

Thin layer solar drying of Moroccan carob pulp (*Ceratonia Siliqua L.*)

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Abstract. Most biological products are highly perishable, so the issue of their conservation during large transportation distances and storage is a sensitive problem. Solar drying is the most useful method of keeping food stuff safe in terms of both energy and time. Our work aims to contribute to the optimization of solar convective drying at the pulp of carob widely produced in Morocco by an experimental approach in an indirect forced convection solar dryer. In this paper, the effect of air temperature on the drying kinetics of carob pulp was investigated in convective solar drying. The relative humidity of air was varied from 15% to 45.5%. This kinetic measurement is carried out at four temperature values of drying air (50, 60, 70 and 80 °C) and also for one value of drying air flow rate D_v ($0.0833 \pm 0.002 \text{ m}^3 \text{ s}^{-1}$). Four models have been used to adjust experimental curves. In conclusion, the experimental study shows that solar drying is adapted for the valorisation of carob pulp. Middili & Kucuk model is the most appropriate to describe drying curves in various drying conditions.

1. Introduction

Carob tree (*Ceratonia siliqua, L.*) is native vegetation in the Mediterranean area; it is mainly in human and animal nutrition. This tree is mainly grown in Italy, Spain, Portugal, Greece and Morocco, considered as the principal producers of carob in the world [1]. Traditionally, the seeds of the pods are used to obtain the carob gum and the pulp is quite rich in sugars [2].

Nowadays, the carob constituents are used for many applications in the food, pharmaceutical and cosmetics industries, with particular interest in locust bean gum made from seeds. Carob pulp contains high levels of sugars, particularly low molecular weight carbohydrates, such as sucrose, therefore is considered as a good source of potential energy for animal feed. In addition, the carob pulp is characterized by a protein content and very low fat content. However, carob pulp has a favorable fatty acid composition due to the presence of essential fatty acids and may be a natural source of acids [3].

The drying of foods is a very important method for the food industry and offers possibilities for novel products to consumers. In recent years, there have been many advances in food drying technology, including pre-treatments, techniques, equipment, energy efficiency and quality.

Drying is among the most ancient method of food preservation. It is aimed at lowering the water content of foodstuff and is used predominately for foods such as fruits, vegetables, spices and other products with a high moisture content, and ones which are considered highly perishable [4]. Dried foods offer multiple benefits including: extended product shelf-life, reduced packaging, storage, handling and transportation.

Energy consumption, in drying industry, is a major problem, because over 85 % of industrial dryers are convective type with either hot air or combustion gases [5]. Being a complex phenomenon involving



simultaneous heat and mass transfer, the process of drying is energy intensive and accounts for roughly 12 to 20 % of energy consumed in the industry sector [6].

Dried product nutritional quality is another major concern. With conventional drying methods using conductive and convective modes of heat transfer, final product preserves its quality and the probability of product contamination is low [4]. For this reasons, over recent years, there has been significant technological advancement in food drying in terms of drying pre-treatments, techniques, equipment and quality [7,8]. These works address the growing need to find an improved solar drying technique to preserve the quality of the end product at improved utilization of energy.

According to many studies [9] which focused on drying of biological products, it has been noted that it is difficult to find a mathematical model governing the evolution of the products during drying. For this reason, only an experimental study allows to determine their drying kinetics. Therefore, it seems useful to study variations of moisture content and those of the drying rate versus time, for different controllable drying parameters, using an indirect solar dryer operating in forced convection. This study is a contribution in the valorization of carob pulp, by using solar energy which is abundant in Morocco.

The aims of this experimental study were to:

- Study the drying kinetics of carob pulp in a convective solar dryer;
- Determine the effects of drying air temperature on the drying kinetics of carob pulp;
- Determine the appropriate model to fit the experimental curves.

2. Material and methods

2.1. Description of the solar dryer

In this study, the experimental approach that consists of determining the kinetic behavior of carob pulp, dried in a thin film solar dryer has been conducted. The experimental set-up, installed at the laboratory of the “Ecole Normale Supérieure” of Marrakesh (Figure 1), was described in detail in the reference [10]. This is mainly an indirect forced convection solar dryer. The components of the dryer are:

- A single solar collector with single glazing, 2.5 m² surface, inclined 30° from the horizontal plane and facing south. The dimensions of the collector are 2.5 m long and 1 m wide. The absorber is opaque in 0.5 mm thick black galvanized iron sheet with a non-selective surface. The rear thermal insulation is 0.05 m thick polyurethane foam sandwiched between two steel sheets. The absorber-insulator distance is 0.025 m and the absorber-to-glass distance is 0.02 m;
- An aspirating aeraulic channel constituted of tunnel whose section parallelepiped;
- A drying chamber consists of ten floors in trays;
- A centrifugal fan to circulate the air inside the dryer;
- A thermo-regulator with a precision range between 0-100 °C, connected to a PT100 platinum to measure drying temperature;
- Electrical resistances with 4 kilowatts of power acting as auxiliary source.

2.2. Experimental protocol

It is noted that drying is carried out under the controlled conditions of temperature and the flow rate of drying air. Indeed, the mass of the carob, comes from the region of Marrakesh (Morocco), used in drying experiments was (40 ± 1) g. They are spread in thin layers on trays in the drying chamber. Samples are uniformly and evenly distributed to ensure homogeneity of diffusion during the drying process.

The variation of the wet mass of the product $M_h(t)$ versus time was determined by a digital weighing apparatus (± 0.1 g).

The duration of manipulations between the preparation of the product, loading the dryer and start-up of measures must be reduced to a minimum level; the evaporation phenomenon of pulp slices takes place very quickly due to the existence of the vapor concentration gradient between the product surface and the atmosphere.

During each drying experiment, the product mass on the tray was measured by removing it from the drying chamber for approximately thirty seconds. These measures were undertaken each 10 min at the

beginning of the experiments until 30 min toward the end of the tests. Then, the temporal evolution of the wet mass $M_h(t)$ of the product to dry has been tracked by successive weighings until it becomes stationary. This is followed by the dehydration of the product, at the end of each experimental test; in an oven whose temperature was fixed at 105 °C during 24 h in order to determine the dry mass M_d of product [11]. Throughout all the experiments, the temperature and the air flow drying rate are fixed. The water content in dry basis is defined by:

$$X(t) = \frac{M_h(t) - M_d}{M_d} \times 100 \quad (1)$$

Were:

$X(t)$: Water content of the product during the experiment (% dry basis);

$M_h(t)$: Wet mass of the product in a specific moment (g);

M_d : Dry mass at the end of the experiment (g);

t : Drying time (min).

Table. 1 Drying conditions during experiments in the solar dryer

Experiment	D_v (m ³ /s)	Drying temperature $\Theta \pm 0.1$ (°C)	Air humidity $R_h \pm 2\%$
1	0.0833	50	15
2	0.0833	60	30.5
3	0.0833	70	45.5
4	0.0833	80	16.5

The different experimental experiments consisted in studying the independent influence of the drying air temperature on the drying process.

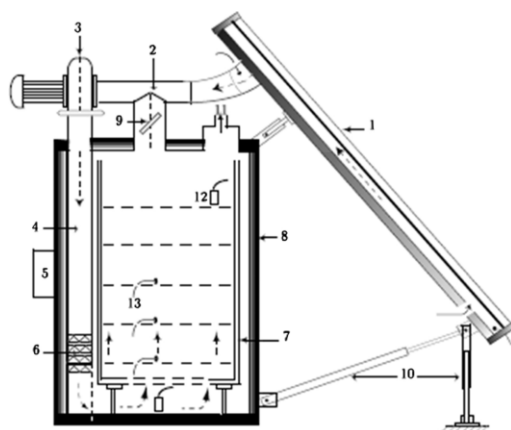


Figure. 1 Schematic diagram of the solar dryer: (1) Solar collector, (2) circulation fan, (3) fan, (4) air flow direction, (5) control box, (6) auxiliary heating system, (7) shelves, (8) drying chamber, (9) recycling air, (10) control foot, (11) exit of air, (12) humidity probes and (13) thermocouples

2.3. Modelling of drying curves

A literature review shows that several models have been developed to describe the drying process. They can be classified into two main categories corresponding to two different approaches, namely (i) phenomenological models arising from theoretical approach of the transport modes (diffusion, diffusion-sorption, and capillarity) and (ii) behavioral models reflecting a macroscopic approach to the problem.

In order to determine the most appropriate empirical equation to describe the shape of drying carob pulp from Marrakesh, four models were chosen: Newton, Page, Logarithmic and Middili & Kucuk. The most appropriate model was selected by the following statistical criteria [10]:

- Correlation coefficient (R);
- Mean bias error (MBE);
- Chi-square (χ^2).

These coefficients were defined by:

$$R = \sqrt{\frac{\sum_{i=1}^N (X_{pre,i}^* - \bar{X}_{exp,i}^*)^2}{\sum_{i=1}^N (X_{exp,i}^* - \bar{X}_{exp,i}^*)^2}} \quad (2)$$

$$MBE = \frac{1}{N} \sum_{i=1}^N (X_{pre,i}^* - \bar{X}_{exp,i}^*) \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^N (X_{pre,i}^* - \bar{X}_{exp,i}^*)^2}{N - n} \quad (4)$$

Where:

X_{exp}^* is the experimental value of reduced moisture content;

X_{pre}^* is the predicted value of reduced moisture content;

\bar{X}_{exp}^* is the average of experimental reduced moisture values;

n is the number of model parameters;

N is the number of conducted experiments.

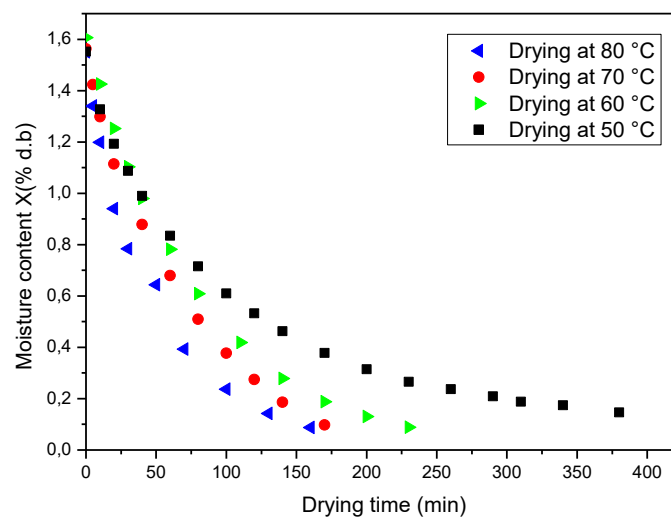
3. Results and discussion

Different experimental drying conditions are presented in the Table 1. Drying experiments have been conducted for four temperature values of drying air (50 ± 0.1 °C, 60 ± 0.1 °C, 70 ± 0.1 °C and 80 ± 0.1 °C) and for one value of drying air flow rate D_v (0.0833 ± 0.002 m³.s⁻¹). The initial moisture content of the carob pulp ranged from 1.5508 % to 1.6065 % g water per g dry basis and was reduced to the final moisture content, which varies from 0.0887% to 0.1246% g water per g dry basis.

Table. 2 Drying time during experiments in the solar dryer

Experiment	t (min)
1	380
2	230
3	170
4	160

Figure 2 illustrates the changes in moisture content versus drying time. As shown in Figures 2 and 3, it was noted the presence of one drying phase in the drying curves of carob pulp. However, in this phase the acquired energy was used to evaporate water from the product and to increase its temperature. This effect is represented by the decrease in the drying rate [10]. As is showed in Table 2 we noted a small difference in drying time between 70 °C and 80 °C (decreasing of 10 min), so we can neglect the influence of air drying temperature for temperatures higher than 70 °C.

**Figure. 2** Variation of moisture content versus drying time for different drying air conditions

As it can be seen from Figure 2, the drying air temperature is influencing the drying kinetics of pulp during the falling drying rate period, at the same flow rate of drying air.

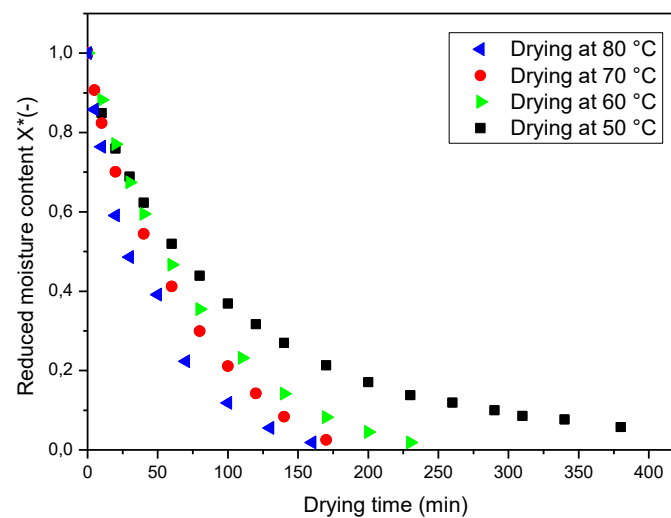


Figure. 3 Evolution of the reduced water content of the carob pulp as a function of the drying time for different drying air temperatures

An increase in drying air temperature resulted in a decrease in drying time. Indeed, as for the majority of porous hygroscopic products several investigators reported considerable increases in drying time when higher temperatures were used for drying various vegetables such as *Citrus aurantium* leaves [12], Prickly pear fruit [13], and *Eucalyptus* globules [14].

Indeed, an increase of drying temperature leads to an acceleration of the drying process. This is due to the increase in the gap between the partial pressures of water vapor on the surface of the product and that of the drying air, which favors the evaporation of the water contained in the product.

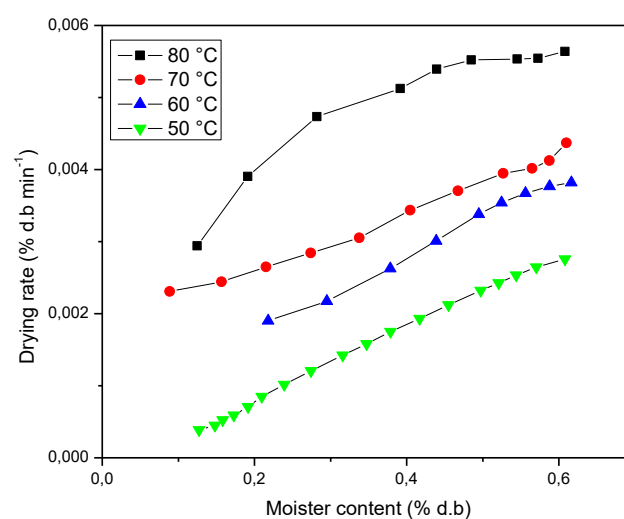


Figure. 4 Influence of drying air temperature on drying rate of Carob pulp at a fixed drying air flow rate $0.0833 \text{ m}^3\text{s}^{-1}$

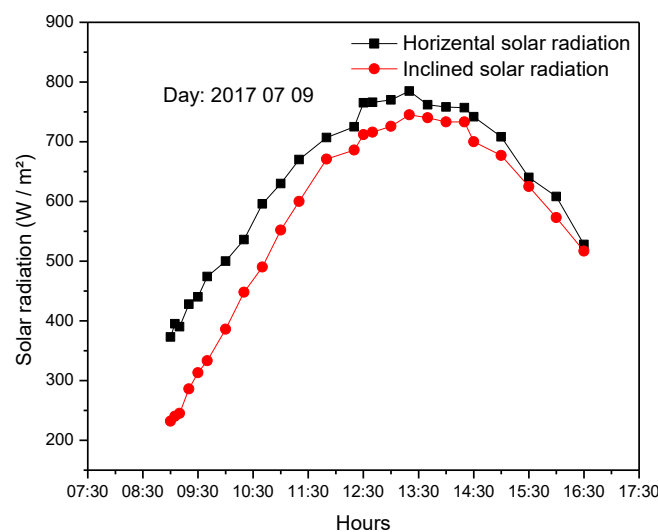


Figure. 5 Variations of horizontal and inclined solar radiation in Marrakesh

Thus, the drying rate evolution is presented in the Figure 4 for the four tests. This figure shows that for the same drying air flow rate, the drying rate increases with increase of the drying temperature values and hence the water content of the carob pulp decreases considerably. It is clear that the drying rate decreases continuously with moisture content and drying time.

There is no constant rate drying period in these curves, and all the drying process was seen to occur in the falling drying rate period. This shows that diffusion is the dominant physical mechanism governing moisture movement in the samples. Similar results were obtained by Kaymak-Ertekin [15] of green and red peppers, Madamba et al. [16] of garlic slices and Midilli et al. [17] of mushroom and pollen.

The solar collector of the experimental dryer is inclined with an angle of 30° . The variations of solar radiation in horizontal and surface of the collector is presented in Figure 5. The measurements are undertaken between 9:00 AM and 16:30 AM (Friday 09 July 2017) in Marrakesh city where the drying of carob pulp is processed. The horizontal solar radiation is higher than the inclined one as is presented in Figure 5.

Indeed, Table 3 shows that the Midilli and Kucuk model offers the best correlation with experimental curves of reduced moisture content (X^*) with the highest value of R and the lowest values of χ^2 and MBE.

Table. 3 Modeling of drying curves and average statistical parameters

Model	θ ($^\circ\text{C}$)	Parameters	R	X^2	MBE
Newton	50 $^\circ\text{C}$	$k=0.0098$	0.9975	0.00085	0.02222
	60 $^\circ\text{C}$	$k=0.01335$			
	70 $^\circ\text{C}$	$k=0.01595$			
	80 $^\circ\text{C}$	$k=0.02247$			
Page	50 $^\circ\text{C}$	$k=0.02457591; n=0.8036211$	0.9986	0.00032	0.01181
	60 $^\circ\text{C}$	$k=0.01037443; n=1.05877689$			
	70 $^\circ\text{C}$	$k=0.0169073; n=0.9863179$			
	80 $^\circ\text{C}$	$k=0.0346247; n=0.8856654$			

Logarithmic	50 °C	k=0.010863; c=0.0608973; a=1.0475	0.9962	0.00041	0.01187
	60 °C	k=0.01262186; c=-0.0495058; a=1.05323174			
	70 °C	k=0.0130; c=-0.0813; a=1.0532			
	80 °C	k=0.021; c=0.0021; a=0.9636			
Middili and Kucuk	50 °C	k=0.02318; n=0.8173; a=0.9965; b=0.0000196	0.9995	0.000153	0.00686
	60 °C	k=0.01264; n=0.9987; a=0.9997; b= -0.0001792			
	70 °C	k=0.02591; n=0.8376; a=0.9997; b= -0.00076614			
	80 °C	k=0.0433; n=0.8045; a=1.0017; b= -0.0004135			

The model Middili and Kucuk is the appropriate model to describe the drying kinetics of carob pulp. To take into consideration the effect of temperature on the parameters, k, a, b and n are expressed as function of temperature (θ).

$$k = -2.2188 + 0.0698\theta - 0.0005\theta^2 \quad (5)$$

$$n = -1.2044 + 0.0677\theta - 0.0005\theta^2 \quad (6)$$

$$a = 0.977 + 0.0005\theta - 3 \times 10^{-6} \theta^2 \quad (7)$$

$$b = 0.0065 - 0.0002\theta + 10^{-6} \theta^2 \quad (8)$$

4. Conclusions

In this study, the experiments of convective solar drying of carob pulp were conducted for four temperatures (50 °C, 60 °C, 70 °C and 80 °C) and for one drying air flow rate (0.00833 m³/s). The experimental drying curve occurred in the falling rate period. From the obtained results, it can be concluded that the drying kinetics of Carob pulp were influenced by the drying air temperature.

Statistical analysis of experimental results in reduced coordinates $X^*(t)$, fitted by four empirical models (Newton, Page, Logarithmic and Middili & Kucuk) allows to conclude that Middili & Kucuk was the most appropriate model to describe the drying kinetics of carob pulp (*Ceratonia siliqua* L.)

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