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Comparative Analysis of Forced Convection and Free Airflow Solar Dehydrators for Sustainable Fruit Preservation in Mexico

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Abstract*– Food waste reduction is essential, making preservation a key area of study. In this context, we present the development and evaluation of solar dehydrators as a sustainable solution to this challenge. Our original comparative analysis specifically evaluates two prototype designs under the particular climatic conditions of central Mexico, characterized by temperature and humidity patterns distinct from other geographic areas. This research is distinguished by the region's atypical rainfall and cloudiness conditions, providing valuable data on dehydrator performance in central Mexico's unique atmosphere. For our investigation, two prototypes were designed and constructed: one with forced convection and another with free airflow, aiming to compare their efficacy in fruit dehydration. Experiments were conducted over extended periods (63-75 hours), with continuous monitoring of temperature, humidity, and mass loss throughout the process. Results showed that the free airflow dehydrator achieved significantly shorter drying times (63 hours vs. 75 hours, $p < 0.05$) than the forced convection model. Despite this difference in processing time, both methods effectively reduced fruit moisture content from 80% to 55.2% ± 1.2%. The quality assessment through organoleptic tests indicated that the dehydrated fruit maintained or improved its sensory characteristics compared to commercial products, with average scores of 8.3/10 for taste and 7.9/10 for texture. We also observed that the initial dehydration rate was 0.37%/h for the free airflow method, gradually decreasing to 0.25%/h at the end of the process. These findings demonstrate the significant potential of solar dehydrators as practical and sustainable tools for food preservation, directly contributing to food security and the achievement of Sustainable Development Goals 2 and 9 of the 2030 Agenda. The implementation of this technology could substantially reduce food waste while empowering rural communities in Mexico and other developing countries.

Keywords-- Solar dehydration, Sustainable agriculture, Forced convection drying, Free airflow systems, post-harvest food processing.

I. INTRODUCTION

Over the past decades, logistical challenges affecting global supply chains have significantly exacerbated food insecurity, especially in developing countries [1]. Events such as the COVID-19 pandemic and geopolitical conflicts have disrupted supply chains and increased prices of essential commodities [2], primarily affecting vulnerable populations and increasing food insecurity by approximately 20% in Latin America [3]. At the same time, food waste remains a critical global issue, with approximately one third of food produced for human consumption being lost or wasted [4], primarily during post-harvest and processing stages in developing countries such as Mexico [5].

This situation has triggered high inflation and exacerbated the scarcity of various products, increasing inequalities in food access and highlighting the vulnerability of supply chains. There is an urgent need to develop innovative solutions to address this problem, both for producers facing input difficulties and for end consumers [6].

Although Mexico is a significant agricultural producer, it still faces challenges in food preservation [7]. In this context, solar dehydrators stand out as an efficient and sustainable technology [8], [9] that harnesses solar energy to extend product shelf life and contribute to food security [10]. They have proven particularly effective in pre-serving fruits and vegetables, reducing post-harvest losses by up to 30% [11].

Despite advances in solar dehydration technology, there is a gap in the literature regarding direct comparison between forced convection and free airflow systems under Mexico's specific conditions [12]. Additionally, there is a lack of studies evaluating the impact of these systems on the organoleptic quality of dehydrated fruits compared to commercial products [13].

This study focuses on developing an efficient and accessible solar dehydrator, aiming to evaluate and compare the effectiveness of two solar dehydration methods: forced convection and free airflow. The hypothesis is that the forced convection method will significantly reduce drying time without compromising the organoleptic quality of the final product, contributing to the preservation of perishable foods.

The intention is to provide a practical and efficient solution that can be implemented in households and communities, especially in regions where electrical infrastructure is limited or nonexistent. The results of this study can significantly contribute to Sustainable Development Goals 2 (Zero Hunger) and 9 (Industry, Innovation, and Infrastructure) of the 2030 Agenda [14], providing innovative and sustainable technology to improve food security in Mexico and other developing countries.

In this context, solar dehydration emerges as a promising technology for food preservation and enhanced food security.

The field of solar dehydration has experienced significant advances reflecting growing interest in the efficiency and sustainability of this technology. Various approaches and designs of solar dehydrators have emerged to address the inherent challenges of food preservation and the use of renewable energy sources [3], [15]. These developments emphasize the importance of developing efficient and cost-effective solar dryers for agricultural products, discussing different types of solar drying systems, such as natural and forced convection dryers, and their applications in drying various agricultural products [16]. The benefits of solar drying include improved product quality and reduced energy costs, establishing a solid foundation for the design and development of efficient and cost-effective fruit dehydrators for the future.

An experimental study on a solar food dehydrator with thermal storage using phase change material is presented in [17]. The dehydrator efficiently dried onions, apricots, and peas, showing significant moisture removal percentages. The incorporation of phase change materials in the thermal storage chamber proved effective in maintaining temperature, even during periods of reduced sunlight. Solar drying applications for fruits and vegetables are addressed, focusing on aspects such as the drying process, economic and environmental assessments, and the application of solar dehydrators in the food industry.

Other research reviews techniques such as cold plasma, pulsed electric field, edible coating, ultrasound, hot air impact blanching with high humidity, infrared blanching, and microwave blanching [18], highlighting their benefits such as shorter drying times, better rehydration capacity, and higher color and antioxidant content. However, areas for future research and development are suggested, including evaluation of the resulting quality of dehydrated products.

In [19], the effect of traditional methods and improved solar drying methods on flavor quality and nutritional composition of mangoes and pineapples is studied. The study finds that the improved solar drying method outperforms traditional methods in preserving sensory quality and nutritional content, suggesting it as a feasible solution for reducing post-harvest fruit losses in East Africa.

In [20], a solar dehydrator with electrical support for fruit drying was investigated, achieving collector thermal efficiencies of 23.37% and overall system efficiency of 18.8%. Their results demonstrated that under favorable conditions, it is possible to achieve reductions in electrical consumption of up to 35%. Additionally, an indirect natural convection solar dehydrator, specifically adapted to the geographical and climatic conditions of Meknes, Morocco, was developed in [21]. This system, inclined at 34° to the ground, reached maximum output temperatures of 58°C and allowed for substantial mass reduction in banana slices, decreasing from 549.76 g to 138.41 g, demonstrating its effectiveness.

Similarly, in [22], a mixed-mode solar dehydrator with vertical air distribution channel was analyzed using CFD. Results indicated that this configuration significantly improves homogeneity in drying air distribution, showing minimal velocity variations (0.015 m/s) and relative humidity differences of 2% between trays.

A comprehensive study on photovoltaic powered solar dryers for sustainable rural development was presented in [23]. This work concluded that approximately 3,500 solar drying units, with an aperture area of 36 m² each, can process approximately 480,000 kg of dried agricultural products per day, representing 25% of the harvest and recovering a significant amount of drinking water during the process.

Other recent studies have continued to expand the knowledge on different aspects of solar dehydration. The thermal performance of the tomato drying process has been evaluated [24], environmental variables during apple dehydration have been analyzed [25], providing valuable data on the influence of climatic factors. In terms of technological innovation, a sensor based approach was developed to optimize production cycles in solar dehydrators [26] and an HMI system was designed to monitor and control the dehydration process [27]. Additionally, other works modeled the drying kinetics for tropical fruits in the Peruvian Amazon region [28] highlighting the importance of adapting these systems to specific geographical conditions.

These advances demonstrate the potential of solar drying systems to establish themselves as a viable and sustainable technology in agricultural product processing. However, challenges and limitations persist, such as variable energy efficiency, which can be affected by changing climatic conditions [17]. These studies, while showing great progress in the development of solar dehydrators, do not provide direct comparative analyses between forced convection and free flow systems under the specific climatic conditions of Mexico, especially in adverse weather scenarios, a gap that the present study addresses.

This study seeks to determine the efficacy of these systems in fruit dehydration under the specific climatic conditions of San Juan del Río, Querétaro, Mexico. By comparing these two methods, we aim to identify the most efficient configuration in terms of drying time and final product quality. The results of this study aim to contribute to the development of more sustainable and accessible food preservation solutions, aligned with Sustainable Development Goals 2 and 9 of the 2030 Agenda, particularly in regions with limited resources or deficient electrical infrastructure.

II. Materials and Methods

A. Design

This study was designed to compare the efficacy of two types of solar dehydrators: one with forced convection and another with free airflow. Following recommendations proposed by Zhang and Zhu [29], which demonstrate their effectiveness in comparative evaluation of solar drying technologies, a 2x2 factorial design was used where the factors were dehydrator type (forced convection vs. free airflow) and drying time. Tests were performed in triplicate for each type of dehydrator, resulting in a total of 12 experiments. This methodology differentiates this research from previous work because it evaluates comparative performance under Mexican climatic conditions, deliberately incorporating periods of adverse conditions, which provides original data on the robustness of both systems in real world implementation contexts.

Hence, the study was conducted under the climatological conditions of San Juan del Río, Querétaro, Mexico, for the months of November and December, based on the period 1991-2020 [30] (see Table I).

TABLE I
CLIMATOLOGICAL NORMS FOR SAN JUAN DEL RÍO, QUERÉTARO

Elements	Nov	Dec
Normal Maximum Temperature	26	25.4
Monthly Maximum	30.9	30.5
Years with data	29	28
Normal Minimum Temperature	10.9	8.8
Monthly Minimum	7.7	5.6
Years with data	29	28
Normal Medium Temperature	18.4	17.1
Years with data	29	28

The experiments were conducted from November 9 to December 11, 2023, a period characterized by atypical weather conditions, including frequent rainfall, high cloud cover, and below normal temperatures. These adverse conditions were deliberately included in the study to evaluate the dehydrators' performance under challenging circumstances. Mugi et al. [15] note that climatic variations significantly influence drying time and can affect product uniformity. Additionally, Bécquer et al.'s recommendation to maintain dehydration temperatures below 65°C to maximize vitamin retention was considered [9]. This approach allowed for a comprehensive evaluation of the dehydration process under real and variable conditions.

Sample size was determined through power analysis using G*Power 3.1 [31], with an expected effect size of 0.8 (considered large according to Cohen), an alpha level of 0.05, and desired power of 0.8. This analysis determined that a minimum of 10 experiments was needed to detect significant differences between treatments; therefore, 12 experiments were conducted to exceed the minimum requirement.

B. Prototype construction

The solar dehydrator prototype was designed and constructed following a modular approach (see Fig. 1), consisting of three main components: the solar collector, the dehydration chamber, and the ventilation system.

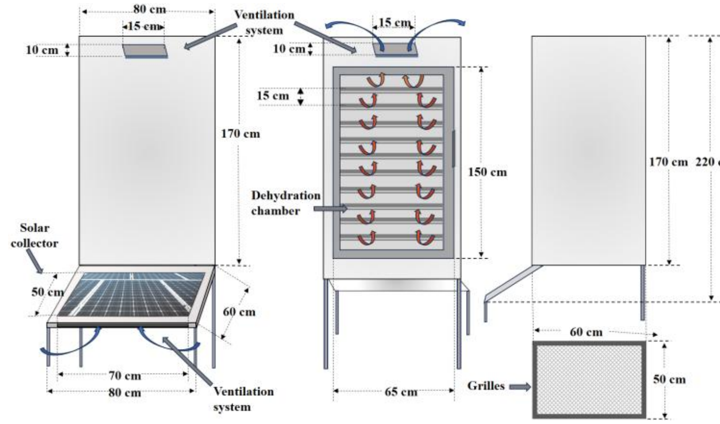

Fig. 1 Schematic design of the solar dehydrator prototype with forced convection.

Solar collector

The solar collector was fabricated using 1.5 mm thick galvanized steel sheet, with dimensions of 2.20 m length, 80 cm width, and 60 cm depth. The interior surface was painted matte black to maximize solar radiation absorption [9]. Tempered glass of 4 mm thickness was installed on the diagonal part of the collector to allow solar radiation entry and create a greenhouse effect.

Dehydration chamber

The dehydration chamber was constructed by installing ten food grade stainless steel mesh trays, each with an area of 3000 cm², uniformly spaced at 15 cm intervals to optimize airflow and heat distribution. The chamber was thermally insulated with compressed natural cork gaskets to minimize heat loss [32].

Ventilation system

The ventilation system consisted of a 100 W centrifugal fan (only for the forced convection prototype), with a maximum flow rate of 200 m³/h, connected to the bottom of the solar collector. The fan was powered by a 150 W photovoltaic solar panel and a 12 V battery to ensure continuous operation during daylight hours [9]. Air ducts of 100 mm diameter were installed to connect the solar collector, dehydration chamber, and fan.

Sensor placement

The optimal sensor position was determined using the Reynolds number (Re), equation (1), a dimensionless quantity that characterizes the flow regime in different airflow situations under various conditions within the dehydrator:

$$\mathrm{Re} = \rho \upsilon D / \mu \,. \tag{1}$$

Where ρ represents air density (kg/m³), v is the characteristic air velocity (m/s), D denotes the dehydrator air duct diameter (m), and μ is the dynamic viscosity of air (kg/m·s).

The Reynolds number calculation facilitated the identification of regions of interest for strategic sensor placement, with the objective of capturing representative airflow data in various zones of the dehydrator. This analysis allowed for the determination and instrumentation of three critical locations: (1) the center of the solar collector, where air begins to heat; (2) the center of the dehydration chamber, where the main heat and mass transfer occurs; and (3) the external environment, to establish reference conditions.

C. Experimental procedures

Comparative trials were conducted between a forced convection dehydrator and a free airflow dehydrator. For each trial, 750 g of fresh apples were processed following a standardized protocol: samples were washed with potable water, peeled, and sectioned into uniform slices of 5.0 ± 0.1 mm thickness using a calibrated mandolin.

The slices were weighed immediately after sectioning using an analytical balance with a resolution of 0.1 g and a measurement uncertainty of ±0.2 g. Subsequently, the samples were homogeneously distributed on the dehydrator trays to ensure uniform air flow exposure.

Monitoring and data collection

The dependent variables under study were: temperature (°C), relative humidity (%), mass loss (g), and organoleptic characteristics of the final product. The dehydration process lasted between 63 and 75 hours, depending on the type of dehydrator used.

For measuring and recording air temperature and relative humidity, DHT22 sensors were employed with a measurement uncertainty of ±0.5°C for temperature and ±2% for relative humidity. These sensors were installed at previously identified critical locations and connected to an Arduino Uno microcontroller, which stored the data on an SD card. Data acquisition was performed automatically at 30 minute intervals, ensuring continuous and consistent monitoring of air conditions throughout the dehydration process in all experimental trials.

Mass loss was determined using a digital balance with a resolution of 0.1 g. Measurements were taken at the beginning and end of the process, with intermediate weightings every 2 hours.

To minimize variability between trials, the same batch of apples was used in all tests, strictly following the same sample preparation and loading protocol. Additionally, tests for both types of dehydrators (forced convection and free airflow) were conducted simultaneously to ensure identical environmental conditions.

Dehydrated fruit quality assessment

The quality of the dehydrated fruit was evaluated through determination of final moisture content and analysis of organoleptic properties. Moisture content was quantified using the oven drying method, following the protocol established in AOAC 934.06 standard [33].

Organoleptic properties (color, aroma, texture, and flavor) were evaluated by a sensory panel composed of 30 semi trained judges (15 males and 15 females, mean age 35 ± 7 years). A 9 point hedonic scale was used to rate each attribute, where 1 indicates "extremely dislike" and 9 indicates "extremely like." Sensory evaluation was conducted in a controlled environment, following the guidelines of ISO 8589:2007/Amd 1:2014 [34] for sensory test room design.

D. Data analysis

Statistical analysis

Temperature, humidity, and mass loss data were analyzed using descriptive statistics. To compare drying times between forced convection and free airflow methods, a Student's t-test for independent samples was performed.

The final moisture content of dehydrated samples was also compared between the two methods using a Student's t-test.

For all analyses, the significance level was set at $p < 0.05$. Statistical analyses were performed using R version 4.2.2 [35] in RStudio version 2022.12.0+353 [36].

Volumetric flow rat estiemation

The volumetric flow rate (Q) of air through the dehydration chamber was estimated using the equation (2) for incompressible flow:

$$Q = A\upsilon \tag{2}$$

Where Q represents the volumetric flow rate (m^3/s), A is the cross sectional area (m^2), and v denotes air velocity (m/s). This equation allowed for the quantification of air movement through the dehydration chamber, a critical parameter for understanding drying kinetics.

Heat transfer modeling

The convective heat transfer rate (Q) within the dehydrator was modeled using Newton's law of cooling, equation (3).

$$Q = hA(Ts - Ta) \tag{3}$$

Where Q represents the heat transfer rate (W), h is the convective heat transfer coefficient ($W/m^2{\cdot}K$), A denotes surface area (m^2), Ts is surface temperature (K), and Ta represents air temperature (K).

System energy balance

The general energy balance in the dehydrator was analyzed using the first law of thermodynamics, equation (4).

$$\frac{dE}{dt} = Qin - TQout \tag{4}$$

Where dE/dt represents the rate of energy change in the system (W), Qin denotes the rate of energy entering the system (W), and Qout is the rate of energy leaving the system (W).

This equation allowed for the evaluation of energy efficiency throughout the dehydration process.

Drying kinetics modeling

The drying rate of fruit samples was modeled using a first order kinetic equation, equation (5).

$$\frac{dM}{dt} = k(M - Me) \qquad (5)$$

Where dM/dt represents the rate of change of moisture content (kg water/kg dry matter), k is the drying constant (s^1), M denotes current moisture content (kg water/kg dry matter), and Me is the equilibrium moisture content (kg water/kg dry matter).

This study was conducted in accordance with the ethical guidelines established by the Tecnológico Nacional de México/Instituto Tecnológico de San Juan del Río. No specific ethical approval was required as the study did not involve human or animal participants.

III. RESULTS

The experiments conducted provided significant data on the efficacy of forced convection (see Fig. 2) and free airflow (see Fig. 3) solar dehydrators for fruit preservation.

Fig. 2 Solar dehydrator prototype without forced convection.

Fig. 3 Solar dehydrator prototype with forced convection.

The following presents the key findings in terms of operating conditions and airflow characterization, drying times and moisture content reduction, drying kinetics, dehydrator performance, and organoleptic analysis.

A. *Operating conditions and airflow characterization*

During the tests, operating conditions in the dehydration chamber were recorded for both prototypes. Table II shows the average conditions observed:

TABLE II
AVERAGE CONDITIONS FOR TESTS WITH FORCED CONVECTION AND FREE AIRFLOW VENTILATION SYSTEMS

Prototype	**Dehydration Chamber Interior**		**Time**
	Temperature °C	**% Humidity**	**Hours**
Forced Convection	25.6 ± 5.6	45.75 ± 2.3	75
Free Airflow Ventilation	31.2 ± 2.1	45.63 ± 2.5	63

Using these temperature data and air velocity measurements, the volumetric flow rate and Reynolds number were calculated for both types of dehydrators. Table III presents the results of these measurements and calculations.

TABLE III
VOLUMETRIC FLOW RATE AND REYNOLDS NUMBER FOR BOTH DEHYDRATORS

Parameter	**Free Airflow**	**Forced Convection**
Air velocity (m/s)	0.15 ± 0.02	0.35 ± 0.03
Cross-sectional area (m^2)	0.25	0.25
Volumetric flow rate (m^3/s)	0.0375 ± 0.005	0.0875 ± 0.0075
Hydraulic diameter (m)	0.5	0.5
Reynolds number	1230 ± 164	2870 ± 246

The Reynolds number values indicate that the flow in the free airflow dehydrator is in the laminar regime (Re < 2300), while the forced convection dehydrator operates in the transition regime (2300 < Re < 4000). This difference in flow regimes significantly influenced the dehydration process efficiency and contributed to the observed differences in drying times.

B. Drying times and moisture content reduction

The free airflow dehydrator achieved shorter drying times (M = 63 hours, SD = 4.2) compared to the forced convection system (M = 75 hours, SD = 5.6). This difference was statistically significant ($t(8) = 2.45$, $p = 0.04$, $d = 0.82$). The effect size ($d = 0.82$) indicates a large practical significance in the difference between the two systems.

The initial moisture content of fresh apples was 80% (SD = 1.5%). After processing, it was reduced to 55.2% (SD = 1.2%) in the free airflow dehydrator and to 55.6% (SD = 1.3%) in the forced convection system. This difference was not statistically significant ($t(8) = 0.56$, $p = 0.59$), suggesting that both systems achieved similar final moisture content despite differences in drying times.

C. Comparative performance analysis

Temperature and humidity parameters were crucial for the dehydration process, as detailed in Table I. A notable disparity in drying times was observed, which can be attributed to temperature differences, particularly affecting the duration of the forced convection test [37]. The temperature profiles showed consistent patterns throughout the drying period, with the free airflow system maintaining higher average temperatures (31.2°C) compared to the forced convection system (25.6°C).

To compare dehydrator performance, a two sample Student's t-test was conducted. Results indicated a significant difference in drying times between the two methods ($t(8) = 2.45$, $p = 0.04$), with the free airflow dehydrator achieving shorter average drying times (M = 63 hours, SD = 4.2) compared to the forced convection dehydrator (M = 75 hours, SD = 5.6). This difference in performance can be attributed to the more efficient heat distribution and natural convection patterns observed in the free airflow system.

D. Drying kinetics

Figure 4 shows the drying kinetics for both dehydration methods. The dehydration rate was observed to be faster in the first 24 hours for both methods, gradually decreasing as the process progressed. This behavior follows the typical pattern of moisture reduction in food dehydration processes, characterized by an initial rapid moisture loss followed by a slower dehydration phase

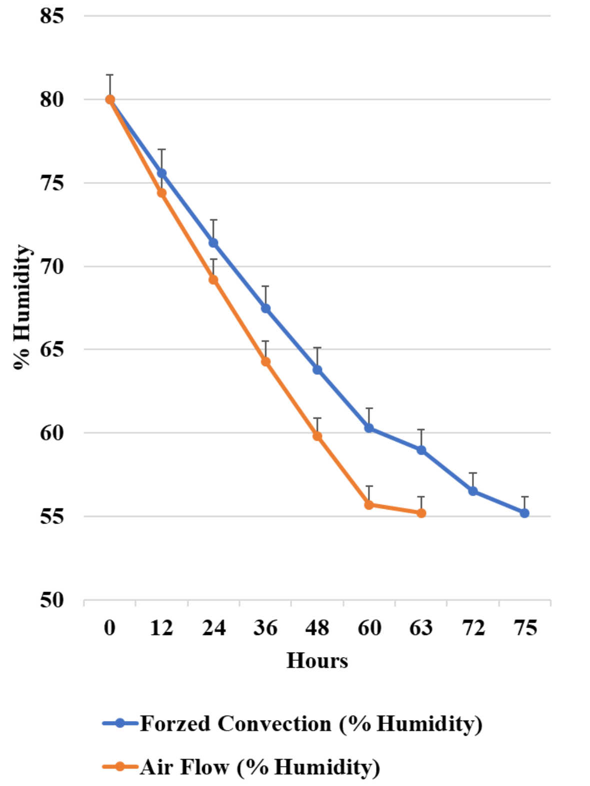

Fig. 4 Moisture content vs. time for both dehydration methods, showing the characteristic drying curves and rate changes throughout the process.

Table IV presents the detailed dehydration rates and moisture content reduction during the process, including hourly measurements for both systems.

TABLE IV
DEHYDRATION RATES AND MOISTURE CONTENT REDUCTION IN FRUIT

Time (hours)	Forced Convection		Free Airflow	
	% Humidity	Rate (%h)	% Humidity	Rate (%h)
0	80.0 ± 1.5	-	80.0± 1.5	-
12	75.6± 1.4	0.37± 0.04	74.4± 1.3	0.47± 0.05
24	71.4± 1.4	0.35± 0.03	69.2± 1.2	0.43± 0.04
36	67.5± 1.3	0.33± 0.03	64.3± 1.2	0.41± 0.04
48	63.8± 1.3	0.31± 0.03	59.8± 1.1	0.38± 0.03
60	60.3± 1.2	0.29± 0.02	55.7± 1.1	0.34± 0.03
63	59.0± 1.2	0.28± 0.02	55.2± 1.0	0.17± 0.02
72	56.5± 1.1	0.26± 0.02	N/A	N/A
75	55.2± 1.0	0.43± 0.05	N/A	N/A

E. Dehydrator Performance

Results obtained during dehydration tests revealed significant variations in environmental conditions, primarily in temperature and humidity, as shown in Figure 5. The temperature monitoring showed clear diurnal patterns, with peak temperatures occurring during midday hours and minimum temperatures during early morning hours.

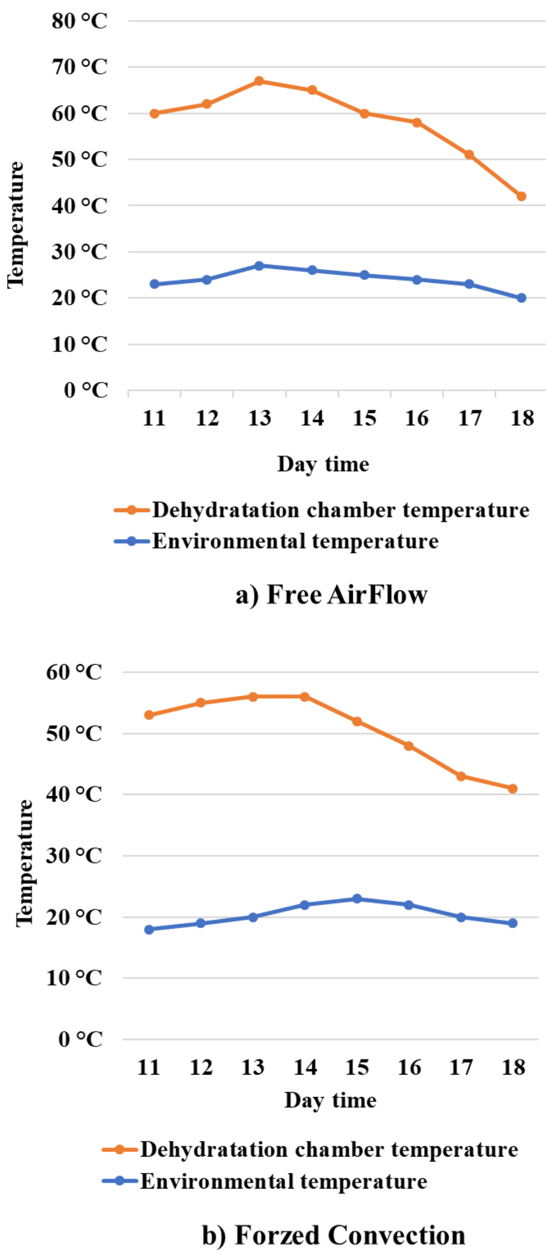

Fig. 5 Comparative hourly internal and ambient temperature.

A moisture content reduction of 24.8% was observed, reaching a final content of 55.2% ± 1.2%, consistent with recommendations by Kant et al. [38]. This reduction was achieved while maintaining product quality and structural integrity.

The visual comparison between samples from both systems showed minimal differences in appearance, see Figure 6 and Figure 7, with both achieving the desired level of dehydration while maintaining product quality.

Fig. 6 Dehydrated Fruit (Free Airflow Test).

Fig. 7 Dehydrated Fruit (Forced Convection Test).

F. *Organoleptic Analysis*

The results of organoleptic tests are presented in Table V, showing average scores for each attribute evaluated by the sensory panel. The evaluation was conducted with 30 semi-trained judges under controlled conditions, following standardized sensory evaluation protocols

TABLE V
RESULTS OF ORGANOLEPTIC TESTS OF DEHYDRATED FRUIT

Attribute	Force Convection	Free Airflow	Commercial Reference
Color	7.8± 0.06	7.5± 0.07	7.6± 0.05
Texture	8.2± 0.05	7.9± 0.06	8.0± 0.04
Flavor	8.5± 0.04	8.3± 0.05	8.1± 0.06
Aroma	8.0± 0.05	7.8± 0.06	7.9± 0.05

The dehydrated samples showed comparable or superior characteristics to commercial dehydrated fruits, highlighting that flavor was maintained or improved in some cases, and color, texture, and aroma were comparable or even more concentrated. Statistical analysis of the sensory evaluation data revealed no significant differences between the two dehydration methods in terms of organoleptic properties ($p > 0.05$ for all attributes). This suggests that both solar dehydrators can be viable and sustainable alternatives for food preservation in Mexico, producing high quality dried products that meet consumer expectations.

IV. DISCUSSION

The results obtained in this study highlight the effectiveness and potential of solar dehydrators as a sustainable solution for food preservation. The solar dehydrator prototype developed demonstrated its capacity to significantly reduce fruit moisture content, thus extending shelf life and contributing to food security.

When comparing both dehydration systems, the free flow system achieved shorter drying times, similar to the findings of Bécquer et al. [9]. Reynolds number analysis revealed distinct flow regimes in each system: laminar in the free flow system ($Re < 2300$) and transitional in the forced convection system ($2300 < Re < 4000$), which likely explains the variation in drying efficiency, as laminar flow seems to create a more uniform distribution of hot air around the fruit samples, while transitional flow can generate more complex patterns that reduce efficiency. This fluid dynamic behavior directly impacts the dehydration process and explains the finding that the non-forced convection system performed better under the specific climatic conditions analyzed.

However, it is important to note that climatic conditions and specific characteristics of the dehydrator design can influence these results [15], [37].

The reduction in fruit moisture content achieved by both dehydration methods is comparable to results reported in the literature. Kant et al. [38] obtained a similar moisture reduction when dehydrating apples in a solar dehydrator prototype, supporting the effectiveness of the dehydration process implemented in this study.

Organoleptic evaluations showed that both dehydration methods generated fruit with sensory properties similar or even superior to those of commercial products, like the results obtained by Mohammed et al. [39], which is crucial for the adoption of the technology in rural communities [40] representing a key advantage over other developed prototypes. Solar dehydrators can improve food security because they use readily available materials making them economical (estimated cost: 1500-2000 MXN) and being easily replicable in resource limited areas in Mexico [5], they represent a viable implementation at the local level.

When comparing the findings of this research with other recent studies, both similarities and significant differences are observed. Although El-Sheikha et al. [24] reported thermal efficiencies of 23.37% in solar dehydration systems, similar to the results of this study in the free Airflow system, they focused on tomatoes under optimal climatic conditions, and this study on apples under adverse climatic conditions, offering complementary perspectives. Martínez-Rodríguez et al. [25] analyzed environmental variables during apple dehydration, although without the direct comparison between the two systems presented in this work. The sensor based approach developed by da Silva et al. [26] could complement our work, particularly in capturing the adverse climatic conditions experienced in this study. Finally, while Yalta Chappa et al. [28] modeled the drying kinetics for tropical fruits in the Peruvian Amazon region, this research provides specific data for adverse temperatures in Mexico, highlighting the importance of considering climatic variations in the design and evaluation of these technologies. In addition to these technical and contextual contributions, the use of solar energy as a heat source reduces dependence on fossil fuels and contributes to climate change mitigation [10], [23].

It is important to acknowledge the limitations of this study. The sample size and duration of tests were limited due to time and resource constraints. Additionally, climatic variability during the test period, with atypical conditions of rain and cloudiness, may have influenced the obtained results. These limitations suggest the need for additional studies with larger samples and under different climatic conditions to obtain more generalizable results.

Future research could explore the use of solar dehydrators for a wider variety of fruits and other food products, as well as evaluate their performance in different geographic locations and climatic conditions [19]. Furthermore, follow up studies could be conducted to assess the acceptance and adoption of this technology by target communities and its long term impact on food security and sustainability [40].

Finally, the results of this study highlight the potential of solar dehydrators as an effective and sustainable solution for food preservation, especially in the context of Mexican conditions. While more research is needed to address the identified limitations and explore additional aspects, the findings obtained establish a solid foundation for the development and promotion of this technology as a valuable tool for improving food security and sustainability in Mexico.

V. CONCLUSIONS

This study demonstrates the effectiveness of solar dehydrators as a sustainable solution for food preservation in Mexico. Both prototypes, forced convection and free airflow, achieved a significant reduction in fruit moisture content, from an initial 80% to a final 55.2% ± 1.2%. Contrary to the initial hypothesis, the free airflow dehydrator showed significantly shorter drying times (63 hours vs. 75 hours, $p < 0.05$), which is partially attributed to the differences in flow regimes identified through Reynolds number analysis.

When comparing the results of this research with recent studies [24], [25], [28], [41], the importance of assessments that consider the specific climatic conditions of each region is highlighted, differentiating this work from previous approaches and providing valuable data for the development of technologies adapted to the Mexican context.

Organoleptic tests revealed that the dehydrated fruit maintained or improved its sensory characteristics compared to commercial products, with average scores of 8.3/10 for taste and 7.9/10 for texture. These results support the use of solar dehydrators, especially free airflow ones, as practical and accessible tools to address food security challenges.

The accessible design and energy efficiency of the developed prototypes make them particularly suitable for implementation in rural communities and areas with limited resources. This technology directly contributes to Sustainable Development Goals 2 and 9 of the 2030 Agenda, offering a viable solution to reduce food waste and improve food security in Mexico and other developing countries, particularly in regions with limited electrical infrastructure.

Future studies should explore the applicability of this technology to a wider range of food products and evaluate its performance under various climatic conditions to validate its effectiveness on a larger scale.

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