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Drying Kinetics and Quality Analysis of Coriander Leaves Dried in an Indirect, Stand-Alone Solar Dryer

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Abstract: In this study, coriander leaves were subjected to three different drying techniques; direct sun, shade, and using an indirect solar dryer. In the developed dryer, hot air obtained from a black-body solar collector was pushed by a blower powered by a solar panel, and sent to the drying chamber with multiple trays for thin-layer drying. Experiments were conducted for summer and winter seasons, and temperature and relative humidity variations in the drying chamber were measured using a data acquisition system. Indirect solar dryer performance was evaluated and compared with sun drying and shade drying for drying kinetics, moisture diffusivity, and product quality. The drying rate curves show a linear falling rate throughout the drying process. The drying kinetic models are well-fitted with the Midilli and Kucuk thin-layer drying model. The effective moisture diffusivity of the dried coriander shows a decreasing trend, sun drying (2.63×10^{-10} m^2/s and 1.05×10^{-10} m^2/s) followed by solar dryer (1.31×10^{-10} m^2/s and 6.57×10^{-10} m^2/s), and shade drying (6.57×10^{-11} m^2/s and 3.94×10^{-11} m^2/s) for winter and summer seasons, respectively. Green color changes from −7.22 to −0.056, −7.22 to 3.15, and −7.22 to −0.35 in indirect solar, direct sun, and shade drying, respectively. The hue angle and Chroma are reduced by 12% and 32% in indirect solar drying, respectively. The total phenol content (TPC) value increases with drying, with summer showing the highest values (365 to 852 mg caffeic acid/100 g dry weight) while the antioxidant capacity reaches 3.41 and 3.53 in winter and summer, respectively from 0.22 μmol Trolox/g dry matter of fresh leaves.

Keywords: indirect solar drying; coriander leaves; drying kinetics; moisture diffusivity; physicochemical properties; color retention

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Citation: Jayasuriya, H.; Pathare, P.B.; Al-Attabi, Z.; Al-Hamdani, A. Drying Kinetics and Quality Analysis of Coriander Leaves Dried in an Indirect, Stand-Alone Solar Dryer. *Processes* **2023**, *11*, 1596. https://doi.org/10.3390/pr11061596

Academic Editors: Won Byong Yoon and Meng-I Kuo (Marie)

Received: 31 March 2023
Revised: 20 May 2023
Accepted: 22 May 2023
Published: 23 May 2023

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1. Introduction

Coriander leaves (*Coriandrum sativum* L.) are one of the most popularly used plants for culinary and medicinal purposes. The plant is utilized in food preparations, perfumes, and cosmetics due to its flavorful capabilities, and it has great commercial appeal. Fresh coriander leaves are perishable in nature and need post-harvest treatment or preservation. Coriander has a high water content, so it is typically dried before it is marketed in order to stop the growth of microorganisms and avoid deterioration due to biochemical processes. Furthermore, drying results in a significant reduction in weight and volume, lowering the cost of packaging, storage, and transportation. Drying is the oldest and most widely used primary method of food preservation. As seasonal and very perishable plants, almost all herbs must be preserved in order to be readily available to consumers and the food processing sector throughout the year.

Usually, fresh herbs are dried in the sun under ambient conditions. Sun drying is still used widely around the world despite its many disadvantages, since it is cheap and effective. Solar energy is an important alternative energy source that is preferred to other energy sources due to its abundance, inexhaustibility, and lack of pollution. It is also affordable, renewable, and environmentally friendly. The most common disadvantages of sun drying include quality losses brought on by insect infestation, loss of important compounds, enzymatic reactions, the growth of microorganisms, and the production of mycotoxin [1]. It is vulnerable to theft, damage, and infection by birds. Additionally, it suffers from a lack of procedural control and inconsistent treatment [2]. Shade drying utilizes solar energy to heat the herb, it is conducted in the shade to prevent direct sunlight from damaging the herb. Using this technique, heated surrounding air dries the herbs, requiring low humidity and ventilation in the drying area. In addition, the method minimizes chemical changes in essential oils, such as oxidation, in light-sensitive materials. Compared to sun drying, this method of drying has the disadvantage of a long drying time [3]. Shade drying preserved the glandular trichomes of spearmint (*Mentha spicata* L.) leaves better than other drying methods such as ovens, vacuums, and infrared [4].

Solar dryers can help to overcome some of the issues with sun drying. Many researchers have looked into how solar energy technologies can be used to dehydrate medicinal herbs, and they found that under carefully monitored and controlled settings of parameters, moisture evaporates swiftly to a saturation level, ensuring superior quality [1,5]. Hidar et al. [6] investigated drying stevia leaves in a solar dryer and found a decrement in the phenolic, chlorophyll content of the dried samples with increased drying air temperature. A study shows that drying fenugreek leaves in a solar dyer produces higher levels of ascorbic acid, total chlorophyll, and color than drying in the open sun [7]. A study of sweet basil leaves dried by solar dryer found a higher content of volatile organic compounds than those found in open sun-dried leaves [8].

However, drying may have a negative impact on the product quality. The color and phenolic components of medicinal herbs are extremely temperature-sensitive. Color is an important indicator to predict quality of dried products as it is closely allied with consumer preference. The active components in medicinal herbs are significantly affected by drying temperature. Due to thermal breakdown, high temperatures usually have an effect on the quality and amount of phenolic compounds [9–11]. The influence of different drying methods on the phenolic content of peppermint leaves was evaluated, and the phenolic concentration was found to be 53% lower in oven-dried samples, 16% higher in sun-dried samples, and 45% higher in microwave-oven-dried samples [9]. Polyphenol oxides and peroxidase activity reduce at high temperatures [12].

Moisture diffusivity of food is a property of the material, and the value of diffusivity is dependent on the conditions present in the material. Diffusion of moisture in solid foods is a crucial part of the complex process of moisture transfer. Hidar et al. [2] found that effective moisture diffusivity was in the range of 5.07×10^{-11} and 3.14×10^{-10} m^2 s^{-1} for stevia leaves in a solar dryer. The effective moisture diffusivity measurements for coriander leaves dried by solar drying are rarely documented in the literature. The design and modeling of mass transfer processes, such as dehydration, moisture adsorption, and desorption during storage, depend on an understanding of effective moisture diffusivity.

Oman receives high solar radiation in the region year round [13]. The small-to-medium-sized enterprises (SMEs) involved in value addition of agricultural produce may benefit from drying that utilizes inexpensive solar energy. Solar drying can take more time than expected and is weather-dependent, which degrades the product's quality and results in losses [14]. There are very few limited research studies in the cited literature that study the drying kinetics, moisture diffusivity, and quality of herbs using solar energy in Oman. Additionally, the indirect solar dryer used a black-body solar collector with convective hot air blow to achieve better quality parameters than open sun drying [5]. Using this technology locally could increase farmer incomes and secure their access to food and nutrition. Therefore, this research aimed to study the performance of a developed stand-alone, indirect solar dryer in producing high-quality dried coriander leaves. This work also evaluated the drying characteristics, effective moisture diffusivity, and quality properties of dried coriander leaves.

2. Material and Methods

2.1. Plant Material

The study was carried out on fresh coriander leaves purchased from the local market in the region of Barka, South Al Batina, Oman. The leaves were separated from the stems for the experiments. The samples were stored in glass containers after sorting and under refrigeration (2–4 °C) for a maximum of 12 h. The leaves were dried in an oven at 105 °C oven for 24 h to determine the initial moisture content and an average value of 4.88 g water/g dry matter was found. Thickness measurements of the leaves were made with Vernier caliper and it was found that they were 0.36 ± 0.04 mm by taking the average. Before being dried, coriander leaves were spread out on four different trays and given time to remove the excess moisture content.

2.2. Drying Process

Experiments with three drying methods were performed using an indirect solar dryer, direct sun, and shade drying. A forced convective hot airflow generated using a solar collector with black body radiation concept, used in the dryer chamber of the indirect solar dryer (Figure 1), is dependent on solar radiation and the ambient weather [5]. The temperature (thermocouples) and relative humidity (Hobo stand-alone sensors) data were recorded with a data logging system with 20 min sampling frequency. The studies were carried out in Barka, North Al-Batinah, Oman, (23°42′26″ N, 58°09′43.7″ E) during the summer (July, August) and winter (December, January) seasons and for comparison, direct sun and shade drying was carried out simultaneously. The average summer sun radiation duration was 11 h, with an average ambiance temperature and relative humidity of 42.5 °C and 44.5%, respectively. In the winter, the average sun radiation duration was 8 h, with an average ambiance temperature and relative humidity of 38.3 °C and 30.8%, respectively. The experiments were continued until the dried leaves moisture content reached about 10–12% [15,16]. The mass loss was measured during experiments every hour in winter and every 0.5 h in the summer. The dried material was placed in resalable zipper bag and keep it in a desiccator for further analysis.

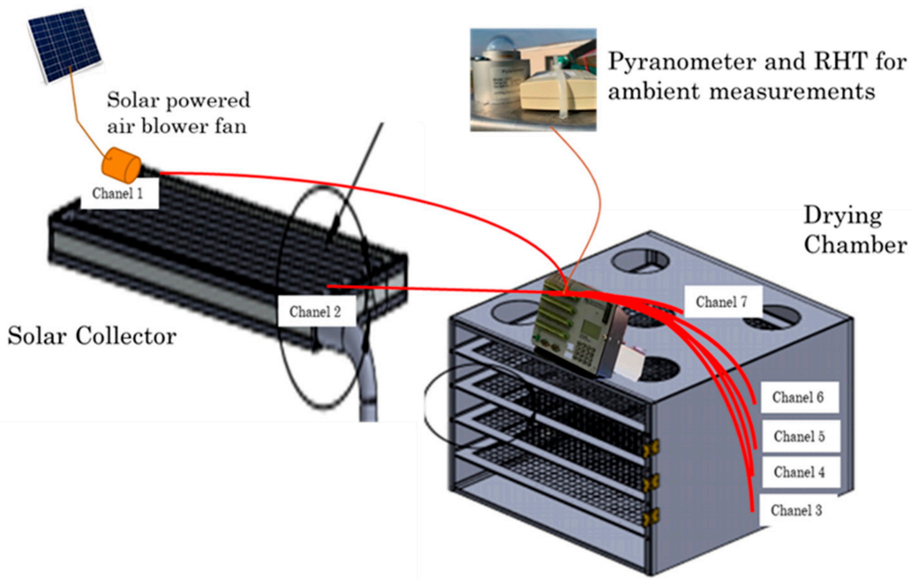


Figure 1. Indirect solar dryer for coriander leaves drying process.

2.3. Mathematical Modeling

Moisture ratio (MR) of coriander leaves during drying was calculated using Equation (1) [17].

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

where M_t represents moisture content at time t (g water/g dry matter), M_o is initial moisture content of the sample (g water/g dry matter), and M_e is equilibrium moisture content (g water/g dry matter). The moisture ratio may be simplified to M_t/M_o because of the value of equilibrium moisture content M*e* is very small compare to M_t and M_o.

The drying rate (DR) of coriander leaves was calculated using Equation (2):

$$\text{DR} = \frac{M_{t1-}M_{t2}}{t_2 - t_1} \quad (2)$$

where t_1 and t_2 are drying times (h); M_{t1} and M_{t2} are moisture content of the samples at (g water/g dry matter/h) at time 1 and time 2, respectively.

Several researchers attempted different empirical models to predict the moisture content of agricultural products as a function of drying time. The mathematical model of Lewis, modified Page, and Midilli and Kucuk [5] represented by Equations (3), (4), and (5), respectively were selected in this study

$$MR = \exp(-Kt) \quad (3)$$

$$MR = \exp\left|-(Kt)^n\right| \quad (4)$$

$$MR = a\ exp(-Kt^n) + bt \quad (5)$$

2.4. Effective Moisture Diffusivity

Moisture diffusivity is used to represent the movement of moisture within a material and is primarily impacted by the moisture content and temperature of the material [18]. The moisture diffusivity of infinite slab is described by Equation (6) [19]. By assuming that there is uniform initial moisture distribution, the surface is at equilibrium with the drying air, and constant moisture diffusivity and shrinkage is negligible, we obtain Equation (7).

$$\frac{\partial M}{\partial t} = \nabla\left[D_{eff}(\nabla M)\right] \quad (6)$$

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left(\frac{(2n+1)^2\pi^2 D_{eff} t}{4L^2}\right) \quad (7)$$

D_{eff} is the effective moisture diffusivity (m^2/s), *t* is the time (min), L denotes half-thickness of samples (m), and n is a positive integer. Moreover, for long drying periods, the above equation can be simplified to the only first term of series:

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

From Equation (8), a plot of ln *MR* versus drying time give a straight line with a slope (K) of

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad (9)$$

2.5. Color Measurements

Fresh and dried coriander leaf color was measured with a portable colorimeter (3nh Precision Colorimeter, NR110, Shenzhen, China) using a white standard and equipped with the D65 illuminant. The color values were assessed in terms of the coordinates L*, a*, and b*. The total color differences (ΔE), the change between fresh and dried coriander leaves (Equation (10)), chroma, which stands for color intensity (Equation (11)), and hue, which stands for color purity (Equation (12)) [20] were also determined. The dark green color index (DGCI) values provided a more reliable estimate of green color. (Equation (13)) [21]. The measurement was performed 5 times for each drying process.

$$\Delta E = \sqrt{\Delta a*^2 + \Delta b*^2 + \Delta L*^2} \tag{10}$$

$$Chroma = \sqrt{a*^2 + b*^2} \tag{11}$$

$$Hue = tan^{-1}\left(\frac{b*}{a*}\right) \tag{12}$$

$$DGCI = \frac{\left[\frac{Hue-60}{60} + (1 - chroma) + (1 - L^*)\right]}{3} \tag{13}$$

2.6. Measurement of Water Activity (Aw)

The water activity of both fresh and indirect solar-dried coriander leaves was measured using a water activity meter (Model: 10972, HygroLab C1, Rotronic, Bassersdorf, Switzerland).

2.7. Measurement of Total Phenol Content

The TPC of fresh and indirect solar-dried coriander leaves was determined according to Singleton and Rossi [22] using Folin–Ciocalteu assay. The sample was prepared by dissolving 10 g of the powdered material in 70 mL of ethanol, and then ultrasonic processing the solution for 30 min. The sample was then filtrated using 0.45 mm microfiltration. A 100 dilution ratio was used to dilute the crude material that was extracted. Folin–Ciocalteau reagent was then added to the diluted sample in a ratio of (1:1). After that, 2 mL of 20% of sodium carbonate solution was added and the mixture was heated for 5 min using boiling water. The absorption of prepared sample was then measured at 650 nm using UV/vis spectrometer (Thermo Scientific Fluoroskan Ascent FL, Waltham, MA, USA). The sample was analyzed in triplicate. Caffeic acid was used as a standard and, thus, the results expressed as mg CAE/100 g dry matter.

2.8. Measurement of Total Antioxidant Capacity (TAC)

The TAC of fresh and indirect solar-dried coriander leaves was measured using Colorimetric Assay Kit (Cat. No.: E-BC-K136-S), which contained 0.2 mL Cu^{2+} reagent, 10 mL assay diluent, 10 mL protein mask, and 1 µmol Trolox standard [5].

2.9. Statistical Analysis

Data analyses were performed using SPSS 20.0 (International Business Machine Crop., Armonk, NY, USA). The impact of experimental variables, i.e., drying methods (indirect solar, direct sun, shade drying) and seasons (winter, and summer), were assessed by performing mean values, which were considered at 5% significance level. Regression analyses such as coefficient of determination (R^2) (Equation (14)), chi-square ($\chi 2$) (Equation (15)), and root-mean-square error (RMSE) (16) were performed as a primary standard to select the best fit of the tested experimental data. The adequately fitted quality parameters were determined with the highest R^2 and lowest X^2, and RMSE.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(MR_{Pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{n}\left(MR_{Pre} - MR_{exp,i}\right)^2} \tag{14}$$

$$X^2 = \sum_{i=1}^{n} \frac{\left(MR_{exp,i} - MR_{Pre,i}\right)^2}{N - n} \quad (15)$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{1}{N} \left(MR_{exp,i} - MR_{Pre,i}\right)^2} \quad (16)$$

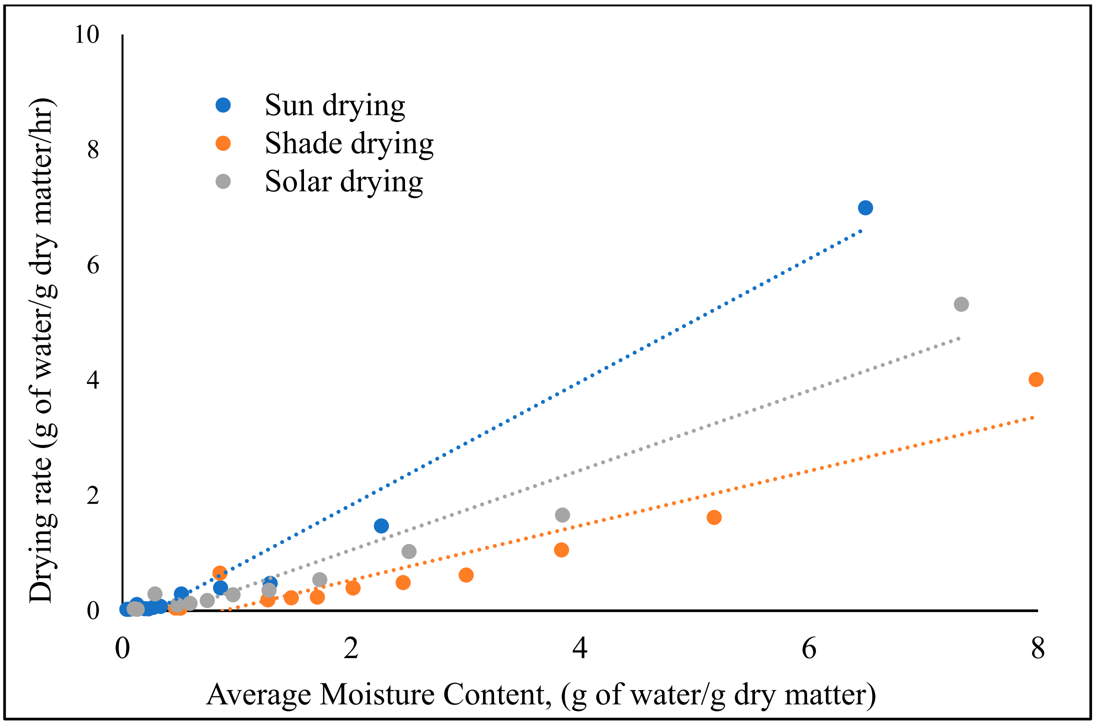
2.10. Result and Discussion

Since the summer season experiences higher levels of sun radiation than winter ones, coriander leaves dry more quickly. The average temperature increase from the solar collector to the dryer chamber was 10 °C. The maximum temperature reached by the drying chamber was 50.8 °C, whereas the maximum temperature of the solar collector was 65.0 °C. The indirect dryer maintained the chamber temperature in the range of 30–50 °C with relative humidity less than 50%.

2.11. Drying of Coriander Leaves

The study shows that moisture is removed across all drying processes for coriander leaves (Figure 2). The most weight loss is experienced by coriander during direct sun drying. A crucial variable in the production of dried leaves is the drying rate. On the kinetics of moisture removal from coriander leaves, there is only limited information available in literature. The effect of three drying methods on the drying rate of coriander leaves was evaluated. The drying rate of leaves is a function of moisture content. Using the drying data, the drying rates were predicted by estimating the change in moisture content, which occurred during each successive time interval and was expressed as g water/g dry matter/h. In Figure 2, the variations of the drying rates in relation to moisture content for winter and season are displayed. It is likely that the drying rates are higher at the beginning of the process due to evaporation and moisture from the surfaces of coriander leaves, while the rates decrease with decreasing moisture content, for all drying conditions, once moisture diffusion controls the drying process. There is no constant rate of drying period, as shown by the curves in Figure 2. The drying occurs throughout under the falling rate of drying period. Internal mass transfer is the main form of mass transfer in the sample during the period of falling drying rates. The generation of internal heat may be the reason of the faster drying rates. Being a leafy material and because a thin layer of product does not give a steady supply of water for an applied amount of time may be the reason of the absence of a constant drying rate period. Additionally, if the product on the surface shrinks, there may be some resistance to the movement of water, which significantly slows down the drying process. In the initial stage of drying, open sun temperature might have increased the sample's temperature and improved drying rates. It is observed that shade drying is the slowest process. It is because drying was carried out under shade and there is no exposure to a steady flow of hot air [23].

To determine the relationship between drying rate and hourly mean moisture content, a linear regression analysis was performed (Table 1). Coefficients of determination (R^2) are in the range of 0.8872 and 0.9987. These findings show that coriander leaves thin-layer drying occurs mainly in the falling rate period.



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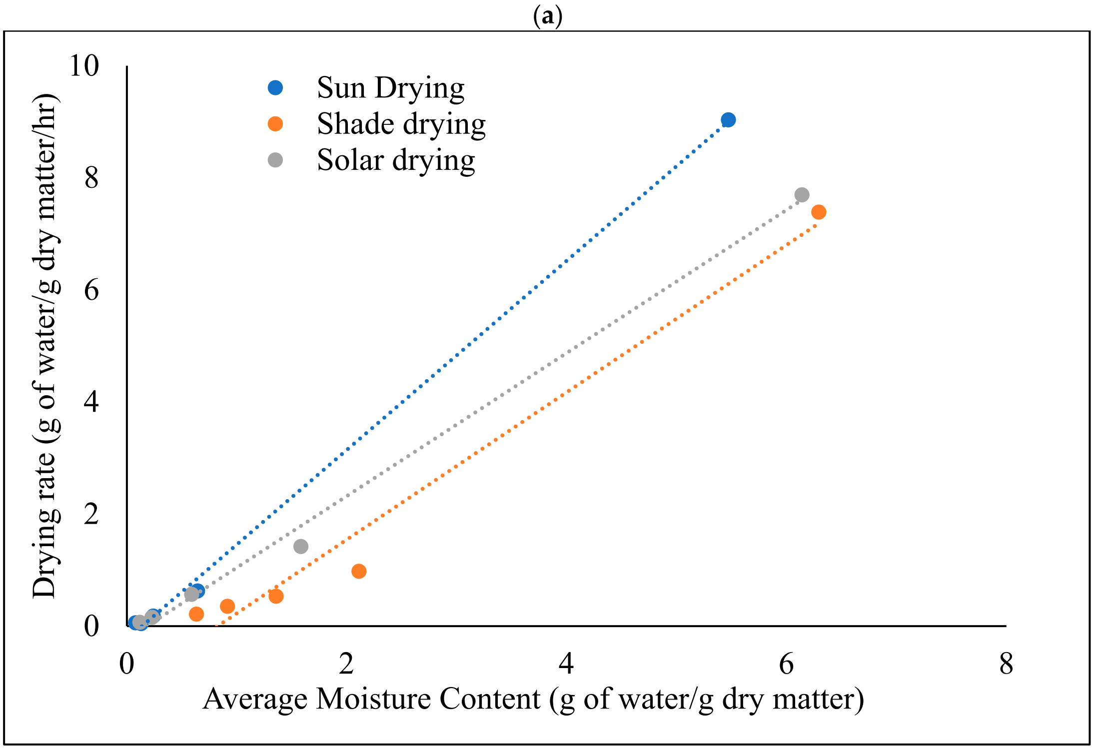

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Figure 2. Effect of moisture content on the drying rate for coriander drying during (**a**) winter and (**b**) summer seasons.

Table 1. The relationship between drying rate D_R and moisture content M of coriander leaves [$D_R = aM + b$].

Season	Drying Method	Drying Coefficient		Coefficient of Determination
		a	b	R^2
Summer	Sun drying	1.6882	−0.2312	0.9987
	Shade drying	1.3141	−1.0828	0.9777
	Indirect solar drying	1.277	−0.2336	0.9958
Winter	Sun Drying	1.0678	−0.2979	0.9720
	Shade drying	0.4738	0.4183	0.8872
	Indirect solar drying	0.6911	−0.3257	0.9421

3. Drying Kinetic Models

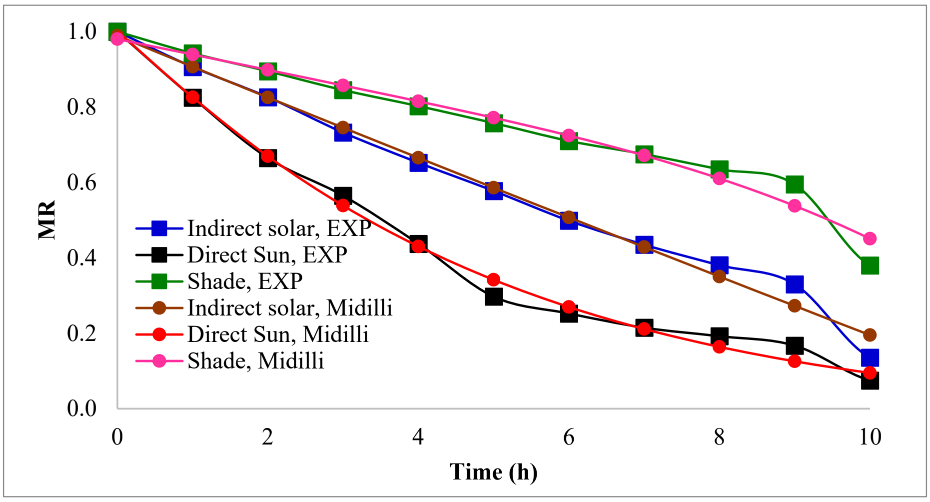
In experiments conducted in winter and summer, comparisons were made with coriander dried using three different methods; developed indirect solar dryer, direct sun drying, and shade drying. A declining moisture ratio is observed for the best three models that obtained leafy vegetables (Table 2). Figure 3 shows that the best fitting model for coriander drying is Midilli–Kucuk in both the winter and summer seasons. As shown in Table 2 the best model has higher R^2 of 0.99832, 0.98983 and lower X^2 of 2.01×10^{-4}, 5.76×10^{-4} and a RMSE of 1.50×10^{-4}, 6.97×10^{-4} in summer and winter, respectively. Furthermore, coriander resembles the Midilli–Kucuk and the modified Page models when dried in the sun and shade. In addition, Figure 3a shows a different slope in moisture ratio after 9 h due to the fact that the experiment was stopped at 6:00 p.m. and started again the next day at 8:00 a.m. Also, Figure 3b shows that the summer drying is faster than winter because of the higher ambient temperatures. Summer drying took 2.5 h and winter took more than 10 h to reach the expected moisture content. Most of the food herbs best resemble the Midilli–Kucuk mathematical model and show a good agreement between predicted and experimental results. Thus, the moisture content at any time during the drying process could be reliably estimated.

3.1. Moisture Diffusivity

The primary mechanism for removing moisture from food products during drying is diffusion. In the falling rate period, moisture diffusion determines the rate of drying, and an increase in effective diffusivity is an indication that the material being dried has less resistance to mass transfer [24]. The average values of effective moisture diffusivities involved during three drying processes of coriander leaves are illustrated in Table 3. The highest effective moisture diffusivity values obtained are 2.63×10^{-10} and 1.05×10^{-10} m^2/s under open sun drying for the summer and winter seasons, respectively. The value ranges from 1.31×10^{-10} and 6.57×10^{-11} m^2/s for the summer and winter season, respectively, under indirect solar drying. Shade drying shows the lowest values for moisture diffusivity for both seasons. Moisture diffusivity values obtained from these processes fall within the general range (10^{-12} to 10^{-8} m^2/s) for agricultural and food products. These values are also comparable to those for leafy herbs that have been reported, for example, coriander leaves [25], rosemary leaves [26], and peppermint leaves [9].

Table 2. Model parameters and statistical analysis of resembled drying kinetic models for coriander leaves.

Season	Model	Drying Method	Parameters				Coefficient of Determination R^2	Chi-Square, χ^2	Root-Mean-Square Error, *RMSE*
			a	k	n	b			
Summer	Lewis	Indirect solar		−0.796			0.96111	3.39×10^{-3}	3.39×10^{-3}
		Direct sun		−1.247			0.99810	1.74×10^{-4}	1.74×10^{-4}
		Shade		−0.384			0.99626	1.87×10^{-4}	1.87×10^{-4}
	Modified Page	Indirect solar		0.784	1.442		0.99782	2.62×10^{-4}	1.99×10^{-4}
		Direct sun		1.256	0.9651		0.99832	1.82×10^{-4}	1.53×10^{-4}
		Shade		0.372	0.9335		0.99745	1.50×10^{-4}	1.27×10^{-4}
	Midilli and Kucuk	Indirect solar	0.996	0.734	1.527	0.013	0.99832	2.01×10^{-4}	1.50×10^{-4}
		Direct sun	1.000	1.327	1.056	0.013	0.99905	1.03×10^{-4}	8.49×10^{-4}
		Shade	0.996	0.393	0.943	0.000	0.99638	1.47×10^{-4}	1.24×10^{-4}
Winter	Lewis	Indirect solar		−0.128			0.94954	4.23×10^{-3}	4.23×10^{-3}
		Direct sun		−0.217			0.99064	7.46×10^{-4}	7.46×10^{-4}
		Shade		−0.067			0.96125	3.72×10^{-3}	3.72×10^{-3}
	Modified Page	Indirect solar		0.134	1.401		0.97951	2.01×10^{-3}	1.78×10^{-3}
		Direct sun		0.215	1.094		0.99340	5.89×10^{-4}	5.35×10^{-4}
		Shade		0.084	1.500		0.97912	2.36×10^{-3}	2.06×10^{-3}
	Midilli and Kucuk	Indirect solar	0.989	−0.004	1.243	−0.087	0.98983	5.76×10^{-4}	6.97×10^{-4}
		Direct sun	1.001	0.190	1.061	−0.002	0.99307	5.38×10^{-4}	5.25×10^{-4}
		Shade	0.980	0.000	4.816	−0.041	0.98374	1.42×10^{-3}	8.50×10^{-4}



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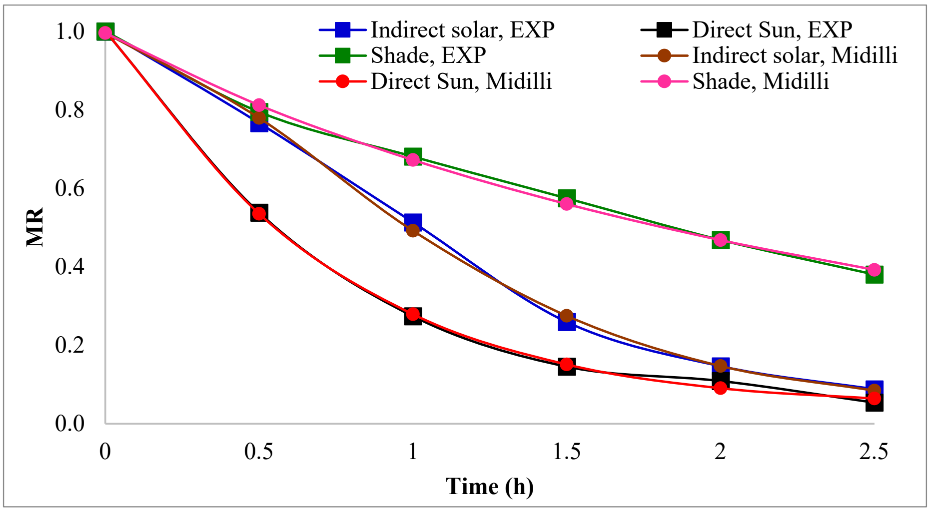


(**b**)

Figure 3. Drying kinetic models for coriander drying during (**a**) winter and (**b**) summer seasons.

Table 3. Effective diffusivity for coriander leaves under different drying.

Drying Method	**Effective Moisture Diffusivity, m^2/s**	
	Summer Season	**Winter Season**
Sun drying	2.63×10^{-10}	1.05×10^{-10}
Shade drying	6.57×10^{-11}	3.94×10^{-11}
Indirect solar drying	1.31×10^{-10}	6.57×10^{-11}

3.2. Physicochemical Quality Parameters

The physicochemical quality of dried coriander leaves was assessed by measuring color, water activity, phenol content, and antioxidants.

3.3. Color Parameters Change

The color parameter is considered to be a crucial indicator of the herbs' quality. Color parameter changes in dried coriander leaves during the winter season are shown in Figure 4. In this study, indirect solar drying of coriander leaves shows good color retention. There is a statistically significant difference ($p < 0.05$) in the change in color parameters, for L*, a*, b*, chroma, and dark green color index (DGCI) values for the independent variables (time and drying methods) used to dry coriander herb. The independent variables (time and drying methods) used to dry coriander herb show a significant difference in color parameters change for L*, a*, b*, chroma, and dark green color index (DGCI) values ($p < 0.05$). However, there is a significant difference between drying time and hue values ($p < 0.05$). Indirect solar drying shows less degradation than other methods (Figure 4). Indirect solar, direct sun, and shade drying all result in a reduction in the lightness of 26%, 121%, and 19%, respectively. Moreover, the drying process influences the green color value of all drying methods, but the indirect solar dying has less effect, and the greenish color changes from −7.22 to −0.056, −7.22 to 3.15, and −7.22 to −0.35 in indirect solar, direct sun, and shade drying, respectively. Also, the yellow color value is diminished by 30% in indirect solar drying, 36% in direct sun drying, and 27% in shade drying. Also, in general, the drying process affect the green color value of dried coriander leaves; however, indirect solar drying has the least impact, changing from −7.22 to −0.056, −7.22 to 3.15, and −7.22 to −0.35 for indirect solar, direct sun, and shade drying, respectively. Direct exposure of leaves to sun radiation results in the leaves being less green in color. Indirect solar drying reduces the yellow color value by 30%, direct solar drying by 36%, and shade drying by 27%. Chlorophyll in plants is made up of a combination of the blue–green chlorophyll and the yellow–green chlorophyll [27]. Thus, the reduction in b* values is attributed to chlorophyll. In addition, indirect solar drying decreases the color and chroma by 12% and 32%, respectively. As a result, the color difference between direct sun drying and indirect solar drying indicates a huge change. During the summer season, a similar trend is observed with dried coriander leaves (data not shown). As mentioned, degradation of chlorophyll may be the cause of color variations in coriander leaves. Chlorophyllase is involved in an enzymatic reaction that leads to the breakdown of chlorophyll [28]. The results of the current study are consistent with those of Yilmaz et al. [29], who find that drying temperature, light, and airflow all have an impact on color reduction. This result is comparable with the color measurement results of coriander color change during the different drying processes [30].

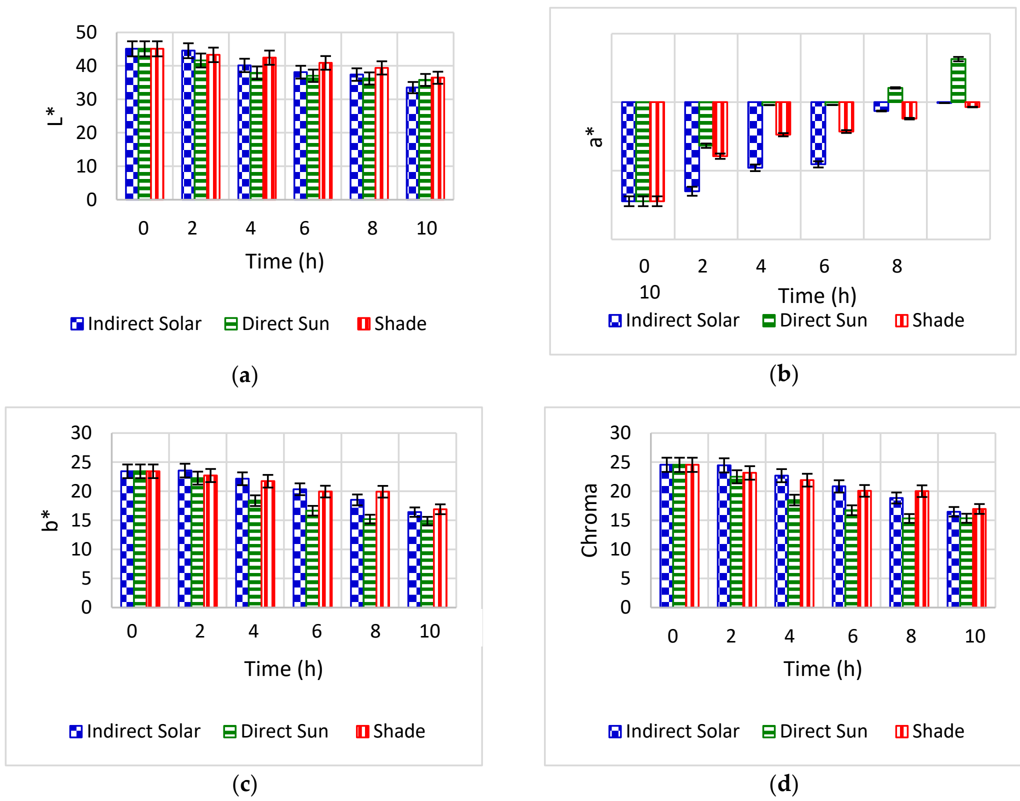
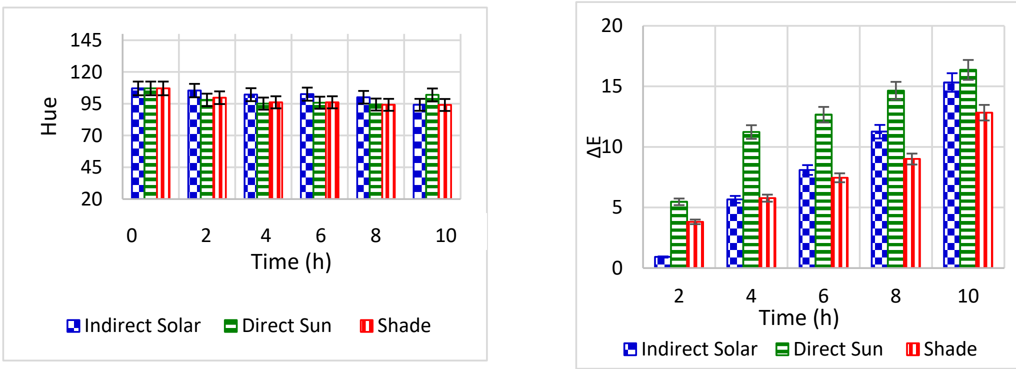


Figure 4. *Cont.*



(e) (f)

Figure 4. Coriander color parameters: (**a**) L*: lightness, (**b**) a*: (+) redness/(−) greenness, (**c**) b*: (+) yellowness/(−) blueness, (**d**) chroma, (**e**) hue, and (**f**) color difference degradation during indirect solar-drying (n = 5).

The Maillard process [31] and the reaction of caramelization during drying [32] both cause a reduction in the L* value, which results in a decrease in luminous intensity, and is symbolized by an increase in the total color difference. Due to direct sun exposure in open sun drying, which causes the leaves to turn a lighter shade of green, it is found that solar-dried samples display a smaller change in color than direct sun-dried samples [33]. Similar findings for forced convection solar dried stevia leaves were reported by Lakshmi et al. [33].

The DGCI for coriander is degraded in all drying methods (Figure 5) but the direct sun shows a clear change in early drying time.

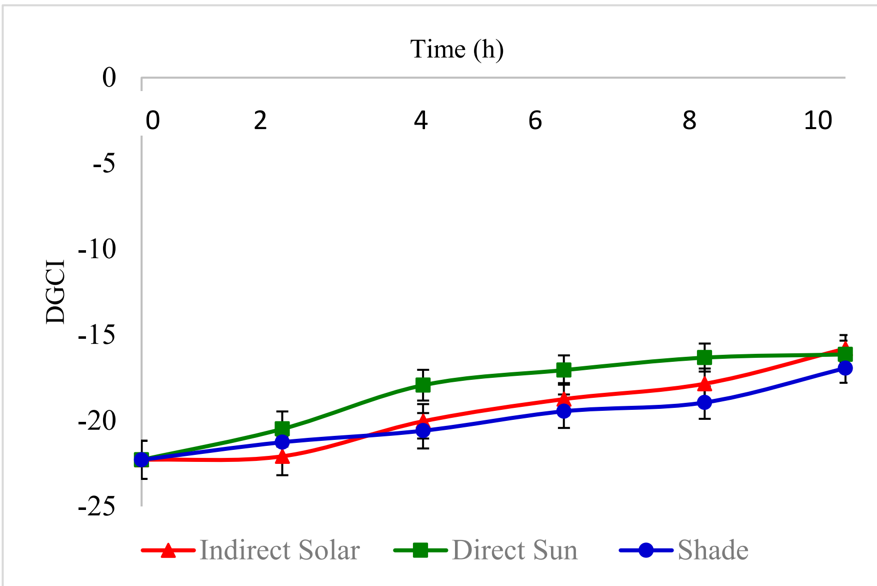


Figure 5. Coriander dark green color index (DGCI) degradation during different dying methods (n = 5).

3.4. Water Activity

Water activity is a highly reliable indicator for food preservation and of microorganism growth and spoilage of dry food products. After the drying process, the A_W of coriander is 0.61 and 0.45 in winter and summer, respectively (Table 4). The resulted value was compared with the initial A_W for coriander leaves (0.93). Molds, yeasts, bacteria, and other microorganisms have a major impact on the quality of food products when water activity is greater than 0.7 [34]. The dissolution of soluble components (mainly carbohydrates) causes the moisture content to rise as the water activity rises. The water activity result in this study is within the permissible limits for microbial growth, enzymatic browning, and non-enzymatic browning.

Table 4. Physiochemical properties of coriander leaves.

Drying Condition	Physiochemical Properties		
	Water Activity (Aw)	Total Phenol Content (mg Caffeic Acid/100 g Dry Matter)	Antioxidants μmol Trolox/g Dry Matter
Fresh	0.93 ± 0.00	365.44 ± 0.18	0.22 ± 0.67
Indirect solar-dried (Winter)	0.61 ± 0.00	577.97 ± 0.15	3.41 ± 2.11
Indirect solar-dried (Summer)	0.45 ± 0.02	852.00 ± 2.29	3.53 ± 0.83

3.5. Total Phenol Content

Table 4 shows the TPC found for indirect solar-dried coriander leaves. It is evident that the TPC increases as the temperature increases. The value of phenol content increases from 365 to 852 mg caffeic acid/100 g dry matter for coriander. The fresh product has the lowest total phenolic concentration. A dry product that weighs the same as a fresh product has around six to seven times more concentrated phenol than fresh since the water in the product evaporates during drying, increasing the concentration of the product. The increase in total phenolics could be attributed to the process's liberation of phenolic chemicals from the matrix. Drying could have expedited the release of more bound phenol compounds from cellular constituent breakdown [35,36]. Jimenez-Garcia et al. [12] evaluated the phenolic content of fresh and thyme dried by convective and microwave drying methods. The findings are in agreement with this study. Additionally, Xylia et al. [37] found that different heat treatments increased the total phenol content of rosemary. Higher values of the TPC may have resulted from the breaking of the phenolic sugar glycosidic bonds and the creation of phenolic aglycons as a result of the moderate heat treatment (50 °C) used by a solar dryer [22].

3.6. Antioxidant Capacity

The antioxidant content of dried coriander leaves in indirect solar drying increased in both seasons (Table 4). The antioxidant capacity reaches 3.41 and 3.53 μmol Trolox/g dry matter for the winter and summer seasons, respectively. Dried herbs have higher antioxidant activity than fresh herbs. In comparison to fresh samples, dried leafy vegetables have a higher antioxidant content, which may be because drying increases phytochemicals. Due to the decreased water activity, enzymes are rendered inactive, retaining their high antioxidant capability in the dried samples. When compared to fresh stevia leaves, dried leaves have significantly higher antioxidant levels [33]. Oboh et al. [38] examined the reduced property and free radical ability of fresh and dried green leafy vegetables. The reducing property of the vegetables was assessed by their capacity to convert Fe (III) to Fe (II).

4. Conclusions

This study investigated the potential use of a stand-alone indirect solar dryer using the black-body radiation concept in drying coriander leaves in Oman. Two other methods were used in this study for comparison: direct sun and shade drying. The drying of coriander leaves falls under falling rate of drying period. The Midilli and Kucuk model could adequately describe the drying of coriander leaves. The effective moisture diffusivity varies between 1.05×10^{-10} m^2/s and 6.57×10^{-11} m^2/s. Indirect solar drying shows less change compared to direct sun and shade drying, although the color characteristics change negatively with drying time for all drying techniques. The color parameters a*, chroma, and dark green color index values receive the most attention as they demonstrate the conservation of the herbs' green color and, consequently, their physicochemical qualities.

Water activity reduction in coriander leaves for the winter and summer is 0.61 and 0.45, respectively. The numerical value of antioxidant capacity is found to be 3.41–3.53 µmol Trolox/g dry matter. This low-cost, stand-alone, renewable-energy-powered drying concept can be used for small-to-medium-sized enterprises in Oman by taking into account the potential contamination with dust and insects under sun or shade drying, and also considering the freely available solar radiation in the region.

Author Contributions: H.J.: Conceptualization, supervision, resources, monitoring and guiding analysis, review and editing, funding acquisition. P.B.P.: Supervision, resources, formal analysis, guiding analysis, writing the original draft, review and editing. Z.A.-A.: Supervision, resources, guiding analysis, review and editing. A.A.-H.: Data collection, investigation, formal analysis. All authors have read and agreed to the published version of the manuscript.

Funding: We would like to thank Sultan Qaboos University for their financial support under the internal grant project with code: IG/AGR/SWAE/20/01.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: Help rendered during the construction of the dryer and conducting experiment by Saif Al-Adawi, Mohammad Al-Balushi, and Intisar Al-Zakwani is thankfully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

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