Equation (13) [48]:

$$m_w = \frac{W_0\left(Y_0 - Y_f\right)}{100 - Y_f} \quad (13)$$

where: W_0 is the mass of the initial sample (kg), Y_0 and Y_f are the initial (t = 0) and final moisture content (% d.b).

The energy efficiency was calculated (Equation (14)) as the ratio of the water evaporation energy and the total energy used [49].

$$n_e = \frac{Q_w}{E_t} \tag{14}$$

where Q_w represents the water evaporation energy (kWh).

Since fruit samples have a higher water content, Equation (15) was used to calculate evaporation energy.

$$Q_w = h_{fg} \times m_w \tag{15}$$

where h_{fg} is the latent heat of vaporization (kJ/kg). It is a function of the air temperature (T abs) and is calculated using the following formulas [46].

$$h_{fg} = 2.503 \times 106 - 2.386 \times 103 \times (T_{abs} - 273.16)273.16 < T_{abs}(K) < 338.72 \tag{16}$$

$$h_{fg} = \left(7.33 \times 1012 - 1.60 \times 107 \times T^2{}_{abs}\right)^{0.5} 338.72 < T_{abs}(K) < 533.16 \tag{17}$$

2.3.5. Mathematical Models

Statistical parameters such as the coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE) were calculated to select the most appropriate model. The χ^2, RMSE, and R^2 were calculated according to the following Equations (2)–(4).

Modeling the drying process is an important key aspect of drying technology. In this study, the experimental drying data of *Arbutus unedo* L. fruits were fitted into nine commonly used thin-layer drying models, listed in Table 1. Constant and comparative indices for each model were determined using the Curve Expert Professional 2.3 software. The selection of the most suitable model describing the process was based on the coefficient of determination (R^2) and chi-square (χ^2). The best performing model has the highest values of R^2 and lowest values of χ^2.

Table 1. Mathematical models used.

Models	Equation
Newton [44]	MR = exp(−kt)
Page [50]	MR = exp(−ktn)
Logarithmic [39]	MR = aexp(−kt) + c
Wang and Singh [51]	MR = 1 + at + bt^2
Diffusion approach [52]	MR = aexp(−kt) + (1 − a)exp(−kbt)
Midilli–Kucuk [44]	MR = aexp(−ktn) + bt
Handerson and Pabis [53]	MR = aexp(−kt)
Two-term [54]	MR = aexp(−k1t) + bexp(−k2t)
Verma et al. [55]	MR = aexp(−kt) + (1 − a)exp(−k0t)

k, n, a, b, c, k0, k1, k2, g, h: models constant.

2.4. Quality Analysis

2.4.1. Sample Treatment

As the fruit is mainly known for its richness of phenolic content, understanding the effect of drying air temperatures on their profiles is a key element before the adoption of the drying technology as an eco-friendly technology. An extract of phenolics was prepared by dispersing 2 g of fruit in 20 mL of methanol and sonicated for about 30 min. The mixture was centrifuged (15 min, 3500 rpm), and the extracts were kept at −4 °C until required.

2.4.2. Instrumentation and Methods

A liquid chromatography system (Thermo Fisher Scientific, San Jose, CA, USA), equipped with a quaternary pump system, an autosampler, and a column oven was used to separate the phenolic compounds. A C18 reverse phase analytical column (100 × 4.6 mm, 2.6 µm particle size) was employed. The solvents used were (A) 0.1% formic acid in water and (B) (methanol). The gradient was as follows: 0–3 min, linear gradient from 5 to 25% B; 3–6 min, at 25% B; 6–9 min, from 25 to 37% B; 9–13 min, at 37% B; 13–18 min, from 37 to 54% B; 18– 22 min, at 54%B; 22–26 min, from 54 to 95% B; 26–29 min, at 95% B; 29–29.15 min, then return to starting conditions at 5% B; and from 29.15 to 36 min, at 5% B. The flow rate of the mobile phase was 1 mL/min. Phenolics were detected in the UV-vis range of 220–380 nm.

For quantitative purposes, the calibration curves obtained by analyzing pure phenolic standards under the same conditions were used. Triplicate injections were made for each standard solution and sample extract.

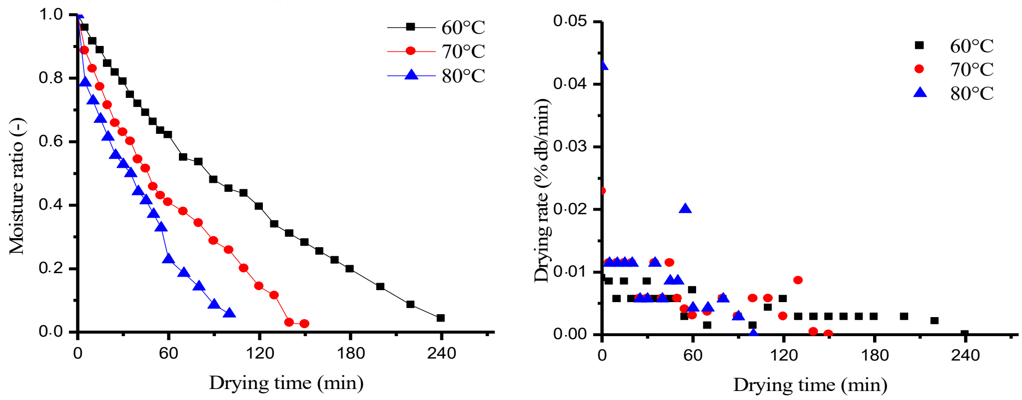
Significant differences in phenolic compounds content in studied samples as affected by drying temperature were assessed with one-way analysis of variance (ANOVA) followed by post-hoc Tukey's test. ($p < 0.05$) using the SPSS statistical pack-age software (SPSS for Windows, Version 20, SPSS Inc., and Chicago, IL, USA).

3. Results and Discussion

3.1. Drying Curves of *Arbutus unedo* L.

The fruit samples' initial and final moisture contents of the *Arbutus unedo* L. varied from 1.8857 to 2.0834% d.b and from 0.8857 to 0.6041% d.b, respectively. The horizontal solar radiation was lower than the inclined one during the daytime (Figure 2).

The evolution of the moisture content and drying rate for each air-drying temperature as a function of time is presented in Figure 3a. The air temperature impacted significantly the drying time of *Arbutus unedo* fruit samples. The drying time decreased as the air-drying temperature increased. The drying curves for the studied samples are similar to those previously described in other crop fruits [31,50–55]. This confirms the quick evaporation of moisture from the samples at the beginning of the drying, then a later decline as the drying time increased. The observed continuous decline in moisture content proves that the internal mass transfer is solely controlled by the diffusion process. While the air-drying temperature increased, an extra energy rate was applied to the *Arbutus unedo* L. fruits which resulted in an increase in the drying rate (Figure 3b). The constant rate was not observed for all curves, and presumably, all the drying cases took place within the declining rate period. This observation validate that the diffusion was mainly physical mechanism controlling moisture movement during the drying process. These observations align with those reported on other fruits [56–58].



(**a**) (**b**)

Figure 3. The trend of the moisture ratio (**a**) and drying rate (**b**) with drying time at 60 °C, 70 °C, and 80 °C.

Regardless of the air-drying temperature, the recorded drying rate neared zero. This observed decline is attributed to the sample's lower evaporation rate [59]. At each studied air-drying temperature, the drying time decreased in response to the increase in the drying rate. These properties are widely observed in numerous biological products [60].

In contrast, the moisture content per sample decreased with the increase in temperature. The unique presence of phase II (phase 0 and I were absent) for drying curves of *Arbutus unedo* L. was noticeable. This is most likely attributed to the difference between the saturated (humidified) air temperature and the initial temperature of the fruit samples, considered negligible. Zheng and co-workers (2011) reported that the moisture content decreases in food products during the drying process [61]. This means that during the drying operations, the water moves from higher moisture to lower moisture points, and the movement of water from the inside to the surface of the food matrix is gouverned by molecular diffusion. These findings were also reported by other authors, such as Karami and co-workers (2021) for rosemary in a solar- convection dryer [62], Doymaz (2012) for sweet potato [63], Tagnamas et al., (2020) for carob seeds in a convective solar dryer [59], and Moussaoui and co-workers (2021) for apple in a hybrid solar-electrical forced convection dryer [64].

3.2. Mathematical Modeling of The Drying Curves

In this study, to better describe the solar drying kinetics of *Arbutus unedo* L. fruits, the experimental drying data were fitted into nine commonly used thin-layer drying models, listed in Table 1. The suitable fitting model was selected based on both the highest (R^2) and the least (χ^2). All tested models had high R^2 and χ^2 with values ranging from 0.9869 to 0.9980 and 0.0171 to 0.0424, respectively. Table 2 highlights the statistical analysis generated for each of the nine models. Although, Logarithmic, Page, and Midilli–Kucuk models fitted well the experimental data, the Midilli–Kucuk model was the best fitting model with the highest R^2 and least χ^2. Similar findings were reported for various fruits drying [65]. The fitting results of Midilli–Kucuk model for all drying experiments are presented in Figure 4. These results prove that the Midilli– Kucuk model fits well with the drying kinetics of *Arbutus unedo* L. fruits.

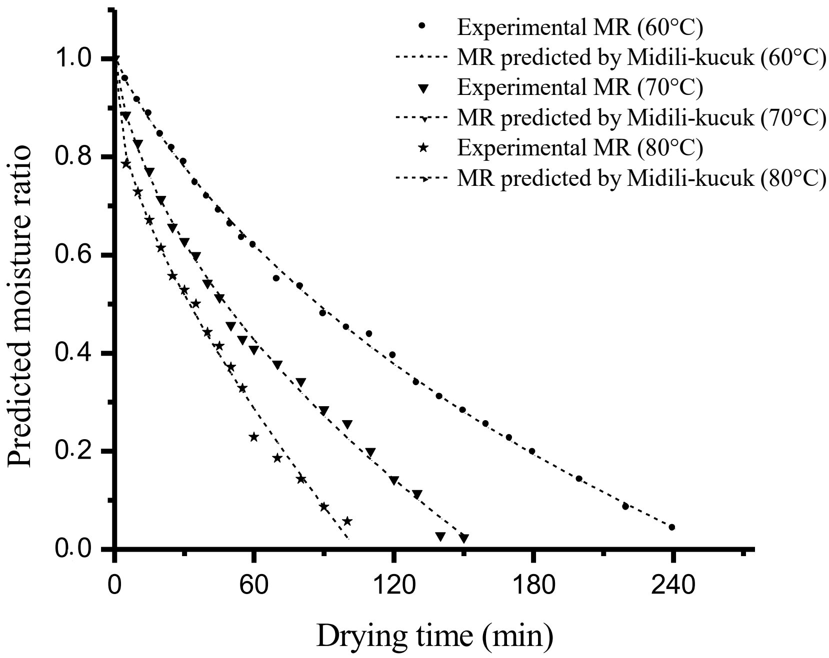


Figure 4. Experimental drying data of moisture ratio versus drying time as fitted with Midilli-Kucuk model.

Table 2. List of statistical results generated from all nine models.

Temperature (°C)	Parameters				Statistical Parameters	
					R^2	χ^2
Newton	k					
60	0.0084				0.9951	0.0274
70	0.0153				0.9920	0.0003
80	0.226				0.9839	0.0469
Average					**0.9903**	**0.0248**
Page	k	n				
60	0.0057	1.0820			0.9964	0.0242
70	0.0160	0.9888			0.9920	0.0358
80	0.0296	0.9286			0.9849	0.0469
Average					**0.9911**	**0.0356**
Wang and Singh	a	b				
60	−0.0067	0.0000			0.9965	0.0237
70	−0.0121	0.0000			0.9861	0.0472
80	−0.0180	0.0000			0.9782	0.0564
Average					**0.9869**	**0.0424**
Logarithmic	a	k	c			
60	1.2398	0.0056	−0.2593		0.9988	0.0136
70	1.1184	0.0106	−0.1720		0.9955	0.0277
80	1.1438	0.0139	−0.2292		0.9915	0.0364
Average					**0.9952**	**0.0259**
Diffusion approximation	a	k	b			
60	5.926×10^3	0.0040	0.9998		0.9983	0.0166
70	3.626×10^3	0.0098	0.9998		0.9928	0.0350
80	3.707×10^3	0.0151	0.9998		0.9844	0.0495
Average					**0.9918**	**0.0337**
Midilli−Kucuk	a	k	n	b		
60	1.0086	0.0128	0.8364	−0.0010	0.9994	0.0096
70	1.0052	0.0393	0.6699	−0.0019	0.9981	0.0181
80	0.9974	0.0918	0.4422	−0.0047	0.9967	0.0236
Average					**0.9980**	**0.0171**
Handerson&Pabis	a	k				
60	1.0134	0.0086			0.9954	0.0273
70	0.9781	0.0149			0.9925	0.0347
80	0.9472	0.0211			0.9872	0.0433
Average					**0.9917**	**0.0351**
Twoterm	a	k_0	b	k_1		
60	−0.0027	−0.0157	0.9944	0.0077	0.9994	0.0099
70	0.4893	0.0149	0.4888	0.0149	0.9925	0.0366
80	22.7230	0.0307	−21.7997	0.0312	0.9886	0.0439
Average					**0.9935**	**0.0301**
Verma	a	k	k_0			
60	−35.1680	0.0127	0.0126		0.9968	0.0231
70	−0.0006	−0.0325	0.0146		0.9954	0.0277
80	−0.0002	−0.0563	0.0219		0.9862	0.0465
Average					**0.9928**	**0.0324**

The validation of the chosen model was completed by comparing the model predicted moisture ratios and the experimental at each studied air-drying temperature. The Figures 4 and 5 show its performance at the three drying temperatures.

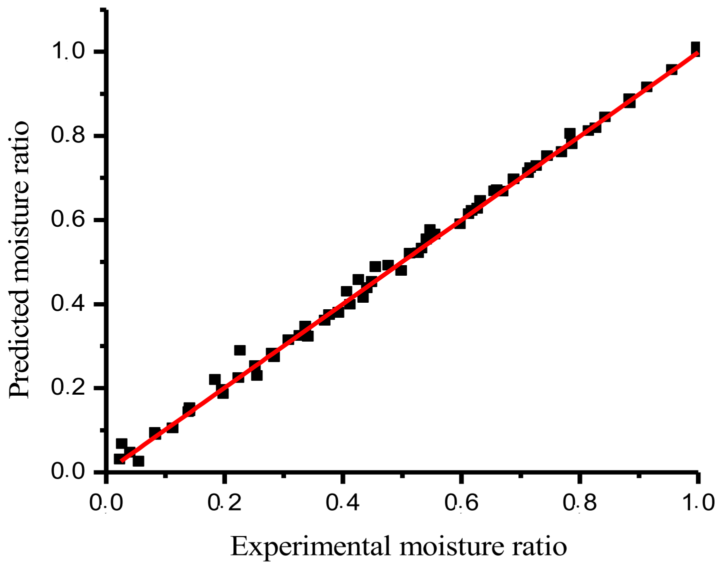


Figure 5. Relationship between moisture ratios as predicted by Midilli-Kucuk model and the observed moisture ratio of the *Arbutus unedo* L. at temperatures (R^2 = 0.9998).

For a given temperature θ in °C, the temperature dependency of the model Midilli-Kucuk parameters was computed. The values of a, b, k and n are used to compute, at any time during the drying process, the moisture content of the product with a greater precision.

$$a = 0.9366 + 0.0025\theta - 2.2 \times 10^{-5}\theta^2 \qquad n = 0.3998 - 0.00143\theta + 1.30 \times 10^{-4}\theta^2$$

$$k = -0.0355 + 0.0012\theta - 9.5 \times 10^{-6}\theta^2 \qquad b = 0.5502 + 0.0231\theta - 3.06 \times 10^{-4}\theta^2$$

3.3. Determination of the Characteristic Drying Curve (CDC)

The relation between the normalized drying rate and the experimental MR is shown in Figure 6. The data obtained at all air-drying temperatures (60 °C, 70 °C, and 80 °C) were plotted. The equation to fit the data well was in the modality of a third-order polynomial. The polynomial equation of the characteristic drying equations (CDE) for *Arbutus unedo* L. is given in Table 3.

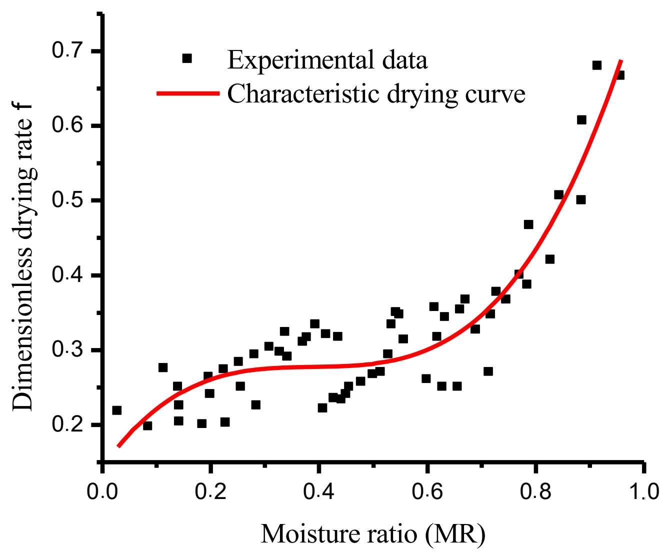


Figure 6. Dimensionless drying rate against moisture ratio of *Arbutus unedo* L. fruits.

Table 3. The polynomial equation of the characteristic drying equations (CDE).

CDE	r	SE
$F = 2.2049MR - 2.5745MR^2 - 1.0123MR^3$	0.9295	0.0926

3.4. Determination of Effective Moisture Diffusivity and Activation Energy

Effective moisture diffusivity (D_{eff}) describes the conductive aspect of every possible mechanism of moisture transfer. It depends mainly on the temperature, the sample's water content, and the product texture temperature. Therefore, it is a key element to describe drying kinetics. In addition, the activation energy is also a fundamental drying parameter that defines the energy required for both moisture evaporation and diffusion, it is derived from experimental drying curves.

The variation of the effective diffusivity coefficient with drying time at the three temperatures is shown in Figure 7. The values of D_{eff} for *Arbutus unedo* L. were 1.51×10^{-9}, 2.68×10^{-9} and 4.70×10^{-9} m^2/s at 60, 70, and 80 °C, respectively (Table 4).

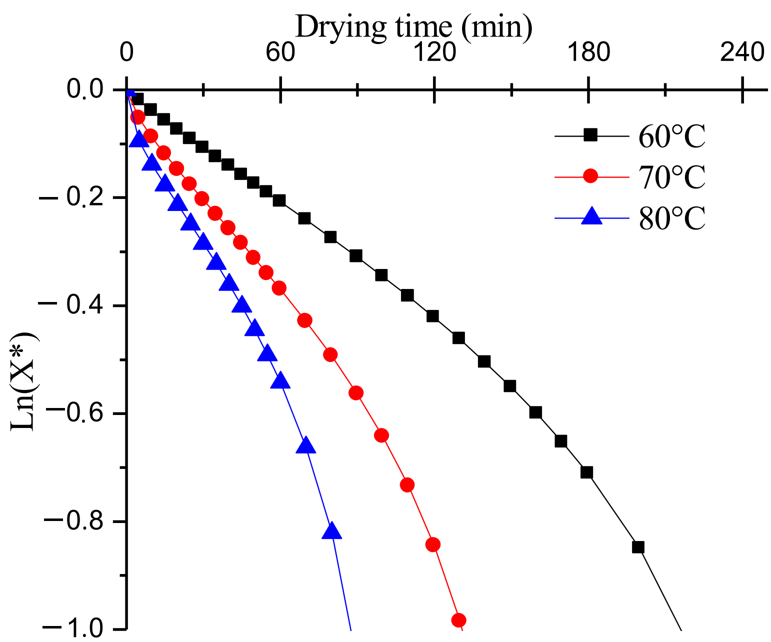


Figure 7. Effects of both air flow and temperature on the effective diffusion coefficient.

Table 4. Values of the effective diffusivity and activation energy of the *Arbutus unedo* L.

Temperature of Drying (°C)	D_{eff} (m^2/s)	r	E_a (kJ/kg)	R
60	1.5147×10^{-9}	0.9750	2203.62	0.9486
70	2.6863×10^{-9}	0.9651		
80	4.7046×10^{-9}	0.9563		

The effective diffusion coefficient increased as the drying air temperature increased. This can be due to the increase in the rate of the air heat supply to the fruit samples, and the agitation and accelerated movement of water molecules inside the fruit matrix, which ended up increasing the drying rate. The increased temperature augmented the energy needed for the rotational, transitional, and vibrational motion of water vapor. This induced a higher gradient of moisture, thus increased the mass transfer rate, which results in higher moisture diffusivity [66]. These moisture diffusivity values obtained for the *Arbutus unedo* L. were within the range given for food materials moisture diffusion (10^{-11} to 10^{-6} m^2s^{-1}) [67,68].

The activation energy is defined as the amount of energy needed to remove moisture of a solid sample. Higher value of the activation energy means higher temperature sensibility of the Deff coefficient [62]. The average activation energy recorded for *Arbutus unedo* L. is 2203.46 kJ/kg with an R^2 of 0.9486 (Figure 8). Similar results were reported for white mulberry [69], and for black mulberry fruits [57].

$$D_{eff} = 1.0588 \times 10^{-3} \exp\left(-\frac{265.0493}{T}\right) \quad (18)$$

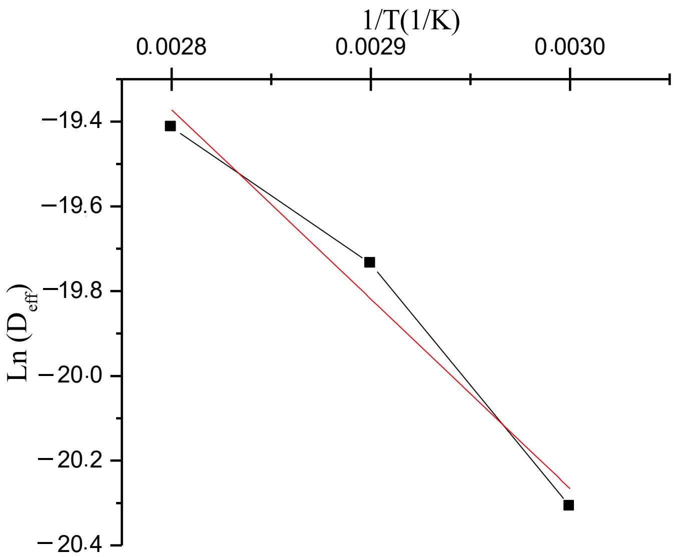


Figure 8. Relationship between effective moisture diffusivity and reciprocal absolute temperature.

3.5. Energy Utilization in The Convective Solar Dryer

3.5.1. Total Energy Utilization of The Forced Convection Solar Dryer

The total energy used by the convective solar dryer to dry the *Arbutus unedo* L. fruit samples at different temperatures is presented in Figure 9.

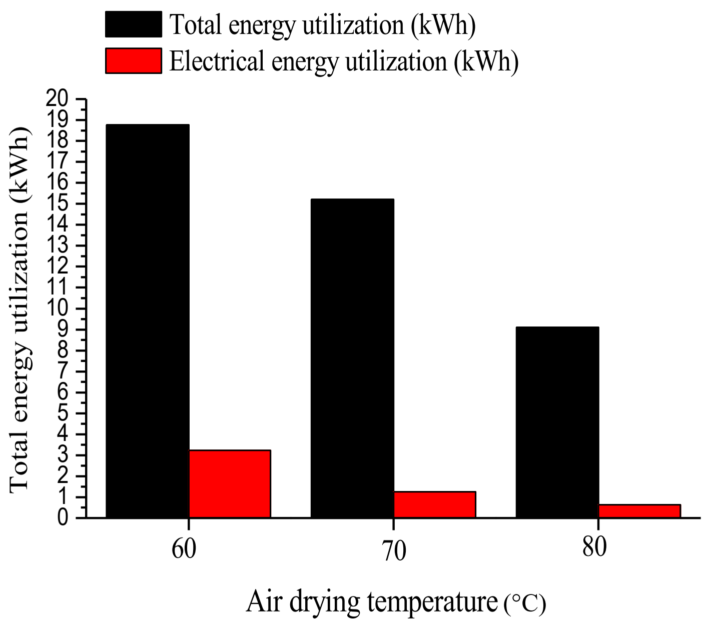


Figure 9. Total electrical energy used in drying the *Arbutus unedo* L. fruits.

The total energy consumption decreased as the temperature increased (Figure 9). This means that a decrease in the drying time has an influence on the total energy usage when the air-drying temperature increases. Similar findings for vegetables and fruits were reported by [65]. The electrical energy utilization of *Arbutus unedo* L. fruit at diverse moisture contents and air-drying parameters was measured by an electric energy meter, it varied from 0.65 to 3.24 kWh. The electrical energy consumption decreased as temperature increased. As a result, the electrical energy utilization depends strongly on the drying time. This latest has a low value in comparison with the total energy utilization.

3.5.2. Specific Energy Consumption (SEC) in Forced Convection Solar Drying

The evolution of the specific energy consumption (SEC) at different air-drying temperatures in the forced convection solar drying is presented in Figure 10.

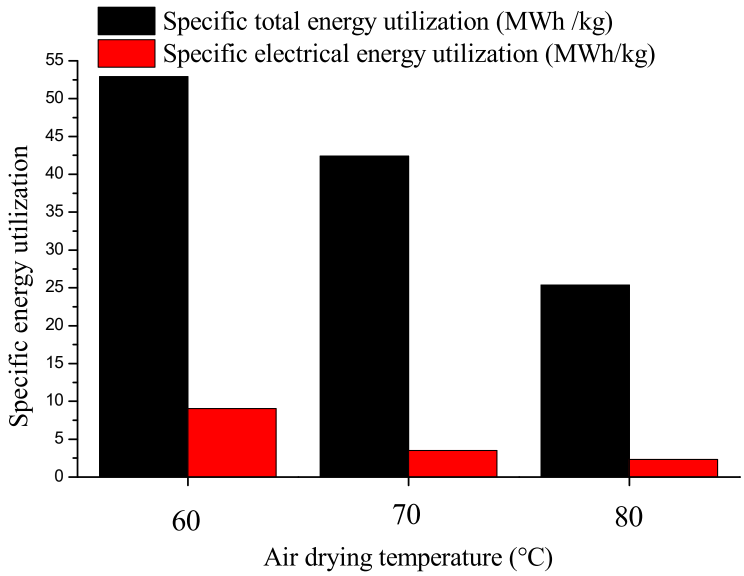


Figure 10. Evolution of specific energy utilization at 60, 70, and 80 °C.

The SEC values (energy necessary per unit mass) varied between 21.40 and 49.91 MWh/kg at drying air temperatures of 60, 70, and 80 °C. The specific energy utilization decreased when the air-drying temperature increased. The decrease in temperature resulted in the increased demand for dryer energy, which is due to the prolonged drying time needed at lower temperatures. Furthermore, we observed an increase in the total energy consumption (Figure 10) at lower drying air temperatures. Same observations were reported in rosemary leaves by Karami et al., (2021) on rosemary leaves [62], by Tagnamas and colleagues on carob pulp [70], and on apple slices by Beigi (2016) [49].

3.5.3. Electrical and Solar Energy Intervention

The contribution of both solar and electrical energy during all drying experiments at different aero-thermal parameters is shown in Figure 11.

The trend of both solar energy and total energy utilization are similar, which means, an increase in air-drying temperature (60~80 °C) results in a decrease in solar energy, this is because at higher values of air-drying temperatures the drying time decreases. Based on these data, it can be concluded that solar energy constitutes the predominant used energy in all drying experiments compared to electrical energy (Figure 11), which allows more savings on energy costs and respects the environment.

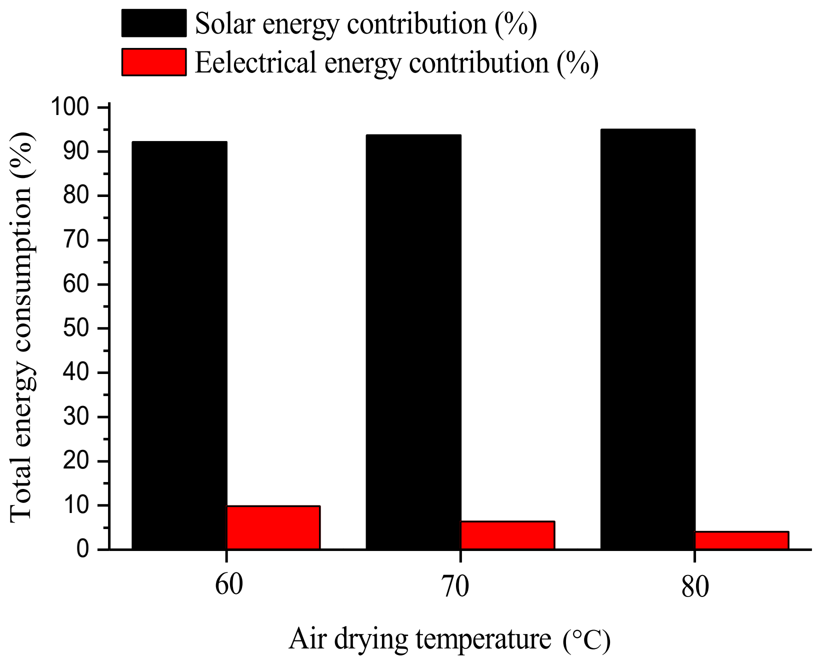


Figure 11. Contribution of solar and electrical energy during the drying process.

3.5.4. Energy Efficiency

Figure 12 shows the energy efficiency and thermal efficiency values for diverse air-drying parameters of *Arbutus unedo* L.

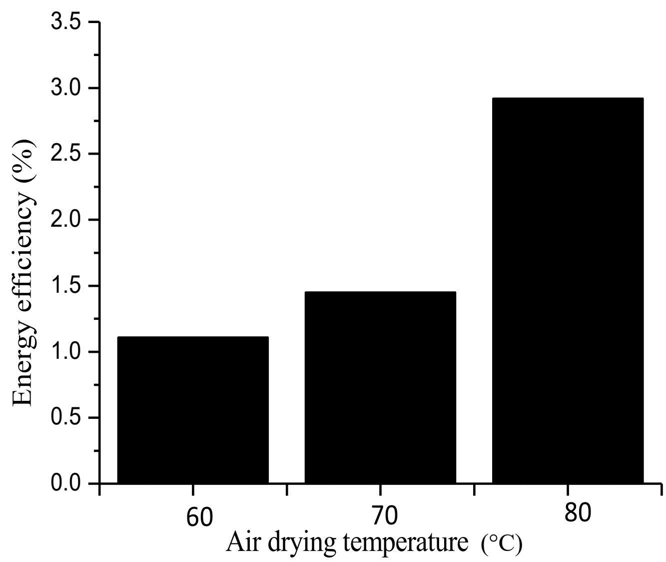


Figure 12. Energy efficiency for drying the *Arbutus unedo* L. fruits at different air-drying temperatures.

The lowest energy efficiency value (1.01%) was recorded at 60 °C, while the highest value (2.92%) was reached at the temperature of 80 °C. Fewer samples used in the experience toward the high values of the inflow energy of the solar dryer enters the drying chamber, leading to the low amount of evaporation energy in the drying chamber and that expresses low values of energy efficiency.

3.6. Quality Evaluation

Chromatographic separation of phenolic compounds identified nine phenolic compounds, including four hydroxybenzoic acid derivatives (gallic, salicylic, chlorogenic, and coumaric acids) and five flavonoids (quercetin, kaempferol, catechins, naringin, and epicatechin) (Table 5). This phenolic profile is similar to those reported by [71].

Table 5. Phenolic compounds contents of undried and dried *Arbutus unedo* L. fruits (Results are expressed as mean values of three determinations; Significant differences at $p < 0.05$ (Tukey's test) are indicated with different letters).

Phenolic Compounds (g/100 g dw)	Undried	Dried at		
		60 °C	70 °C	80 °C
Phenolic acids				
Gallic acid	16.62 a	14.41 b	17.66 c	15.29 d
Salicylic acid	1.23 a	0.96 b	0.73 c	0.94 b
Chlorogenic acid	12.31 a	11.69 a	9. 20 b	6.11 c
Coumaric acid	0.03 a	0.14 b	0.02 a	0.03 a
Flavonoïdes				
Quercetin	14.61 a	11.66 b	8.23 c	5.03 d
Kaempferol	1.61 a	0.93 b	0.43 c	0.43 c
Catechin	5.77 a	3.56 b	2.45 b	1.25 c
Naringine	8.36 a	7.73 a	6.58 b	6.34 b
Epicatechin	2.68 a	2.31 a	2.48 a	2.11 a
Total	63.22 a	53.39 b	38.58 c	37.53 c

The total phenolic compounds of *Arbutus unedo* L. was 63.22 mg/100 g dry solids (Table 5). Total phenolic compounds of dried fruits were less compared to fresh ones. Higher temperature resulted in a decrease from 15.54% (60 °C) to 62.78% (80 °C) in total phenolic compound content. Likewise, in a study conducted on cherry laurel fruits, a significant decrease was noticed in both total phenolic and total flavonoid content of dried samples at 50, 60 and 70 °C when compared with fresh fruits [72]. The degradation of phenolic compounds observed after drying can be attributed to the activation of some enzymes, such as peroxidase and polyphenol oxidase, which can catalyze the oxidation of phenolic compounds.

It can also be noticed that the total phenolic content decreased as the temperature elevated. Similarly, an increase in the drying temperature from 25 to 60 °C was linked to a decline in the total phenolic content of dried strawberry *Fragaria vesca* L. fruits [73]. This loss in the phenolic compounds content may be attributed to oxidation, thermal degradation and polyphenol oxidase activity [72]. However, these outcomes are quite different from those reported in a study conducted by Patrón-Vázquez and co-workers on *Citrus lemon* (L.) waste [74]. Drying lemon residues at different temperatures ranging between 40 and 110 °C induced an increment in total phenolic content at higher temperatures (from 90 to 110 °C). An eventual explanation of this trend is that higher temperatures may enhance the solubility of phenolic compounds through the breakdown of cellular structures and thereby the release of these compounds [75]. In another investigation, the total polyphenols content of sweet cherries was not affected by drying temperatures at 60 °C, 70 °C, and 80 °C [38].

Focusing attention on individual phenolic compounds, gallic acid and chlorogenic acid were the most abundant phenolic acids in the studied samples and quercetin was by far the main flavonoid. Increasing the drying temperature from 60 to 80 °C was responsible for the substantial loss of all phenolic compounds except gallic acid which was enhanced from 14.41 at 60 °C to 17.66 g/100 g of dw at 70 °C then decreased to 15.29 g/100 g of dw at 80 °C. These findings are in a good agreement with those reported by Turkmen and co-workers (2020) as there was a significant decline in the contents of individual phenolic compounds in dried cherry laurel fruits [76]. M'hiri et al., (2020) explained that in dried matrices, the extraction is challenging due to the fact that the components in the cells are more attracted to each other [77]. However, Patrón-Vázquez and co-workers found that phenolic compounds behave differently regarding drying temperatures [74]. Indeed, while the content of some compounds increased linearly with drying temperature, other compounds declined and could not be detected at higher temperatures. These various effects on drying on single phenolics were supported by other authors [78,79]. They reported that the effect of oven drying temperatures were different on numerous individual phenolic compounds. These can be attributed to the difference in the molecular structures of these phenolic molecules, which may or may not be subjected to enzymatic degradation/co-pigmentation, or oxidation reactions at specific drying temperatures. Drying method can vary in their effect on phenolic compounds, and this is mainly attributed to the drying temperatures. Snoussi et al., (2021) reported a double fold increase in phenolic compounds content in *Myrtus communis* L. [80] when dried *via* microwave than in air dried samples, whereas, oven drying at higher temperature (100 and 120 °C) resulted in significant reduction (30% and 60% reduction at 100 and 120 °C, respectively). Also, Ho and Lin (2008) showed that applying low temperatures (<100 °C) to dry citrus peels reduced the destructive power on the most key phenolic compounds as compared to higher temperature (150 °C) [81].

4. Conclusions

This is the first study to investigate the potential use of a solar dryer under Moroccan environmental conditions, to dry a very perishable fruit (*Arbutus unedo* L.) as an eco-friendly, low energy-intensive drying technique to be adopted by small farmers in remote rural areas. The study fully described the drying kinetics of the indirect forced convection solar dryer (effective diffusivity, activation energy, total energy usage). Also, the effect of the drying process on the phenolic content was investigated for the first time using the liquid chromatographic separation technique. The main highlights of the present study are as follows: Based on these results, we can conclude that the selection of higher temperature resulted in faster drying rates, which is translated to a faster dehydration process, with important economic benefits for farmers. At lower temperature (60 °C), the drying period was longer and didn't benefit extensively from the solar radiation. Moreover, the temperature was limited at 80 °C to avoid any further degradation of phenolic compounds and, therefore, preserve the original color, original flavor and nutritional quality of the dried strawberry tree fruits. In the temperature range of 60–80 °C, the effective moisture diffusivity varied between 1.5147×10^{-9} and 2.7046×10^{-9} m^2/s. It increased proportionally as the temperature increased. The activation energy recorded a value of 2203.62 kJ/kg.

The electrical heating consumption was less than 5%. This emphasis on this solar dryer is viable, eco-friendly, efficient, and can be considered an affordable alternative to conventional open sun drying.

The Midilli–Kucuk drying model described well the solar drying kinetics of *Arbutus unedo* L. fruits.

Higher temperature resulted in a decrease from 15.54% (60 °C) to 62.78% (80 °C) in total phenolic compounds content.

Consequently, for optimal preservation of bioactive compounds and maintaining the quality of the dried fruits, it is recommended to adopt the investigated drying conditions that have been defined for the convective solar dryer. Overall, the solar dryer can be applied for industrial purposes especially by farmer cooperatives in rural areas for drying harvested strawberry tree fruits as it consumes least time and energy while extending the shelf life of a very sensitive and perishable seasonal fruit.

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