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# Drying kinetics of Cecina from Yecapixtla using a forced flow indirect solar dryer

# Cinética de secado de Cecina de Yecapixtla usando un secador solar indirecto de flujo forzado

A. Tlatelpa-Becerro[1*], R. Rico-Martínez[2], M. Cárdenas-Manríquez[2], G. Urquiza[3], L.L. Castro-Gómez[3], F.B. Alarcón-Hernández[4], C. Torres[4] and E. Montiel[4]

[1] *Escuela de Estudios Superiores de Yecapixtla-UAEM. 62820, Mor., México.*
[2] *Tecnológico Nacional de México-Instituto Tecnológico de Celaya. 38000, Gto. México.*
[3] *Universidad Autónoma del Estado de Morelos-CIICAp. 62209, Mor., México.*
[4] *Escuela de Estudios Superiores de Xalostoc-UAEM. 62715, Mor., México.*

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## Abstract

This study presents the drying behavior of Cecina from Yecapixtla Morelos through an indirect solar dryer to obtain the drying kinetics. The behavior of the drying kinetics was examined, observing significant effects related to the levels of pH, salinity, and density of the Cecina. Artisanal dry Cecina samples are compared versus the dry Cecina of this study. The results showed a higher concentration of salinity and a lower pH of the dry Cecina of this study versus the dry artisanal Cecina. Solar drying through the indirect dryer present in this work is a viable alternative to give added value to the production of Cecina from Yecapixtla in Morelos, Mexico.
*Keywords*: Drying kinetics, effective diffusivity, solar dryer, Cecina from Yecapixtla.

## Resumen

Este estudio presenta el comportamiento de secado de la Cecina de Yecapixtla Morelos mediante un secador solar indirecto para obtener la cinética de secado. Se examinó el comportamiento de la cinética de secado, observándose efectos significativos relacionados con los niveles de pH, salinidad y densidad de la Cecina. Se comparan muestras de Cecina seca artesanal versus la Cecina seca de este estudio. Los resultados mostraron una mayor concentración de salinidad y un menor pH de la Cecina seca de este estudio versus la Cecina artesanal seca. El secado solar a través del secador indirecto presente en este trabajo es una alternativa viable para darle valor agregado a la producción de Cecina de Yecapixtla en Morelos, México.
*Palabras clave*: Cinética de secado, difusividad efectiva, secador solar, Cecina de Yecapixtla.

* *Corresponding author. E-mail*: angel.tlatelpa@uaem.mx
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## 1 Introduction

Currently, the municipality of Yecapixtla in the State of Morelos is recognized for the traditional and artisanal preparation of Cecina from beef. Above all, it is unique for its incomparable flavor and quality. The word Cecina comes from the Latin "siccus," which means dry. The preparation technique of this meat has more than 200 years of tradition. The best cuts for this preparation are the beef leg and loin. The cut is considered fillets and very thin since it is a characteristic of the Cecina from Yecapixtla that it is thin and easy to chew. The preparation has always been considered a ritual because it is prepared with hands. No equipment is used in the process, and the ritual is interesting; the meat is spread with lard, salt, and exposed to the sun for its drying process, which can absorb its nutrients, obtaining the Cecina. The drying method used is open sun drying, used in most tropical and subtropical countries for food preservation (Bala and Debnath, 2012; El-Beltagy *et al*., 2007). This process becomes a good alternative, but the food is contaminated by dust, insect infestation, microbial contamination and may become unfit for human consumption. Likewise, direct exposure to the sun deteriorates the product, changing its texture, color, and flavor due to the direct radiation that reaches it.

In the last decade, producers have had a considerable increase in Cecina sales in the region and distribute their products throughout Mexico and internationally. The increase in its sales has allowed it to produce more products. However, the problem focuses on high transport costs due to freezers due to the quantities of product to be transported. For this reason, producers have thought of looking for other alternatives for drying, such as using equipment that uses non-renewable energies (Gas LP, electric, and hybrid) to eliminate the most significant amount of moisture in the Cecina for conservation, storage, and transportation (Figueroa *et al*., 2020). However, this equipment becomes expensive in the acquisition, operation, maintenance, and, above all, polluting the environment (Ekechukwu *et al*., 1995; Jha and Tripathy, 2021; Lingayat *et al*., 2017; Pirasteh *et al*., 2014).

Searching for alternatives with equipment that uses renewable energy sources like solar drying is a new challenge. Solar drying is considered today one of the most promising areas for its implementation using radiant energy from the sun. Therefore, solar dryers are a good option, since they are usually low cost, as are their maintenance, operation, and above all, they have provided good characteristics in drying products, preserving their flavor, color, consistency, and appearance. These types of equipment are devices that capture the sun's radiant energy to increase the temperature of the fluid (air) inside the drying chamber. Although there are different designs (Bala & Debnath, 2012), this technology has been used in the area of agriculture; such as mainly in the drying of fruits, vegetables, and legumes, obtaining good results (Çiftçioğlu *et al*., 2020; Dufera *et al*., 2021; El-Beltagy *et al*., 2007; Fudholi *et al*., 2014; Pruengam *et al*., 2021; García *et al*., 2022). And above all, improving its appearance, texture, taste, and smell, preventing its deterioration, and improving its quality (Pirasteh *et al*., 2014).

Also, this equipment has been used with other products. For example: in the drying of wood (Fuentes *et al*., 2003; Nelli *et al*., 2021; Solís *et al*., 2003), in the drying of residues (sludge) from sewage (Kamil *et al*., 2007), to mention some other applications. However, exist very few studies on the solar drying of meat from different animal species for its conservation. Some authors have carried out studies on the drying of camel (Chaouch *et al*., 2018) and Eland meat (Kučerová *et al*., 2018). Meanwhile, they have also dried beef naturally or with seasoned infusions using different solar equipment (Apata *et al*., 2013; Mewa *et al*., 2019; Nguyen & Nguyen, 2014; Subbian *et al*., 2019). All these studies have obtained satisfactory results in their processes. In reference (Kučerová *et al*., 2018), the researchers carried out the Eland drying process using a double-pass solar dryer and a laboratory dryer. Analyzes were performed on the changes in the organoleptic properties and the physicochemical characteristics before and after drying. Their results show that the organoleptic properties of Cecina are like the use of the solar dryer versus the laboratory dryer.

The literature shows that solar drying of meat has not been widely explored. Therefore, solar technology continues to be studied and is especially promising for drying meat in the industrial field.

In this research work, the drying kinetics of Cecina from Yecapixtla has been studied using an indirect forced-flow solar dryer. Fick diffusion model is implemented to know the drying behavior of Cecina. However, to guarantee the effective drying process, the product's physicochemical properties such as pH, density, and salinity are measured before and after drying to know the change in these parameters.

For this, weather conditions such as solar radiation and temperature play a very important role in this drying process. Since both the pH, density, and salinity are significantly affected by temperature. Finally, a comparison is made of the physicochemical and appearance properties between the dried artisan Cecina versus the dried by the solar dryer.

## 2 Materials and methods

This section presents the study material that is Cecina. The Cecina samples were collected for different production dates to proffer the drying process. Subsequently, the importance of measuring the physicochemical properties and the product's physical characteristics for drying are described. Next, the experimental equipment used for drying the product is described. Finally, the use of the Fick model for drying kinetics is described.

Three samples of Cecina have been collected from different producers, with dates of elaboration in the municipality of Yecapixtla Morelos, latitude 18°52'26.5" N and longitude -98°51'15.5" W, see Figure 1. The samples used were stored in a freezer at 4 ° C until their drying processing. The samples are subjected to a drying process using a solar dryer under different environmental conditions to obtain the drying kinetics and their effect in the physicochemical properties and geometric dimensions, in order to validate the use of such equipment for commercial purposes.

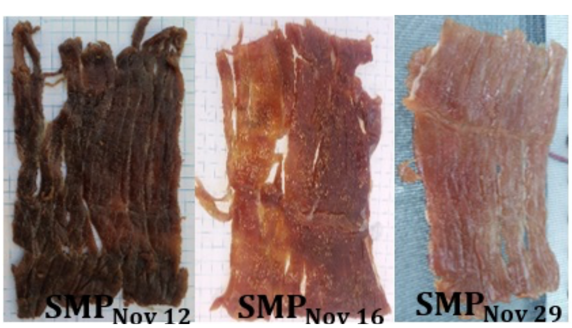


Figure 1. Cecina samples on different days. $SMP_{Nov12}$, $SMP_{Nov16}$ and $SMP_{Nov29}$ correspond to November 12, 16, and 29, 2021.

### 2.1 *Physicochemical and physical characteristics*

The pH, salinity, and density are key physicochemical properties for Cecina conservation. If these properties vary, they may be an indication of early degradation of the product. In validating the use of a solar drier for Cecina production, one seeks that these parameters are similar to the observed for the artisanal product. For this reason, the physicochemical characteristics are calculated from the pulp of Cecina. Hence, the pH, density and salinity, moisture content, and weight loss are calculated to estimate the meat's adequate drying time in the experiments. pH value is evaluated with an ATC refractometer (MPN: 43217-71864). Density and salinity concentrations are estimated with an ATC refractometer with a pressure of 1% (1.000 a 1.070 kg/m$^3$ ; 0 a 100 ppt). Weight was determined using a digital scale (KUBEI Jewelry scale) with a precision of 0.001g with an error of ±0.003g. Physical dimensions are measured with a digital Vernier caliper (YUGENER) with an accuracy of ±0.02mm.

### 2.2 *Experimental configuration of the solar dryer*

The solar dryer used for the experiments is located at the Escuela de Estudios Superiores de Yecapixtla in the State of Morelos, Mexico, at latitude 18°51'09.6" N and longitude -98°52'11.0" W. The solar dryer works outdoors, facing south and with an inclination angle of 24° for the solar collector. The equipment comprises a solar energy collector and a drying chamber made of stainless steel. The dimensions of the collector are length ($L_c$ ) 2.145 m, width ($W_c$ ) 0.95 m and height ($D_c$ ) 0.13 m. For the camera, the following: height ($L_{ch}$) 1.01 m, width ($W_{ch}$) 0.455 m and depth ($D_{ch}$) 1.27 m (Figure 2a).

The air inlet for the solar collector the drying chamber are located at the bottom, and the air outlet is at the top of each element. The airflow that enters the collector passes through the painted matt black ducts to absorb the maximum radiant energy; this raises its temperature and is transported to the drying chamber (Figure 2a). At the same time, the airflow that enters the solar chamber flows upwards through the trays and is expelled at the chamber's top, Figure 2b. The drying chamber contains spaces for a maximum of fifteen mobile trays. The trays are used to dry the meat. For this investigation, a tray is used in the chamber's center. The tray is constructed of an anodized aluminum frame and nylon mesh.

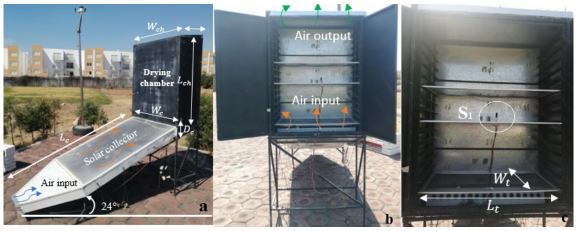


Figure 2. Geometry and dimensions of the solar dryer. Air flows in a forced way through the pipes of the solar collector towards the interior of the drying chamber.

Trays are arranged horizontally with the following dimensions: length ($L_t$) 0.88m and width ($W_t$) 0.41m (Figure 2c).

## 2.3 Data acquisition and electronic control

The drying chamber was instrumented with a DHT22 ($S_1$) temperature and humidity sensor with a precision of ± 0.1 °C in its center, Figure 2c. Two NMB-type fans of 12 Volts at 1.3 Amps are installed at the entrance of the solar collector. The fans supply the flow to the solar collector and transport it to the drying chamber for drying the Cecina, Figure 2a,b. Airflow is controlled with FZ0430 voltage modules and ACS712 current modules. Flow velocity is measured with a UT363 type anemometer. The measurement range is from 0 to 30 m/s with an accuracy of ± 5% rdg + 0.5. An Arduino-Mega type microcontroller is used for the fan's interconnection, the temperature and humidity sensor, and data acquisition and recording. The microcontroller was directly connected to a personal computer via a USB port. LabVIEW software is used to communicate with the microcontroller and control the airflow speed supplied by the fans.

## 2.4 Environmental condition

An Ambient Weather WIFI OSPREY model weather station (WS-2902A) to measure ambient conditions is used. Solar radiation and ambient temperature are taken into consideration for the drying process. The specifications of the temperature sensor corresponding to a range between -4.4 to 60 °C. While for solar radiation between 0 to 120k Lux (W/mm$^2$ , lux, fc). The weather station was installed next to the solar dryer at the height of 3.5m to obtain accurate and reliable data. The acquisition and recording of radiation and temperature data was made remotely on a personal computer; also monitored via a display console.

## 2.5 Drying kinetics

Food drying is represented through mathematical models to interpret the phenomena related to this process. The most important phenomenon is moisture's diffusivity, which depends on the drying conditions and the material's properties. Assuming that the material is homogeneous isotropic, the resistance to moisture transfer and the diffusion coefficient are uniform within the material; the effective diffusivity is evaluated using Fick's second law. This model, in its non-steady state, is represented by Equation 1.

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \tag{1}$$

The analytical solution present in Equation 1 has been developed and described by Crank, 1975. It has been used to solve various shapes of materials, such as rectangular, spherical, and cylindrical bodies. Even recent studies have used this solution model for food drying cases with different conditions and successfully predicted the effective diffusion coefficient (Srikiatden and Roberts, 2008; Barati and Esfahani, 2012; Salehi and Satorabi, 2021; Sahoo *et al.*, 2022). In this study, the one-dimensional Fick diffusive model describes the transport mechanism in regions of decreasing drying rate; this expression is reduced to Equation 2. Where M is the moisture content (g water/g dry mass); t time (s), × length (m), and D$_{eff}$ effective diffusion coefficient of moisture in solids (m/s$^2$) under drying temperature conditions.

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M)}{\partial x^2} \tag{2}$$

Considering the Cecina samples in the form of flat sheets of thickness L that dry on both sides and under boundary conditions at t = 0, x = 0, x = L, $M = M_0$, where $M_e$ and $M_0$ represent the content of equilibrium and initial humidity. Assuming a uniform distribution of moisture in the sample mass, and the mass transfer is symmetric to the center, the balance between the moisture surface and the surrounding air; negligible mass transfer resistance on the surface compared to the internal resistance of the sample; dough. The transfer is done by diffusion; the diffusion coefficient is constant, and the contraction is negligible (Rao *et al.*, 2005). Under these assumptions and premises, the solution of the Fick diffusion equation is presented in

Equation 3.

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \left\{ \exp\left( -\frac{\pi^2 D_{eff}}{4L^2} t \right) - \frac{1}{9} \left( \frac{9\pi^2 D_{eff}}{L^2} t \right) + \cdots + \frac{1}{(2n+1)^2} \exp\left[ -(2n+1)^2 \right] \frac{\pi^2 D_{eff}}{4L^2} t \right\} \quad (3)$$

Where MR is the moisture ratio (dimensionless term); n is the number of terms of the Fourier series, and L is the half-slab thickness of the slices (m). For long periods in the drying process, Equation 3 can be simplified as follows:

$$MR = \frac{8}{\pi^2} \exp\left[ -\frac{\pi^2 D_{eff}}{4L^2} t \right] \quad (4)$$

The effective diffusivity coefficient is calculated from Equation 4. Therefore, the properties of logarithms are applied, and the equation is obtained as follows

$$\ln(MR) = -\frac{\pi^2 D_{eff}}{4L^2} t + \ln \frac{8}{\pi^2} \quad (5)$$

Thus, the coefficients of the effective diffusivities are usually predicted by plotting the drying time (t) against the experimental values of the logarithmic moisture ratio ln(MR), giving a straight line with a slope ($S_{lope}$).

$$S_{lope} = \frac{\pi^2 D_{eff}}{4L^2} \quad (6)$$

# 3 Results and discussions

## 3.1 Climate data

All the drying experiments were carried out on November 12, 16, and 29, 2021, from 10:00 a.m. to 4:00 p.m. Solar radiation and ambient temperature play a significant role in the drying processes. Therefore, Figure 3 provides the meteorological data for the experimental period. The variation of the magnitudes of radiation and ambient temperature over time is due to weather conditions with cloudiness for short periods.

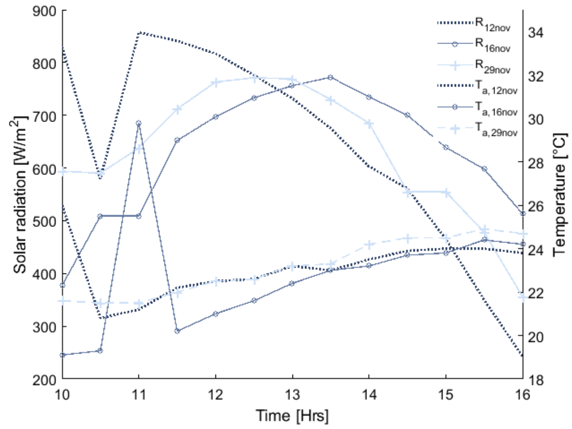


Figure 3. Meteorological data of three days during the experimental period. The solar radiation $R_{12nov}$, $R_{16nov}$, and $R_{29nov}$, and the ambient temperature $T_{a,12nov}$, $T_{a,16nov}$, and $T_{a,29nov}$ correspond to the days 12, 16 and 29 November 2021.

## 3.2 Calculation of physicochemical properties and geometric characteristics

Cecina samples were used for the experiments, see Figure 1. These samples are considered as similar as possible, both in weight and geometric dimensions for processing. Physical measurements and determined physicochemical properties are shown in Table 1. Also, properties such as density, salinity, and pH are compared with the dried samples.

## 3.3 Calculation of weight loss and moisture content with the oven method

Before the drying process of the Cecina with the experimental equipment, the initial moisture content was determined for three samples, from the change in weight of each Cecina sample after the evaporation of the water absorbed in the oven, applying Equation 7. The oven-drying method is used for this process at a constant temperature of 105 °C (Tirado *et al*., 2015). The characteristics of the samples are presented in Table 1.

$$\%Moisture = \frac{(M_1 - M_2) * 100}{M} \quad (7)$$

Where $M_1$ = Weight of the crucible with the moisture sample, $M_2$ = Weight of crucible with dry sample, and M = sample weight.

Table 1. Physicochemical properties and geometric characteristics.

| Day | Samples | Weight (g) | Length (cm) | Width (cm) | Thickness (cm) | Salinity (%) | Density kg/m$^3$ | pH |
|---|---|---|---|---|---|---|---|---|
| Nov 12th | $SMP_{o,1}$ | 15,59 | 9,5 | 7,4 | 1,5 | - | - | - |
| | $SMP_{SD,1}$ | 40 | 14,3 | 9,9 | 1,5 | 9 | 1.006 | - |
| Nov 16th | $SMP_{o,2}$ | 12,087 | 9 | 7 | 1,1 | - | - | - |
| | $SMP_{SD,2}$ | 37 | 13,89 | 9,8 | 1,1 | 7 | 1.005 | 5.3 |
| Nov 29th | $SMP_{o,3}$ | 11,186 | 8,3 | 5,5 | 2 | - | - | 5.3 |
| | $SMP_{SD,3}$ | 39 | 14,87 | 7,4 | 2 | 6 | 1.004 | 5.3 |

Table 2. Initial weight and moisture of the Cecina samples.

| Condition | $SMP_{o,1}$ | | $SMP_{o,2}$ | | $SMP_{o,3}$ | |
|---|---|---|---|---|---|---|
| | $W_{SMP_{o,1}}$ | $W_{SMP_{o,2}}$ | $W_{SMP_{o,3}}$ | $W_{SMP_{o,1}}$ | $W_{SMP_{o,2}}$ | $W_{SMP_{o,3}}$ |
| Initial | 15,59 | 60,8851828 | 12,087 | 60,9746008 | 11,186 | 60,2628285 |
| Final | 6,098 | 23,815128 | 4,717 | 23,7955814 | 4,445 | 23,9467435 |

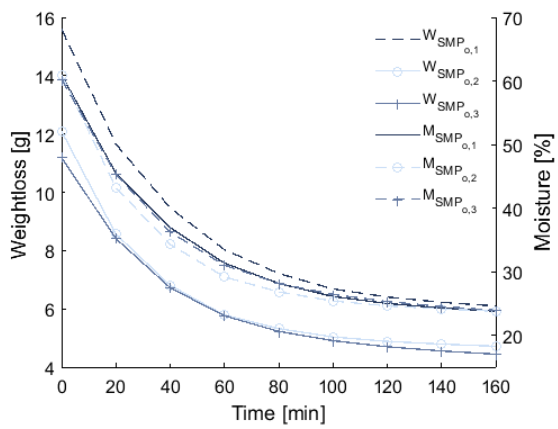


Figure 4. Moisture and weight loss. $M_{SMP_{o,1}}$, $M_{SMP_{o,2}}$ and $M_{SMP_{o,3}}$ correspond to moisture losses. While $W_{SMP_{o,1}}$, $W_{SMP_{o,2}}$ and $W_{SMP_{o,3}}$ correspond to weight loss.

The results of the initial moisture content and weight of the samples $SMP_{o,1}$,$SMP_{o,2}$ and $SMP_{o,3}$ are presented in Table 2. Effective weight loss is determined with oven equipment was used for the drying process. Figure 4 shows the behavior of weight loss and moisture content concerning time. Here it is observed that, as of minute 120, the weight loss for each sample remains without significant changes. However, between minute 120 and 160 the samples $SMP_{o,1}$, $SMP_{o,2}$ and $SMP_{o,3}$ lose weight ($W_{SMP_{o,1}}$, $W_{SMP_{o,2}}$ and $W_{SMP_{o,3}}$) and humidity ($M_{SMP_{o,1}}$, $M_{SMP_{o,2}}$ and $M_{SMP_{o,3}}$) with an average of 0.154, 0.083 and 0.127 g and 0.601, 0.418 and 0.684 %, respectively. The final weight loss and moisture results for this drying method are presented in Table 2.

### 3.4 *Drying kinetics of Cecina with the use of solar dryer*

The experiments were repeated three times to estimate the experimental error. For this, the geometric and physicochemical characteristics of the samples were considered. $SMP_{SD,1}$, $SMP_{SD,2}$ and $SMP_{SD,3}$, see Table 1. The air flow supplied by the fans at the entrance of the solar collector is between 2.7 and 3.7 m/s.

The results of the drying curve are shown in Figures 6 and 7. The behavior of the drying kinetics of the three samples is exponentially decreasing as time passes. For the sample: $SMP_{SD,1}$, it is observed that during the first 300 minutes, it loses the most significant amount of weight ($W_{SMP_{SD,1}}$) and moisture ($M_{SMP_{SD,1}}$). Therefore, after 300 minutes, the curves maintain an asymptotic and stable behavior; this is achieved because the radiation $R_{12nov}$ is high, and because of this, the temperature $T_{SMP_{SD,1}}$ in the drying chamber is higher, and remains stable during the drying process, see Figure 5. However, for the sample $SMP_{SD,2}$ at 360 minutes, it reaches final moisture ($M_{SMP_{SD,2}}$) and weight ($W_{SMP_{SD,2}}$) of: 18.128% and 11g, respectively. These results are very close compared to the $SMP_{SD,1}$ sample with a difference of 0.092% for moisture and 1 g for the weight of the Cecina samples. The solar radiation $R_{16nov}$ is lower during the experiment compared to $R_{12nov}$; therefore, the temperature $T_{SMP_{SD,2}}$ inside the drying chamber tends to be lower because of this. Thus, the drying time is 60 minutes longer than the $SMP_{SD,1}$ sample. In contrast, the results for the sample $SMP_{SD,3}$ moisture loss ($M_{SMP_{SD,3}}$) and weight ($W_{SMP_{SD,3}}$) are reached at 360 minutes with values of 24.723% and 16 g, respectively.

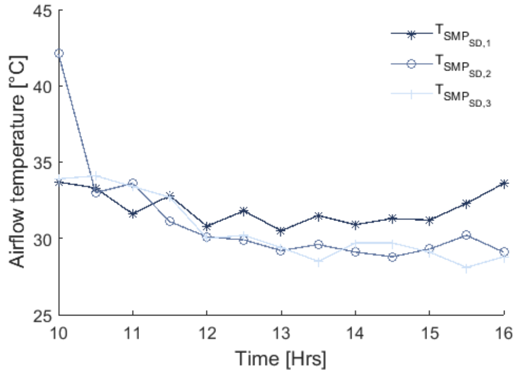


Figure 5. The temperature of the air flow inside the drying chamber. $T_{SMP_{SD,1}}$, $T_{SMP_{SD,2}}$ and $T_{SMP_{SD,3}}$ are the temperatures inside the drying chamber.

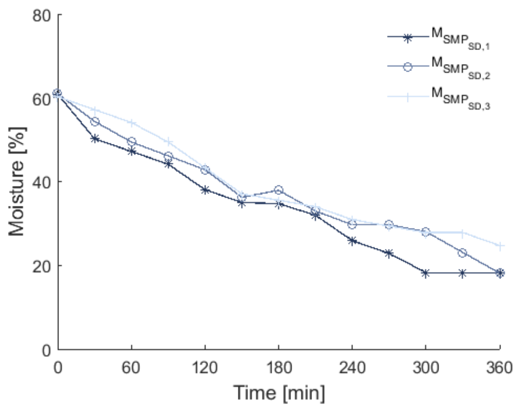


Figure 6. Moisture loss. $M_{SMP_{SD,1}}$, $M_{SMP_{SD,2}}$ and $M_{SMP_{SD,3}}$ correspond to the moisture loss for each sample.

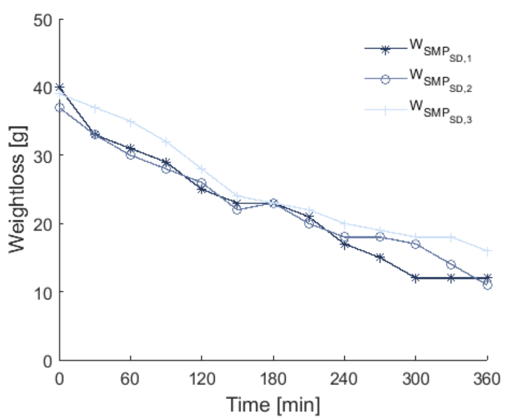


Figure 7. Weight loss. $W_{SMP_{SD,1}}$, $W_{SMP_{SD,2}}$ and $W_{SMP_{SD,3}}$ correspond to the weight loss for each sample.

The effective diffusivity $D_{eff}$ is a coefficient that encompasses various phenomena related to water loss in food. The coefficient is calculated by fitting experimental data using mathematical models like the Fick diffusivity model. This model manages to predict the drying kinetics, neglecting the sample's contraction. Temperature plays an important role in drying kinetics; therefore, the higher the temperature, the greater the effective diffusivity, improving mass transfer. However, the mass transfer decreases when the moisture in the product increases proportionally. Therefore, in the structure of the Cecina samples, the interstitial spaces increase when the moisture content tends to decrease proportionally, and as a result, it facilitates the elimination of water. Therefore, the effective diffusivities of each sample can be seen in Table 3. The maximum effective diffusivity coefficients for the samples $SMP_{SD,1}$, $SMP_{SD,2}$ and $SMP_{SD,3}$ are $5.673{\times}10^{-9}$, $2.644{\times}10^{-9}$,$2.133 \times10^{-8}$ $m^2/s$, respectively. In addition, the diffusivity model has been adjusted to the experimental data of the drying process with the temperatures reached inside the drying chamber. However, the thickness becomes present, and the diffusivity improves when the thickness of the sample is less even though the temperatures vary during the drying time. Therefore, at low temperatures, the surface of the samples dries very slowly. While, when the temperature increases and is as stable as possible, the surface dries more quickly, and the movement of water is controlled by diffusion inside the meat, see Table 3.

These results are obtained because the radiation $R_{29nov}$ is much lower (see Figure 4) than the other radiations $R_{12nov}$ and $R_{16nov}$. Consequently, these values indicate that it requires a longer drying time to reach adequate humidity and weight.

However, studies have been carried out on beef drying of meat and have reported effective diffusivity coefficients very close to those found in this study. For example, reference (Ahmat *et al*., 2015) performed the drying kinetics at different temperatures (40, 50, and 60 °C) for fresh meat with dimensions of approximately 12 cm long and 7 cm wide at different thicknesses (2, 3, and 4 mm). They obtained a shorter drying time, a temperature of 60 °C at a speed of 3 m/s for the three thicknesses of the product. Similarly, the reference (Mewa *et al*., 2018) has dried beef for the following thicknesses: 0.25, 0.5, 0.75, and 1 cm. Drying was carried out at temperatures of 30, 40, 50, and 60 °C, considering a constant airflow at 24 V.

Table 3. Influence of the temperature inside the drying chamber and the thickness of the sample on the effective diffusivity $D_{eff}$.

| Sample $SMP_{SD,2}$ | | | Sample $SMP_{SD,1}$ | | | Sample $SMP_{SD,3}$ | | |
|---|---|---|---|---|---|---|---|---|
| Thickness (cm) | T (°C) | $D_{eff}$ (m$^2$/s) | Thickness (cm) | T (°C) | $D_{eff}$ (m$^2$/s) | Thickness (cm) | T (°C) | $D_{eff}$ (m$^2$/s) |
| 1,1 | 42,1 | 3,5553×10$^{-8}$ | 1,5 | 33,7 | 7.9790×10$^{-8}$ | 2 | 33,9 | 1.0537×10$^{-7}$ |
| | 33.0 | 2,3800×10$^{-8}$ | | 33,3 | 7.4559×10$^{-8}$ | | 34,1 | 1.0432×10$^{-7}$ |
| | 33,6 | 1.4398×10$^{-8}$ | | 31,6 | 6.9506×10$^{-8}$ | | 33,4 | 9.5100×10$^{-8}$ |
| | 31,1 | 1.4398×10$^{-8}$ | | 32,8 | 4.2909×10$^{-8}$ | | 32,7 | 8.5353×10$^{-8}$ |
| | 30,1 | 1.0578×10$^{-8}$ | | 30,8 | 3.5462×10$^{-8}$ | | 30.5 | 7.6132×10$^{-8}$ |
| | 29,9 | 4.7013×10$^{-9}$ | | 31,8 | 2.2696×10$^{-8}$ | | 30,2 | 7.6132×10$^{-8}$ |
| | 29,2 | 7.3458×10$^{-9}$ | | 30,5 | 2.2696×10$^{-8}$ | | 29,4 | 4.4520×10$^{-8}$ |
| | 29,6 | 7.3458×10$^{-9}$ | | 31,5 | 1.7377×10$^{-8}$ | | 28,5 | 3.7934×10$^{-8}$ |
| | 29,1 | 4.7013×10$^{-9}$ | | 30,9 | 1.2766×10$^{-8}$ | | 29,7 | 3.7934×10$^{-8}$ |
| | 28,8 | 4.7013×10$^{-9}$ | | 31,3 | 1.0727×10$^{-8}$ | | 29,7 | 2.6343×10$^{-8}$ |
| | 29,3 | 4.7013×10$^{-9}$ | | 31,2 | 5.6740×10$^{-9}$ | | 29,1 | 2.6343×10$^{-8}$ |
| | 30,2 | 2.6445×10$^{-9}$ | | 32,3 | 5.6740×10$^{-9}$ | | 28,1 | 2.6343×10$^{-8}$ |
| | 29,1 | 2.6445×10$^{-9}$ | | 33,6 | 5.6740×10$^{-9}$ | | 28,8 | 2.1338×10$^{-8}$ |

In their results, they show that for the sample with less thickness (2.5mm) at a drying temperature of 60 °C was faster compared to the thicker samples. Therefore, the effective diffusivity in their samples was determined to be between 4.2337×10$^{-11}$ a 5.5899×10$^{-10}$ m$^2$/s. The effective diffusivity values for the samples $SMP_{SD,1}$, $SMP_{SD,2}$ and $SMP_{SD,3}$ in this study were calculated from 5.673×10$^{-9}$,2.644×10$^{-9}$, 2.133×10$^{-8}$. These values are very close and even equal to the values reported in the literature for beef (Mewa *et al*., 2018, 2019) and other types during drying at different conditions (Aksoy *et al*., 2019; Elmas *et al*., 2020).

On the other hand, during the drying process, as the time elapses, these samples shrink. Thus, the Cecina dimensions have reduced in length, with, and thickness with the following values 11.4, 6.1, 0.4 ($SMP_{SD,1}$), 11.5, 5, 0.3 ($SMP_{SD,2}$), and 12.7, 5.15, 0.9 ($SMP_{SD,3}$) cm. However, the drying process also causes a darkening during the change in its geometric characteristics. The color ranges from light brown to dark brown, as does the brightness intensity, Figure 8. Also, the hardness and the separation between the structures manifest during drying time. However, the odor is concentrated much higher than in the natural state.

#### *3.4.1 Physicochemical and appearance properties of artisan dry Cecina versus dry Cecina with solar equipment*

In the meat industry, pH is one of the important parameters to measure the quality of the product, and it is related to the water retention capacity and its useful life (Urieta *et al*., 2001). Some researchers have analyzed the pH values in beef at different storage temperatures, finding deals between 5.4 to 5.6 at a temperature of 0 °C (García *et al*., 2015). Also, present pH values are between 5.3 to 5.0 and have a temperature of 4°C. Likewise, Nikola and Rosemary, 2006) reported equal pH values (5.4 to 5.6) in their studies to García *et al*., 2015. However, another author has determined pH values between 5.47 to 6.69 for beef cuts in fillets 48 to 96 hours after harvest, vacuum-packed (Ribeiro *et al*., 2021). For our case, the properties of pH, density, and salinity are determined to determine the effect of drying on the Cecina samples, Table 4. The pH results before and after drying are 4. 4.92, 4.98, 4.95, and 5.77, 5.76, 5.77, respectively. The pH values determined for both cases are among those reported by the authors.

Meanwhile, the salt content and the density of the samples show significant changes. The increase in density and salinity is due to the rise in temperature in the drying process. However, the temperature variation affects the concentration of these parameters, which in turn depends on the amount of solar radiation during the day-table 4.

Now, samples of dry artisanal Cecina were obtained to be compared against the Cecina samples of the solar equipment. For this, its physicochemical characteristics were determined, as well as its appearance. $SMP_{SA,1}$, $SMP_{SA,2}$ and $SMP_{SA,3}$ have been considered for the comparative analyses; see Figure 9. As can be seen, the samples $SMP_{SA,1}$, $SMP_{SA,2}$ and $SMP_{SA,3}$ show significant color changes in different regions of each sample, from light brown to dark brown, not having uniformity. Likewise, these samples do not maintain their shape (sheet), much less their thickness, but rather, they take on a wavy shape, and their thickness is variable throughout the area. And even the fat contained in the meat melts between it, changing color and appearance; see sample $SMP_{SA,3}$ in the center vertically, Figure 8.

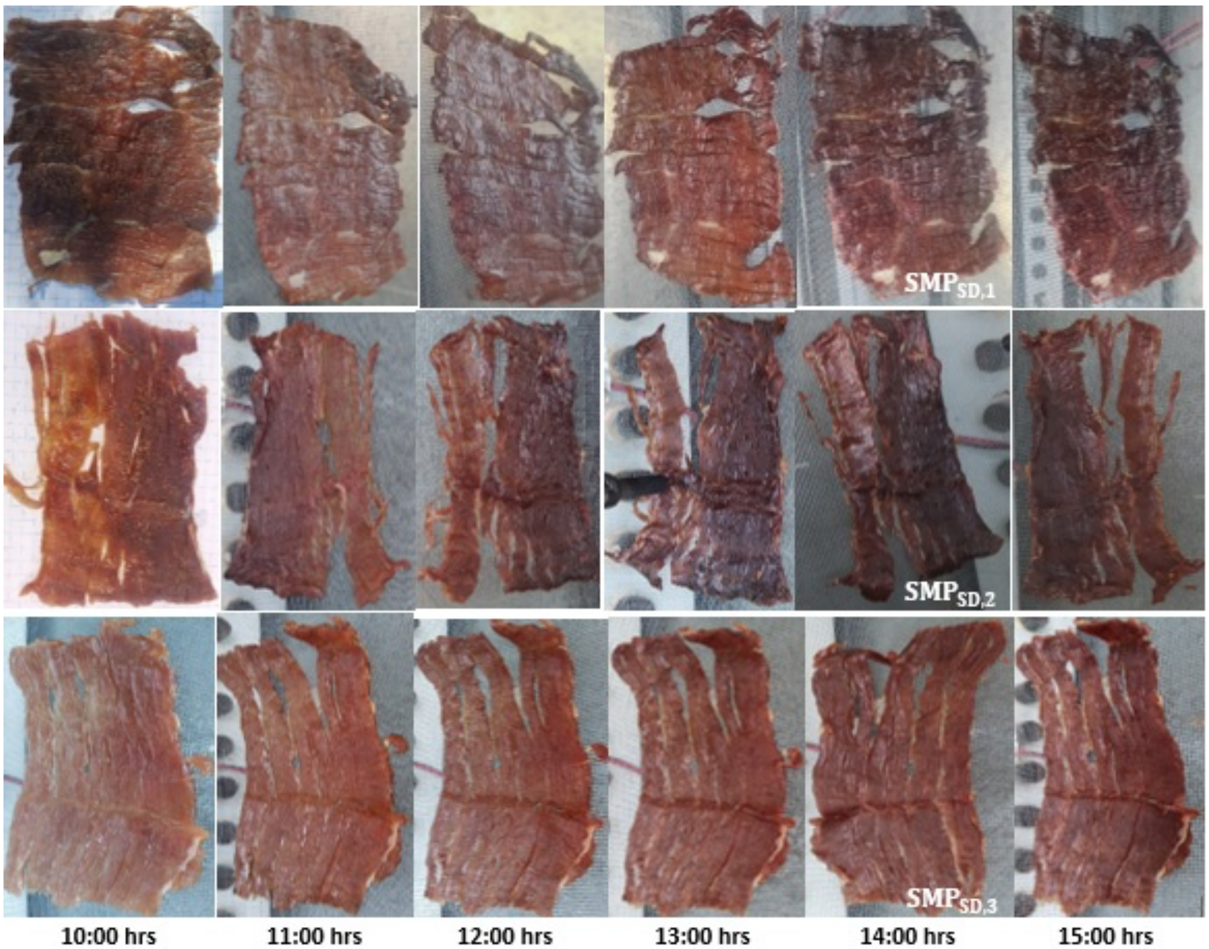


Figure 8. Physical characteristics of the Cecina samples during the drying period. The color change with drying time is represented from left to right of the image.

Table 4. pH, salinity, and density of Cecina samples before and after drying.

| Sample | pH | | Salinity (%) | | Density (kg/m$^3$) | |
|---|---|---|---|---|---|---|
| | Before | After | Before | After | Before | After |
| $SMP_{SD,1}$ | 4.98 | 5,77 | 7 | 44 | 1,005 | 1,034 |
| $SMP_{SD,2}$ | 4,92 | 5,76 | 6 | 37 | 1,004 | 1,028 |
| $SMP_{SD,3}$ | 4,95 | 5,77 | 9 | 33 | 1,006 | 1,024 |

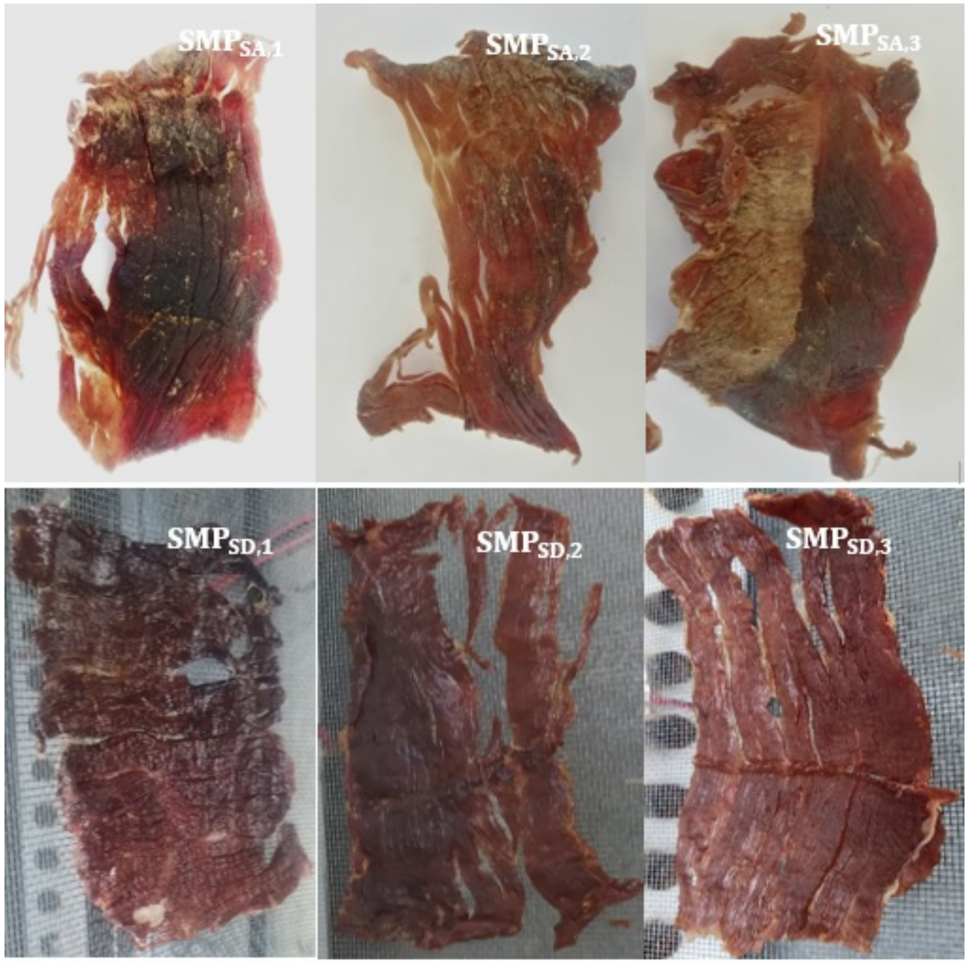


Figure 9. Comparison of dried artisanal Cecina versus dried Cecina by the solar equipment.

The physicochemical properties of the artisanal dried Cecina samples change considerably. Therefore, a comparison is made between the artisanal Cecina samples $SMP_{SA,1}$, $SMP_{SA,2}$ and $SMP_{SA,3}$ versus the dry samples with the solar equipment $SMP_{SD,1}$, $SMP_{SD,2}$ and $SMP_{SD,3}$. Figure 9 presents the best aspect between both drying processes, which corresponds to drying with solar equipment. This result is reflected; with the remaining color uniform throughout the samples, the present fat shrinks without melting, maintaining the yellow-white color. Also, the thickness remains almost uniform throughout the size of the Cecina samples.

In the case of pH, the artisan Cecina pH values are 5.86, 5.81 y 5.77. Therefore, this indicates has higher alkalinity, and tends to increase its water retention capacity. However, salinity (27, 31 and 21 %) and density (1.022, 1.023 and 1.016 kg/m$^3$ ) tend to be lower versus dried Cecina with solar equipment, see Table 4.

On the contrary, the samples pH values ($SMP_{SD,1}$, $SMP_{SD,2}$ and $SMP_{SD,3}$) remain almost the same, but salinity is concentrated in a higher proportion. This salinity concentration tells us that it can be a suitable conservation parameter against microbial attacks to improve the product's shelf life.

In general, the results with the drying process through the solar dryer provide better physical and chemical characteristics and appearance, as has been discussed. Therefore, solar drying is a good option for drying meats such as Cecina from Yecapixtla. The equipment used in this research is a technology that provides similar results with those of dry artisanal Cecina.

## Conclusions

Cecina from Yecapixtla is a cut of meat in very thin fillets and extremely long. Its process is still handmade today. Its preparation consists of spreading lard salt and being exposed to the sun for a short period until its consistency is obtained. An indirect solar dryer with the forced flow has been used in this study to reduce the drying time and improve the product's characteristics.

In the drying processes, satisfactory results have been obtained. The effective diffusivity coefficient has obtained parameters very close to those reported in the literature. The $D_{eff}$ obtained from the samples in this study are 5.673×10$^{-9}$, 2.644×10$^{-9}$, 2.133×10$^{-8}$ m$^2$/s. The variation of the effectiveness coefficient is affected by the temperature and the thickness of the sample. Also, the physicochemical properties are present. Such is the fact that the pH in each of the dry samples improves its alkalinity. These parameters have been compared with other studies in the range (Nikola and Rosemary, 2006) and others very close (Ribeiro *et al*., 2021). However, density and concentration of the dry samples are present with a considerable increase; this is due to the increase in the airflow temperature inside the drying chamber. This flow passes through the interstitial spaces, causing water evaporation, reducing weight and humidity, and consequently increasing the concentration of salts.

Artisan dry Cecina and dry Cecina have been compared with solar equipment. The results have shown that they have similar physicochemical characteristics. While the use of the solar dryer, it provides better appearance characteristics, both in color, thickness, and the presence of intramuscular fat. Also, the smell seems to have a higher concentration.

The solar dryer used has reached temperatures between 30 to 35 °C inside the drying chamber, for solar radiation $R_{12nov}$, $R_{16nov}$, and $R_{29nov}$ and ambient temperatures $T_{a,12nov}$, $T_{a,16nov}$, and $T_{a,29nov}$ between 20 and 25 °C, Figure 6. Weather conditions were for a day with partial cloudiness.

The results have shown that ideal appearance characteristics are not obtained with the open drying method. At the same time, solar equipment has been shown to have considerably better drying capacity, even better when the sun is abundant, without cloudiness and rain. Also, technology, such as the one in this work, can reduce dust contamination and insect infestation in Cecina. Therefore, the solar dryer becomes a good option for drying meat, such as the Yecapixtla's Cecina. However, this research is demonstrated that this technology can replace traditional drying (open method).

It is considered to carry out a study of the change in the organoleptic properties and nutritional elements of the Cecina before and after drying to guarantee the product's quality and replace the artisan drying method with solar equipment. Also, conduct studies of the rehydration capacity and comparison with other drying methods.

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## References

Ahmat, T., Barka, M., Aregba, A. W., & Bruneau, D. (2015). Convective drying kinetics of fresh beef: an experimental and modeling approach. *Journal of Food Processing and Preservation 39*(6), 2581-2595. https://doi.org/10.1111/jfpp.12508

Aksoy, A., Karasu, S., Akcicek, A., & Kayacan, S. (2019). Effects of different drying methods on drying kinetics, microstructure, color, and the rehydration ratio of minced meat. *Foods 8*(6). https://doi.org/10.3390/foods8060216

Apata, E. S., Osidibo, O. O., Apata, O. C., & Okubanjo, A. O. (2013). Effects of different solar drying methods on quality attributes of dried meat product (Kilishi). *Journal of Food Research 2*(1), 80. https://doi.org/10.5539/jfr.v2n1p80

Bala, B. K., & Debnath, N. (2012). Solar drying technology: potentials and developments. *Journal of Fundamentals of Renewable Energy and Applications 2*, 1-5. https://doi.org/10.4303/jfrea/r120302

Barati, E. and Esfahani, J.A. (2012). Mathematical simulation of convective drying: Spatially distributed temperature and moisture in carrot slab. *International Journal of Thermal Sciences 56*, 86 - 94. https://doi.org/10.1016/j.ijthermalsci.2012.01.003

Chaouch, W. B., Khellaf, A., Mediani, A., Slimani, M. E. A., Loumani, A., & Hamid, A. (2018). Experimental investigation of an active direct and indirect solar dryer with sensible heat storage for camel meat drying in Saharan environment. *Solar Energy 174*, 328-341. https://doi.org/10.1016/j.solener.2018.09.037

Çiftçioğlu, G. A., Kadirgan, F., Kadirgan, M. A. N., & Kaynak, G. (2020). Smart agriculture through using cost-effective and high-efficiency solar drying. *Heliyon 6*(2). https://doi.org/10.1016/j.heliyon.2020.e03357

Crank, J. (1975). *The Mathematics of Diffusion*. Oxford University Press, London.

Dufera, L. T., Hofacker, W., Esper, A., & Hensel, O. (2021). Physicochemical quality of twin layer solar tunnel dried tomato slices. *Heliyon 7*(5). https://doi.org/10.1016/j.heliyon.2021.e07127

Ekechukwu, V., Norton, B., Anyanwu, E. E., Onyegegbu, S., Ekechukwu, O. v, & Norton, B. (1995). Review of solar-energy drying systems ii: an overview of solar drying technology. *Energy conversion & Management 40*(99), 615-655. https://www.researchgate.net/publication/283089795

El-Beltagy, A., Gamea, G. R., & Essa, A. H. A. (2007). Solar drying characteristics of strawberry. *Journal of Food Engineering 78*(2), 456-464. https://doi.org/10.1016/j.jfoodeng.2005.10.015

Elmas, F., Bodruk, A., Köprüalan, Ö., Arikaya, Ş., Koca, N., Serdaroğlu, F. M., Kaymak-Ertekin, F., & Koç, M. (2020). Drying kinetics behavior of turkey breast meat in different drying methods. *Journal of Food Process Engineering 43*(10). https://doi.org/10.1111/jfpe.13487

Félix Urieta, L., Félix Urieta, D., De, M., Salud, L., Lozano, R., Danilo, R., Medina, M., Manuel, A., & García, T. (n.d.). Análisis comparativo de carne y productos cárnicos de cabrito Alpino Francés y Alpino Francés. *Técnica Pecuaria en México 39*(3), 237-244.

Figueroa-Garcia, E., Farias-Cervantes, V., Segura-Castruita, M., Andrade-Gonzalez, I., Montero-Cortés, M., & Chávez-Rodríguez, A. (2020). Using artificial neural networks in prediction of the drying process of foods that are rich in sugars. *Revista Mexicana de Ingeniería Química 20*(1), 161-171. https://doi.org/10.24275/rmiq/Sim1403

Fudholi, A., Sopian, K., Yazdi, M. H., Ruslan, M. H., Gabbasa, M., & Kazem, H. A. (2014). Performance analysis of solar drying system for red chili. *Solar Energy 99*, 47-54. https://doi.org/10.1016/j.solener.2013.10.019

Fuentes-Salinas, M., Luna-Sánchez, D., Osorio-Suárez, J., & Corona-Islas, J. (2003). Construcción y validación de un secador solar para madera aserrada. *Revista Chapingo Serie Ciencias Forestales y del Ambiente 9*(2), 171-176.

García-Valladares, O., Cesar-Munguía, A., López-Vidaña, E., Castillo-Téllez, B., Ortíz-Sánchez, C., Lizama-Tzec, F., & Domínguez-Niño, A. (2022). Effect by using a modified solar dryer on physicochemical properties of carambola fruit (*Averrhoa Carambola* L.). *Revista Mexicana de Ingeniería Química 21*(1), Alim2650. https://doi.org/10.24275/rmiq/Alim2650

Jha, A., & Tripathy, P. P. (2021). Recent advancements in design, application, and simulation studies of hybrid solar drying technology. *Food Engineering Reviews 13*(2) 375-410. Springer. https://doi.org/10.1007/s12393-020-09223-2

Kamil Salihoglu, N., Pinarli, V., & Salihoglu, G. (2007). Solar drying in sludge management in Turkey. *Renewable Energy 32*(10), 1661-1675. https://doi.org/10.1016/j.renene.2006.08.001

Kučerová, I., Marek, Š., & Banout, J. (2018). Solar Drying and Sensory Attributes of Eland (Taurotragus oryx) Jerky. *Journal of Food Quality 2018*. https://doi.org/10.1155/2018/1067672

García, A.L., Brugnini, G., Rodríguez, S. and Mir, A. (2015). Vida útil de carne fresca de res envasada al vacío a 0°C y +4°C. *Producción Agropecuaria y Desarrollo Sostenible 4*, 27-45.

Nikola, L.K. and Rosemary, W. (2006). Does it look cooked? A review of factors that influence cooked meat color. *Journal of Food Science 71*(4), 31-40.

Lingayat, A., Chandramohan, V. P., & Raju, V. R. K. (2017). Design, development and performance of indirect type solar dryer for banana drying. *Energy Procedia 109*, 409-416. https://doi.org/10.1016/j.egypro.2017.03.041

Mewa, E. A., Okoth, M. W., Kunyanga, C. N., & Rugiri, M. N. (2018). Drying modelling, moisture diffusivity and sensory quality of thin layer dried beef. *Current Research in Nutrition and Food Science 6*(2), 552-565. https://doi.org/10.12944/CRNFSJ.6.2.29

Mewa, E. A., Okoth, M. W., Kunyanga, C. N., & Rugiri, M. N. (2019). Experimental evaluation of beef drying kinetics in a solar tunnel dryer. *Renewable Energy 139*, 235-241. https://doi.org/10.1016/j.renene.2019.02.067

Nelli, S.S., Mantulak, M.L. Feltan, C.M and Bresciani, J.C. (2021). Medición de variables de experimentación en un prototipo de secador solar para madera. *Revista de Ciencia Tecnología e Innovación 3*(2), 9-21.

Nguyen, H.-B., & Nguyen, H. (2014). A study on beef drying regime towards sustainable energy. *Asia Pacific Journal of Sustainable Agriculture Food and Energy (APJSAFE) 2*(2), 41-46. Journal online http://journal.bakrie.ac.id/index.php/APJSAFE

Pirasteh, G., Saidur, R., Rahman, S. M. A., & Rahim, N. A. (2014). A review on development of solar drying applications. *Renewable and Sustainable Energy Reviews 31*, 133-148. https://doi.org/10.1016/j.rser.2013.11.052

Pruengam, P., Pathaveerat, S., & Pukdeewong, P. (2021). Fabrication and testing of double-sided solar collector dryer for drying banana. *Case Studies in Thermal Engineering 27*. https://doi.org/10.1016/j.csite.2021.101335

Rao, M. A., Rizvi, S. S. H. and Datta, A.K. (2005). *Engineering Properties of Food*. Taylor and Francis, New York.

Ribeiro, F. A., Lau, S. K., Furbeck, R. A., Herrera, N. J., Henriott, M. L., Bland, N. A., Fernando, S. C., Subbiah, J., Sullivan, G. A., & Calkins, C. R. (2021). Ultimate pH effects on dry-aged beef quality. *Meat Science 172*. https://doi.org/10.1016/j.meatsci.2020.108365

Sahoo, M., Titikshya, S., Aradwad, P., Kumar, V., & Naik, S. N. (2022). Study of the drying behaviour and color kinetics of convective drying of yam (*Dioscorea hispida*) slices. *Industrial Crops and Products 176*. https://doi.org/10.1016/j.indcrop.2021.114258

Salehi, F. and Satorabi, M. (2021). Influence of infrared drying on drying kinetics of apple slices coated with basil seed and xanthan gums. *International Journal of Fruit Science 21*, 519 - 527. https://doi.org/10.1080/15538362.2021.1908202

Solís Rodríguez, L. E., Cerón Cardeña, M. A., & Ahumada, I. G. (2003). Diseño y operación de una estufa solar para secar madera. *Ingeniería, Revista Académica 7*(3), 35-48.

Subbian, V., Nadanakumar, V., Christupaul, R., & Kalidasa Murugavel, & K. (2019). Mathematical and experimental analysis of solar tunnel dryer for drying beef as a biological product. *International Journal of Mechanical and Production 9*(4), 489-498.

Srikiatden, J. and Roberts, J.S. (2008). Predicting moisture profiles in potato and carrot during convective hot air drying using isothermally measured effective diffusivity. *Journal of Food Engineering 84*, 516-525. https://doi.org/10.1016/j.jfoodeng.2007.06.009

Tirado, D. F., Montero, P. M., & Acevedo, D. (2015). Estudio comparativo de métodos empleados para la determinación de humedad de varias matrices alimentarias. *Informacion Tecnologica 26*(2), 3-10. https://doi.org/10.4067/S0718-07642015000200002