CHEMICAL ENGINEERING TRANSACTIONS

VOL. 120, 2025

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Bing Shen How, Viknesh Andiappan, Denny K.S. Ng, Hon Loong Lam, Petar S. Varbanov

ISBN 979-12-81206-21-2; **ISSN** 2283-9216

DOI: 10.3303/CET25120010

Minimization of Drying Time and Thermo-Economic Evaluation during Solar Dehydration of Apple

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Standardizing the fruit dehydration process with solar technology is a challenge to be solved due to the variability of solar resources. Long process times limit production and increase the unit cost of the product. In 2023, around 27 % of the total harvested apple in Mexico, a major product in market, was wasted. Dehydration is a process to prevent so much waste. This study concluded how the average absorption area and the site's environmental conditions direct dehydration temperature control. The characterization of the system significantly reduces drying times, favoring the increase in its production and lowering the cost of the product. Through the variation of the absorber area of the solar collector, the operating temperature control and minimum drying time were achieved. In an indirect solar dehydrator with forced convection, 20 experimental tests were carried out in two consecutive years. Apple was dehydrated with a constant air mass flow of 0.7 kg/s, heated by 9.6 m^2 of absorber area. In all experiments, the operating temperature was controlled at 46 °C (average irradiance = 850 W/m^2). The maximum operating temperature recorded in both years was 46 °C and the minimum 45 ºC. The maximum drying time was 11.4 h and the minimum 5 h. The average mass of dehydrated products was 0.75 kg per batch (12 % wet basis). The maximum drying efficiency for 2024 was 54 % and 59.7 % for 2023, which are higher than those reported in the literature. The incident energy decreased by up to 87 % with respect to the reduction of the absorber area. The annual net profit, with production of two batches per day, was $ 17,106.8 with a selling price of 0.07 $/g. The control of the operating temperature, based on the existing relationships between the environmental conditions and the solar absorber area, allows us to minimize the operating time.

1. Introduction

Indirect solar dehydrators have emerged as a more efficient alternative to traditional food drying, maintaining food safety and improving the quality of the final product (Sandali et al., 2020), as well as increasing production per square foot (Shrivastava and Kumar, 2017). Srivastava et al. (2025) evaluated the performance of an indirect solar dehydrator during the drying of potato slices and compared it with the traditional sun drying method. For two days (16 h) authors recorded maximum and minimum temperature ranges inside the drying chamber of 42 and 33 ºC. Maximum values of the color change of the sample were 6.32 and 8.13 for the solar device and traditional dehydration methods, respectively, concluding the final product improved noticeably its quality within the solar dehydrator. However, these technologies still have technical (Udomkun et al., 2020), operational and financial limitations (Goel et al., 2023) due to the equipment design (Shimpy et al., 2024), dependence on environmental conditions (Kimaro et al., 2024), low efficiency, high investment and production costs (Swellam et al., 2024) and control of operating conditions (Moheno-Barrueta et al., 2021). This impacts on the kinetics, drying time, unit cost of the product and the return on investment of the equipment, reporting ranges between 0.5 to 5.5 y (Kamarulzaman et al., 2021).

Several studies have analyzed the main operating variables that affect the drying process, such as the temperature and speed of the drying air. Depending on the food, the drying process tends to be carried out within a temperature range from 30 °C to 75 °C for some fruits and vegetables (Fudholi et al., 2010). The most

Paper Received: 20/04/2025; Revised: 26 August 2025; Accepted: 18 September 2025
Please cite this article as: Martínez-Rodríguez G., Olmos-Cruz R.A., Sánchez-García E., Baltazar J.-C., 2025, Minimization of Drying Time and Thermo-Economic Evaluation during Solar Dehydration of Apple, Chemical Engineering Transactions, 120, 55-60 DOI:10.3303/CET25120010

studied operating temperature control during dehydration is achieved by varying the air mass flow rate (Avargani et al., 2023). Moheno-Barrueta et al. (2021) conducted a theoretical-experimental study to optimize the drying speed of an indirect solar and forced convection dehydrator during the dehydration of taro and plantain. By measuring the fan voltage, they found the optimal air speed to be 9 V, recording a drying time of 7.7 h and 8.25 h for plantain and taro, respectively. Martínez-Rodríguez et al. (2022) studied temperature control in an indirect solar dehydrator, with forced convection and loaded with strawberries, by varying the absorber area of a solar collector network. They calculated the outlet temperature of an air solar collector using experimental data of irradiance, ambient temperature, inlet temperature and absorber area. Using the efficiency curve of the air solar collector, the useful heat and the collector outlet temperature were calculated. It was determined that drying temperature of the fruits is a function of the absorber area. Outlet temperature of the collectors decreased by 35.4 % by covering half of the total absorber area of 9.7 m^2, with irradiance levels of 914 W/m^2.

In Mexico, approximately 220,000 t of apples are wasted each year, representing nearly 40 % of the total fruit and vegetable waste in the country (SEMARNAT, 2019). Therefore, indirect drying is a viable alternative for utilizing these perishable foods and reducing their waste.

Controlling the drying temperature is essential to ensure the quality of the final product, increase production capacity and reduce product costs. This study examined ambient conditions and the absorber area to control the operating temperature of an indirect, forced-convection solar dehydrator. Twenty experimental trials were conducted, dehydrating apples with a constant air flow and an initial absorber area of 9.6 m^2, which varies depending on the incident solar energy. The operating temperature was maintained between 45 °C and 46 °C, and the dehydration time varied between 5 h and 11.4 h during the four seasons. The characterization of the system significantly reduces drying times.

2. Methodology

2.1 Indirect solar and forced convection dehydrator

The experimental dehydration of 4.5 kg of Golden Extra apples was carried out in a novel indirect solar dehydrator operating with forced convection and a constant air mass flow rate of 0.7 kg/s. The drying chamber is connected to a solar collector system with a total area of 9.6 m^2. The absorber area of the dehydration system is mechanically varied according to the amount of solar energy incident on the system. The drying temperature and relative humidity inside the drying chamber were measured using DHT22 sensors (0.1 °C resolution).

2.2 Drying kinetics and efficiency

For two consecutive years (2023 and 2024), 20 experimental trials were carried out, of which 11 were developed in 2023 and 9 in 2024. The experiments began at 8:00 h. with the preheating of the dehydrator and the pretreatment of the raw material (washing, disinfection and cutting), which lasted approximately 1 h. The drying test began at 9:30 h. The apple moisture content (M_t) and the moisture ratio (M_r) at any drying time are calculated with Eq(1) and Eq(2).

$$M_t = \frac{m_i - m_f}{m_f} * 100 \tag{1}$$

$$M_r = \frac{M_t}{M_o} \tag{2}$$

where m_i and m_f are the initial and final weight of the food respectively [kg], M_t and M_o are the moisture contents at any initial time t on a dry basis [kg water/kg dry product].

The drying efficiency (η_d) of the dehydrator is calculated using the Eq(3).

$$\eta_d = \frac{E_{vap}}{E_{in}} \tag{3}$$

where E_{vap} represents the amount of energy needed to evaporate the free moisture from the food [kJ], and E_{in} is the total energy incident on the dehydrator [kJ] and is given by the Eq(4) and Eq(5).

$$E_{evap} = m_w \, \lambda_{vap} \tag{4}$$

$$E_{in} = G \cdot A \cdot \, t \tag{5}$$

where m_w is the total amount of water evaporated [kg], λ_{vap} is the latent heat of vaporization [kJ/kg], G is the irradiance [W/m^2], A is the variable absorber area [m^2], and t is the total drying time.

2.3 Economic analysis of the dehydrator

Production cost (C_p) it is estimated with Eq(6) by adding the costs of the fresh product (C_{fp}), cost of labor (C_l) and indirect manufacturing costs (C_{if}), which are the expense of services such as water and electricity.

$$C_p = C_{fp} + C_l + C_{if} \tag{6}$$

The cost of sales of the product (C_s) is calculated using Eq(7), which is a function of the production costs (C_p) and operating expenses (C_o). The latter refers to the costs associated with packaging, product storage, distribution, marketing, and sales.

$$C_s = C_p + C_o \tag{7}$$

Finally, the selling price (C_{sp}) is calculated with the Eq(8).

$$C_{sp} = \frac{C_s}{N_{sp}} + \left(\frac{C_s}{N_{sp}} + f_g\right) \tag{8}$$

where N_{sp} is the number of products sold and f_g is the profit margin considered 20 % (Vimpod, 2025). In previous work (Olmos-Cruz et al., 2024) reported the calculus of capital expenditures (capex), operating expenses (opex) and payback. The first includes the cost of material and equipment construction, yielding a total value of $ 2,073.74. Annual operating cost (opex) considers expenses by raw materials, maintenance, labor, and packaging, yielding a total of $ 2,187.42. Payback is 0.92 y, which drops by up to 50 % if daily production is doubled.

3. Results

3.1 Drying kinetics

Twenty drying tests were carried out over the four seasons for the years 2023 and 2024. 600 data points were recorded for each of the environmental conditions considered: ambient temperature, relative humidity, wind speed, and irradiance, giving a total of 48,000 data points. Measurements were made at a meteorological station located at the Pueblito de Rocha Campus of the University of Guanajuato, Mexico, with coordinates 21°01'36"N, 101°16'10"W. Table 1 shows the average values for each measured variable and for each test.

Table 1: Environmental conditions and drying time.

Date	Ambient temperature [°C]	Relative humidity [%]	Wind velocity [m/s]	Irradiance [W/m^2]	Drying time [h]	Minimum available area [m^2]
January 03, 2023	17.91	44.93	3.54	518.75	6.3	4.8
February 12, 2023	18.73	40.20	2.45	611.52	6.0	3.1
March 05, 2023	23.30	19.86	2.48	638.22	5.7	2.0
March 25, 2023	24.16	18.31	3.36	743.07	5.5	1.4
April 21, 2023	26.94	15.75	3.07	780.02	5.0	1.2
May 01, 2023	23.52	24.04	3.30	657.05	6.5	1.7
July 05, 2023	24.11	51.94	2.14	751.89	7.1	1.4
July 19, 2023	25.79	34.46	2.14	712.16	6.8	1.7
August 31, 2023	20.82	44.12	1.65	471.72	8.4	7.2
October 09, 2023	21.35	54.14	1.96	456.13	9.2	7.2
December 13, 2023	14.72	57.78	1.37	316.55	11.4	9.6
January 31, 2024	18.39	29.46	1.57	257.93	7.4	9.6
February 01, 2024	19.54	37.27	2.53	476.23	6.0	4.8
February 24, 2024	23.06	28.21	2.30	674.02	5.5	3.0
March 16, 2024	24.80	20.00	3.00	709.70	5.2	1.2
March 31, 2024	24.40	20.27	3.12	719.65	5.1	1.1
September 13, 2024	23.21	60.12	2.03	731.84	6.5	1.7
October 11, 2024	21.42	32.93	2.16	673.99	5.6	2.4
November 06, 2024	22.94	36.65	2.23	574.11	5.8	3.8
December 09, 2024	19.27	44.08	1.94	515. 63	6.0	4.3

For each batch, 4.5 kg of apples were dehydrated, obtaining an average final weight of 0.7 kg in each test and reducing their moisture content from 86 % to 12 % (wet basis). Figure 1 (a) shows the drying rate of the apple samples for March 16, 2024. There is no constant drying period, but rather it begins in the decreasing period. This period begins with the critical moisture content (M_c) of the sample and has a value for the apple of 5.32 g/g dry solid. It is observed that the apple experiences a second critical point of 2.5 g/g dry solid. The environmental conditions on this day are shown in Figure 1 (b). The maximum, minimum, and average values for ambient temperature, relative humidity, wind velocity, and irradiance were 28.3, 17.5, and 24.8 ºC, 33, 12, and 20 %, 8.1, 0.15, and 3.1 m/s, and 1,055, 120.1, and 710 W/m^2, respectively. Drying time decreased as irradiance levels increased, and relative humidity of the ambient air decreased. The shortest drying times were recorded on April 21, 2023, and March 31, 2024, days with average irradiance levels above 730 W/m^2 and low relative humidity levels of 15 and 20.27 %, respectively. During the tests carried out in 2024, the average drying time was 5.9 h, compared to 6.5 h in 2023. These results, like the drying times presented in Table 1, are below those reported in the literature for a fresh apple load above 2.0 kg.

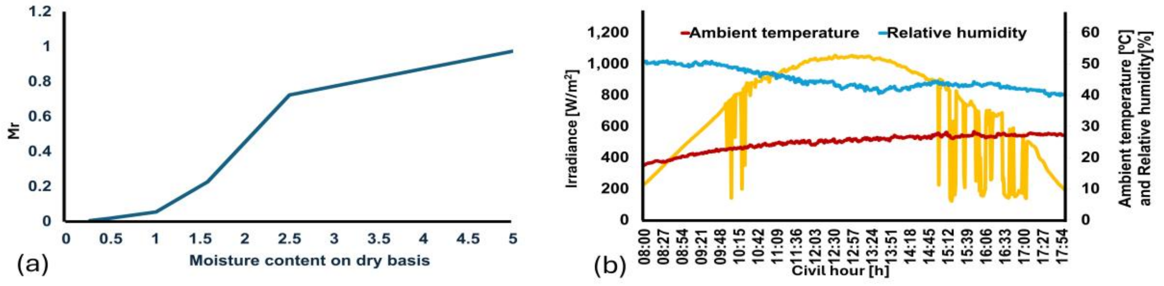

Figure 1: (a) Drying velocity rate curve (16/03/2024) and (b) Environmental conditions (16/03/2024).

3.2 Temperature control based on the absorber area

During preheating (8:10 to 9:30 h), the available absorber area is equal to the total of 9.6 m^2 and the amount of incident energy is 2.58 kW. As the dehydration process progresses, irradiance increases until reaching its maximum value at solar noon (1,055 W/m^2), generating an amount of energy up to 9.82 kW. This causes the drying temperature to increase (reaching temperatures above 85 °C in winter conditions), compromising product quality. Temperature control was carried out by mechanical variation of the available absorber area; the results are shown in Table 2. Under the environmental conditions of Figure 1 (b), the target temperature of 45 °C was reached at 9:03 h and was maintained for 30 min. Once temperatures reached 45 °C, the available absorber area decreased by up to 37.5 % at 9:20 h (Figure 2). By midday, the available area had a minimum value of 1.2 m^2, representing a reduction of up to 87.5 % for the absorber area and 87 % for the amount of incident energy. Figure 2 shows the behavior of the drying temperature entering the dehydrator (T_{in}), which was maintained in the range of 45 and 46 ºC for a period of 5 h during the drying test carried out on March 16, 2024. The outlet temperature (T_{out}) corresponds to the temperature of the air leaving the dehydrator. During preheating (8:10 to 9:30 h) both temperatures are observed to be 45 ºC. Once the drying test begins (9:30 h), the air temperature at the chamber outlet decreases by up to 35 %. As the air heats up, its capacity to remove moisture increases, allowing it to extract a greater amount of free water from the surface of the food. This causes the air to humidify and reduce its temperature. As the moisture content of the food gradually evaporates, Tout increases until it reaches the drying temperature of 45 ºC. This indicates that the fruit contains a minimum amount of moisture and is in equilibrium with the drying air. Drying temperature was controlled for each test, and the value of the minimum available area for the remaining days is shown in Table 2.

Table 2: Reduction in the absorber area for the March 16, 2024, test.

Civil hour	8:10	9:20	10:46	12:10	14:02
Available area [m^2]	9.6	6.0	2.4	1.2	2.0
Energy [kW]	2.58	3.42	2.13	1.23	1.98
Temperature [ºC]	18.2	45.3	45.5	45.2	45.5

3.3 Drying efficiency

Figure 3 shows the drying efficiency for each test. Drying efficiency is inversely related to the amount of energy received by the solar dehydrator. Therefore, as the absorber area is reduced, the amount of energy incident on the dehydrator also decreases, increasing the drying efficiency for the amount of food to be dehydrated. It is observed in Figure 3 (a), April 21, 2023, had the highest efficiency at 54 %, followed by March 25th with 42.5 %. Also, Figure 3 (a) shows the amount of incident energy with respect to the minimum absorber area available in 2023. The minimum amount of energy is reached when the minimum area available is available, which corresponds to April 21st, 2023, recording an area of 1.2 m^2. Figure 3 (b) shows the drying efficiencies for 2024. The highest efficiency was 59.7 % for the March 31, 2024, test, followed by March 16 and February 24, with values of 52.5 % and 58.2 %, respectively. The 2024 tests showed lower levels of solar intermittency, so the absorber area varied considerably, even in tests conducted during fall and winter conditions (October 11, November 6, and December 9). The drying efficiency for these days increased by up to 62 % compared to 2023. Figure 3 (b) shows the amount of incident energy with respect to the minimum available absorber area for 2024. The minimum amount of energy is reached when the minimum available area is available, which corresponds to March 31, 2024.

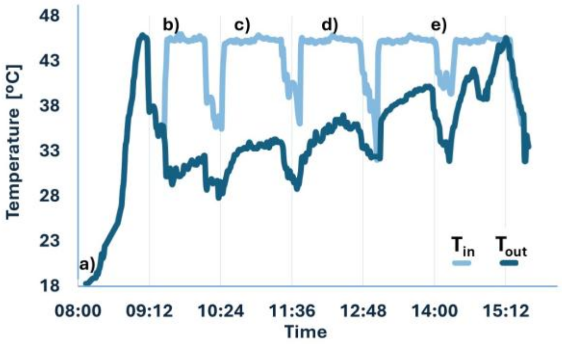

Figure 2: Drying temperature behavior throughout the test on March 16, 2024, in which the absorbent area was varied: a) 9.6 m^2, b)6.0 m^2, c) 2.4 m^2, d) 1.2 m^2 and e) 2.0 m^2.

Figure 3: Apple drying efficiency for each test and amount of energy incident on the dehydrator. (a) Tests from 2023, (b) Tests from 2024

3.4 Economic Analysis of the Dehydrator

The production cost of the indirect solar and forced convection dehydrator considers raw materials, labor, and indirect utility costs such as electricity, water, packaging, etc., (Sharma et al, 2023). The average cost of Golden Extra apples for 2023 and 2024 was between \$ 0.9 and \$ 1.5 per kg. The average raw material cost for the analysis was \$ 1.2. If 4.5 kg of apples are processed, the raw material cost per batch is \$ 5.4. If the indirect solar dehydrator operates 360 d a year, the annual raw material cost is \$ 1,908.0. If water is used as the primary service, as well as the use of packaging and food sanitizer, then the annual indirect manufacturing and labor costs are \$ 4,510.7. Therefore, the annual production cost is \$ 6,418.7. The retail cost of 1 gram of apple was determined to be \$0.07. If the dehydrated product is packaged locally in 30 g packages, the cost per gram is \$ 2.10. Considering production of one batch per day, the annual gross profit is \$ 17,993, and the annual net profit (annual gross profit - annual production costs) is \$ 11,761.7. Considering two batches per day, the annual gross profit increases by up to 50 %, totalling \$ 23,523.4, so the annual net profit would be \$ 17,106.8.

4. Conclusion

Standardizing the dehydration process is essential to ensure a viable market. Controlling the drying temperature of the indirect solar dehydrator through the absorber area allows for a reduction in drying time of apple dehydration by up to 50 % compared to those reported in the literature, in addition to allowing for the control of apple drying kinetics to obtain high-value, high-quality dehydrated products. When producing one batch per day, the annual net profit is $ 11,761.7, this is increased when shorter production times let to produce two batches (annual net profit of $ 17,106.8). The drying temperature was controlled within a range of 45 and 46 °C in the 20 experimental tests carried out during the years 2023 and 2024 and was maintained for up to 7 hours under favorable environmental conditions. The minimum absorber area available during the years 2023 and 2024 was 1.2 m^2, reducing the amount of incident energy by up to 87.5 % under favorable environmental conditions. The maximum drying efficiency for both years is 54 % and 59.7 % for 2023 and 2024, respectively.

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