



PERFORMANCE EVALUATION OF A MULTI-ARC RIBBED MIXED SOLAR DRYER FOR QUINOA DRYING

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ABSTRACT

Objective: The objective of this research was to evaluate a forced convection mixed solar dryer incorporating an artificial multi-arc ribbed roughness coupled to the top of the absorber plate for the drying process of quinoa (*Chenopodium quinoa* Willd) and compare it with open sun drying.

Theoretical Framework: The study is based on the thermal efficiency of the solar air heating collector and the overall thermal efficiency of the mixed dryer.

Method: The solar dryer is low cost and easy to construct, consisting of a solar air heating collector, a drying chamber and an air blower system powered by photovoltaic energy. The thermal efficiency for quinoa was evaluated for mass flow rates of 0.189 kg/min, 1.197 kg/min, 1.547 kg/min and 1.893 kg/min.

Results and Discussion: The maximum average thermal efficiency of the solar collector is 77 % for an average solar irradiance of 1055 W/m² and for a mass flow rate of 1.197 kg/min where the average drying temperature was 56 °C. The maximum average overall efficiency achieved was 23.28% and the minimum drying time was 2.1 hours.

Research Implications: The mixed solar dryer has a maximum efficiency for a forced flow of 1.02 kg/min and the drying time is reduced to 68% compared to open sun drying.

Originality/Value: This research reveals the drying process of quinoa and a way to increase the efficiency of the arc-ribbed solar dryer that reduces drying time by more than half compared to open sun drying.

Keywords: Mixed Solar Dryer, Forced Convection, Multiple Arc Rib, Drying Efficiency, Quinoa.

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AVALIAÇÃO DO DESEMPENHO DE UM SECADOR SOLAR MISTO COM NERVURAS DE MÚLTIPLOS ARCOS PARA A SECAGEM DE QUINOA

RESUMO

Objetivo: O objetivo desta pesquisa foi avaliar um secador solar misto de convecção forçada que incorpora uma rugosidade artificial com nervuras em vários arcos acoplada ao topo da placa absorvedora para o processo de secagem de quinoa (*Chenopodium quinoa Willd*) e compará-lo com a secagem ao sol aberto.

Referencial Teórico: O estudo se baseia na eficiência térmica do coletor de aquecimento de ar solar e na eficiência térmica geral do secador misto.

Método: O secador solar é de baixo custo e fácil de construir, consistindo em um coletor de aquecimento de ar solar, uma câmara de secagem e um sistema de soprador de ar alimentado por energia fotovoltaica. A eficiência térmica da quinoa foi avaliada para taxas de fluxo de massa de 0.189 kg/min, 1.197 kg/min, 1.547 kg/min e 1.893 kg/min.

Resultados e Discussão: A eficiência térmica média máxima do coletor solar é de 77% para uma irradiância solar média de 1.055 W/m² e para uma taxa de fluxo de massa de 1.197 kg/min, em que a temperatura média de secagem foi de 56 °C. A eficiência geral média máxima alcançada foi de 23.28% e o tempo mínimo de secagem foi de 2.1 horas.

Implicações da Pesquisa: O secador solar misto tem uma eficiência máxima para um fluxo forçado de 1,02 kg/min e o tempo de secagem é reduzido em 68% em comparação com a secagem ao sol aberto.

Originalidade/Valor: Esta pesquisa revela o processo de secagem da quinoa e uma maneira de aumentar a eficiência do secador solar com arco de nervuras que reduz o tempo de secagem em mais da metade em comparação com a secagem a céu aberto.

Palavras-chave: Secador Solar Misto, Convecção Forçada, Arco Múltiplo com Nervuras, Eficiência de Secagem, Quinoa.

EVALUACIÓN DEL RENDIMIENTO DE UN SECADOR SOLAR MIXTO CON NERVADURA EN FORMA DE ARCO MÚLTIPLE PARA EL SECADO DE LA QUINUA

RESUMEN

Objetivo: El objetivo de esta investigación fue evaluar un secador solar mixto de convección forzada que incorpora una rugosidad artificial de nervaduras en forma de arco múltiple acoplada en la parte superior de la placa absorbente para el proceso de secado de la quinua (*Chenopodium quinoa Willd*) y comparar con el secado al sol abierto.

Marco Teórico: El estudio se fundamenta en la eficiencia térmica del colector solar calentador del aire y la eficiencia térmica general del secador mixto.

Método: El secador solar es de bajo costo y de fácil construcción, consta de un colector solar calentador de aire, una cámara de secado y un sistema de sopladores de aire que funciona con energía fotovoltaica. Se evaluó el rendimiento térmico para la quinua, para flujos masicos de 0.189 kg/min, 1.197 kg/min, 1.547 kg/min y 1.893 kg/min.

Resultados y Discusión: La eficiencia térmica promedio máxima del colector solar es del 77 % para una irradiancia solar media de 1055 W/m² y para un caudal masico de 1.197 kg/min donde la temperatura promedio de secado fue 56 °C. La eficiencia general promedio máxima alcanzada fue de 23.28% y el tiempo de secado mínimo fue de 2.1 horas.

Implicaciones de la investigación. El secador solar mixto tiene una máxima eficiencia para un flujo forzado de 1.02 kg/min y el tiempo de secado se reduce a un 68% en comparación del secado al sol abierto.



Originalidad/Valor: Esta investigación revela el proceso de secado de la quinua y una forma de aumentar la eficiencia del secador solar con nervaduras en forma de arco que reduce el tiempo de secado a mas de la mitad comparada con el secado al sol abierto.

Palabras clave: Secador Solar Mixto, Convección Forzada, Nervaduras de Arco Múltiple, Eficiencia de Secado, Quinoa.

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1 INTRODUCTION

The use of renewable resources is of great interest due to the energy needs, their availability and lower environmental impact compared to other forms of energy, which makes it very important to use them. Solar energy in the Puno region (Peru), located in the global south (Ukoba et al., 2024), is abundant and can be used to generate great benefits and mitigate obstacles to access to energy (Fernandes & Tavares, 2024).

Solar collectors are devices that collect solar energy and efficiently transfer it to the working fluid, heating it so that it can be used for some purposes such as heating, product drying, and cooling (Goel et al., 2021). Solar air heaters are the types of solar collectors where air is heated by absorbing solar radiation and air is the working fluid. The solar air heater consists of a black painted metal absorber plate to increase its radiation absorption capacity, a glass or polycarbonate cover with high transmissivity and low absorptivity that reduces radiation losses, and an insulated wooden duct. Solar air heaters are especially suitable for food drying in the temperature range of 40 °C to 70 °C (Ekka et al., 2021; Kamarulzaman et al., 2021). The efficiency of a solar heater is low due to the low thermal conductivity of air, the main cause being the laminar sublayer that forms near the absorbent surface as the air flows over the plate. One way to eliminate the laminar sublayer is through artificial roughness that generates turbulence in the air and increases the efficiency (Ahirwar & kumar, 2024; Goel et al., 2021). The literature shows that there are various ways to incorporate artificial roughness in the absorbent flat plate, which can be single flow or double flow, the most prominent ones being in the form of multiple V-ribs and multiple arch-shaped ribs (Ahirwar & kumar, 2024; Goel et al., 2021; Kumar et al., 2019; Pandey et al., 2016).

Food drying involves removing water from food through heat and mass transfer to prevent bacterial growth, which can positively affect product quality and serves to prolong the storage time of food for consumption (Kong et al., 2024; Saha et al., 2024). Traditional drying,



called open sun drying (OSD), involves spreading the food on the ground, on cloths or trays, in the open air (Kumar et al., 2016). Open sun drying has several disadvantages: it is easy to be contaminated with dirt or dust, it can be damaged by animals such as birds and insects, it degrades upon exposure to direct solar radiation, and the food deteriorates, negatively affecting product quality (Kong et al., 2024). One of the innovative techniques to solve the disadvantages of open sun drying is the solar dryer (Kamarulzaman et al., 2021; Kherrafi et al., 2024). Solar dryers can be classified into several groups, depending on the incidence of solar radiation and the type of hot air flow. Depending on the incidence of radiation, the dryer can be: open sun dryer (OSD), inside a space with a transparent top (direct mode), or with an air-heating collector (indirect mode) and with an air-heating collector and a transparent drying chamber (mixed mode). The hot air flow is provided by natural convection or by forced convection with a fan (Kamarulzaman et al., 2021; Kherrafi et al., 2024; AB Lingayat et al., 2020).

There are various studies conducted on different types of dryers such as natural convection and forced convection dryers, which have contributed to the development of mathematical models and thermodynamic analysis providing a scientific basis for solar dryers. The results found demonstrate that solar dryers reduce drying time compared to open sun drying. Solar dryers with artificial roughness of forced convection have higher efficiency (Kamarulzaman et al., 2021; AB Mugi et al., 2020; Saini et al., 2023). There are studies on forced convection solar dryers with blowers powered by photovoltaic solar panels that makes the drying process autonomous and more efficient compared to traditional drying (Bhavsar & Patel, 2021; Ekka et al., 2021; Mbakouop et al., 2023; Mugi & VP, 2022; Rani & Tripathy, 2021).

In the reviewed research, food products such as fruits, vegetables and cereals have been dried. Quinoa (*Chenopodium quinoa* Willd) is an Andean product that is mainly grown in Peru and Bolivia with a high nutritional content, so it can play an important role in global food security and to consume it, it is necessary to process it, washing it and drying it, which producers usually dry in a traditional way (Angeli et al., 2020; Nowak et al., 2016; Pereira et al., 2019; Vega-Galvez et al., 2010). No study was found on the drying of quinoa using a mixed forced convection solar dryer, nor are there any studies analyzing the drying kinetics of quinoa.

Therefore, the present work aims to develop and evaluate a single-flow mixed-type solar dryer with multiple arc-shaped ribbed roughness attached on the top of the flat absorbent plate for the drying process of quinoa (*Chenopodium quinoa* Willd). This study also investigates the effect of air mass flow rates on the performance parameters such as drying temperatures, drying efficiency and drying time to compare with open sun drying.



2 THEORETICAL FRAMEWORK

2.1 THERMAL EFFICIENCY

The thermal efficiency of the solar collector is the relationship between the useful heat transferred to the air and the total solar energy incident on the collector, which is estimated using the following equation (Duffie & Beckman, 2013):

$$\eta_{t,c} = \frac{\dot{m}_a c_a (T_{o,c} - T_{i,c})}{IA_c} \quad (1)$$

Where:

$\dot{m}_a = \rho_a A_{st} V_{prom}$ is the total mass flow of air (in kg/s) (with ρ_a as air density, A_{st} cross-sectional area and V_{prom} average air speed), c_a is the specific heat of air at constant pressure (in J/kg°C), $T_{o,c}$ is the temperature of the air leaving the collector, and $T_{i,c}$ is the temperature of the air entering the collector (in °C). The solar radiation or irradiance incident on the solar collector cover is represented by I (in W/m²), and A_c is the area of the solar collector (in m²).

2.2 OVERALL THERMAL EFFICIENCY

In mixed mode solar dryer, the drying chamber receives useful heat gain from collector air and direct solar radiation incident on it and it is one of the advantages. The overall thermal efficiency of the dryer is defined as the ratio of energy required to remove water from the feed to heat supplied to the dryer (Essalhi et al., 2017; AB Lingayat et al., 2020). The overall thermal efficiency of the mixed type dryer can be obtained by considering the fan power consumption by the following equation (Kumar et al., 2024; AB Lingayat et al., 2020; Rani & Tripathy, 2021):

$$\eta_d = \frac{\dot{m}_w h_{fg}}{[(A_c I + A_{dc} I)(\tau\alpha)_\theta + P_{fan}] t_d} \quad (2)$$

Where:



m_w is the amount of water lost or evaporated from the product obtained by subtracting the mass from the initial mass of the product (m_i) minus the final mass of the product (m_f) at the end of the total drying period (Mugi & VP, 2022; Reddy Mugi & Chandramohan, 2021) h_{fg} is the latent heat of vaporization of water (in J/kg), which can be determined by the equation, $h_{fg} = 4186(597 - 0.56T_{pr})$ where T_{pr} is the surface temperature of the food product in °C (Nikpey et al., 2024; Youcef-Ali et al., 2001). A_{dc} is the area of the tray where the quinoa is dried. The product of the transmittance and absorptivity for a given angle of incidence θ $(\tau\alpha)_\theta = k_{\tau\alpha}(\tau\alpha)_n$ where $k_{\tau\alpha} = 1 - 0.136[(1/\cos\theta) - 1]$ is valid for $\theta < 60^\circ$ (Duffie & Beckman, 2013). P_{fan} is the power used by the blowers to pump the air into the system, and t_d is the time that the drying lasted (in s).

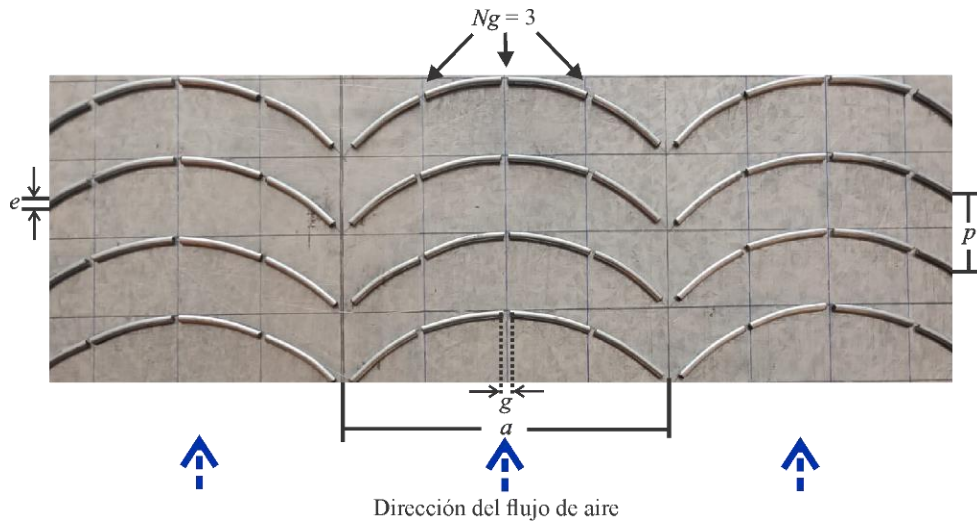
3 METHODOLOGY

The mixed solar dryer consists of a solar air heater, a drying chamber and a direct current air blower system powered by a photovoltaic solar panel. The solar air heater is low cost and is mounted to supply hot air to the drying chamber. The structure of the solar air heater is built with 3.2 cm x 6 cm pine wood. A trapezoidal duct was mounted at the inlet of the solar heater where the two fans that propel the air were inserted. To prevent thermal dissipation of the collector, 2.9 cm polystyrene was used and installed under the absorber plate. The absorber plate was constructed of 0.8 mm thick galvanized iron sheet, measures 129.5 cm long and 77.5 cm wide, is painted matte black, and an artificial roughness consisting of multiple arc-shaped ribs of 3 mm galvanized iron wire has been attached to the top of the absorber plate, similar to those investigated by (Kumar et al., 2019), (Pandey et al., 2016) and (Singh et al., 2014), as shown in Figure 1.



Figure 1

Absorbent plate with multiple arched ribs made of 3 mm wire.



The desired shape of the ribs is obtained by means of a wooden cylinder whose diameter is obtained by the equation $D = a/\cos(90 - \alpha)$ (Singh et al., 2014) where, the chord $a = 155$ mm, $p = 36$ mm, $e = g = 3$ mm, $\alpha = 60^\circ$, obtaining the diameter $D = 180$ mm that allows the maximum performance.

The collector is protected by a 0.6 cm UV-protected alveolar polycarbonate cover (Rodríguez-Ramírez et al., 2021), the hydraulic diameter of the channel through which the air flows is 5.96 cm, and the hot air leaving the solar heater enters the drying chamber. The drying chamber is made of pine wood and polycarbonate; to reduce heat loss, a double layer of 0.6 cm polycarbonate was installed on the sides. The surface of the drying tray is 0.271 m^2 . The direct current blower system consists of two centrifugal blowers and a speed controller. This system works with a 35 W solar panel, an 18 Ah battery and a charge controller. The humidity generated by the product to be dried during the entire drying process leaves the drying chamber through a 70 cm x 1.5 cm rectangular channel. The solar air heater was installed at an angle of 15° to the horizontal as shown in Figure 2. The solar dryer was built with low-cost and easily accessible material that costs approximately 100 USD without considering the photovoltaic system.

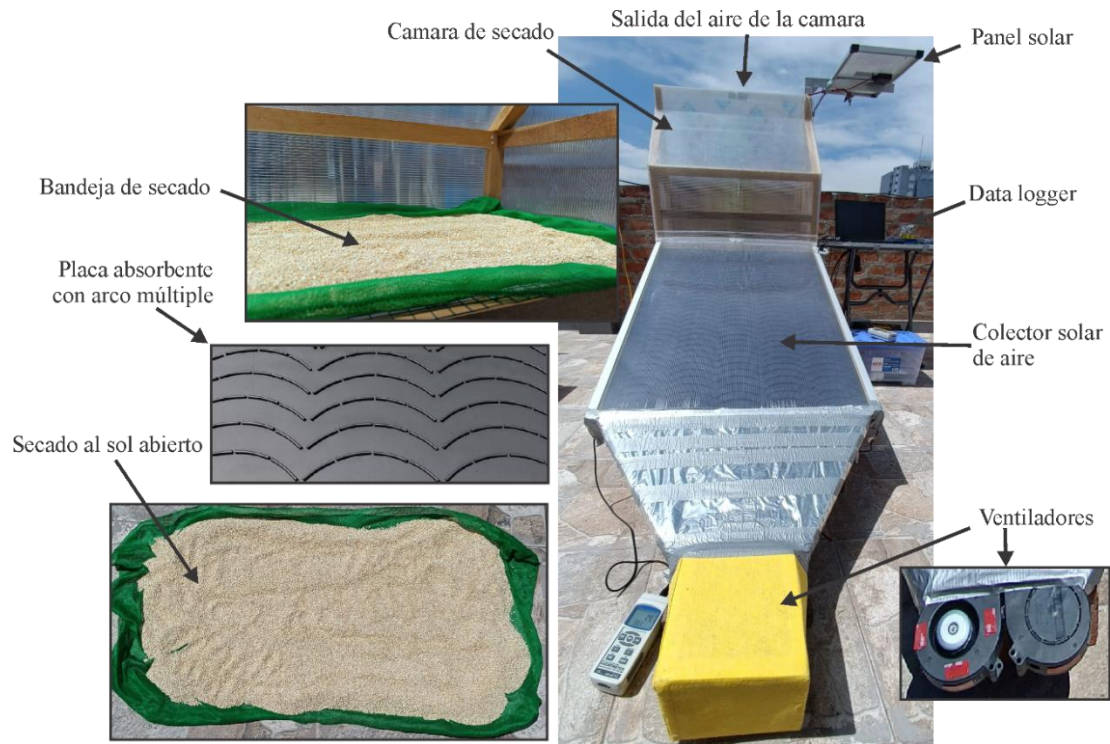
The solar dryer was designed, built and evaluated in the climate of the Puno region (Peru), at a site located at latitude $15^\circ 49' 21.4'' \text{S}$ and longitude $70^\circ 00' 45.4'' \text{W}$. The relative height to sea level was 3825 m. The solar dryer was designed for a capacity of 5 kg of quinoa grains. The quinoa used for the experiment was the variety called white Juli, which was scarified and washed before drying. Samples of 154 g of freshly washed quinoa were used to put it on



the drying tray of the solar dryer and in the same way, on the floor for open sun drying, with a thickness of approximately 1.5 cm of quinoa.

Figure 2

Experimental setup of the mixed solar dryer.



The tests were carried out in October 2024, the test period was from 9:00 am to 3:00 pm every day. This period was chosen after carrying out previous tests by drying in the open sun so that the mass of the dried sample reached an equilibrium state within 6 hours. During the test, data was recorded every 10 minutes, the parameters recorded were: air temperature at the collector inlet (T1-air), air temperature at the collector outlet (T2-air), absorbent plate temperature (T3-plate), ambient temperature (T4-ambient), drying chamber temperature (T5-chamber), drying chamber outlet temperature (T6-chamber), solar radiation, relative air humidity at the collector inlet, air speed. The weight of the quinoa samples was measured with a time interval of 30 minutes.

The instruments used are shown in Table 1. The experimental tests were carried out for three forced flows of 1,197 kg/min, 1,547 kg/min and 1,893 kg/min, and for the natural flow the trapezoidal duct was removed, so the mass flow was 0.189 kg/min.

**Table 1***Instrument specifications.*

Tools	Brand/Model	Range	Precision
Hot wire anemometer	Lutron AM-4224SD	0-25 m/s	±5%
Pyranometer	Apogee SP-420	0-1750 W/m ²	±10 W/m ²
Moisture Meter	Lutron AM-4247SD	5-95%	±3%
Data logger	Peak TC-8	-270-1820 °C	-
Thermocouple	Type K	-200-1372 °C	±0.5 °C
Ammeter	UNI-T UT61E+	0-220 A	±0.5%
Analytical balance	Baoshishan	0-200 g	±0.1 g

4 RESULTS AND DISCUSSIONS

The experiments were carried out during sunny days, when the climatic parameters were similar. The relative humidity of the air varied from 8% to 21%, being higher in the morning hours and decreasing at midday. The effect of the wind was present mainly in the afternoon hours with an average speed of 2 m/s. Before drying, the quinoa was scarified and washed, removing the saponin so that it was suitable for human consumption. The quinoa was dried on the drying tray of the drying chamber, under forced convection conditions for three air mass flows of 1.197 kg/min, 1.547 kg/min, 1.893 kg/min, and for natural convection flow, the trapezoidal duct installed at the collector inlet was removed, so that the mass flow was 0.189 kg/min. In addition, the quinoa was dried in the open sun simultaneously in the four tests carried out to later compare them.

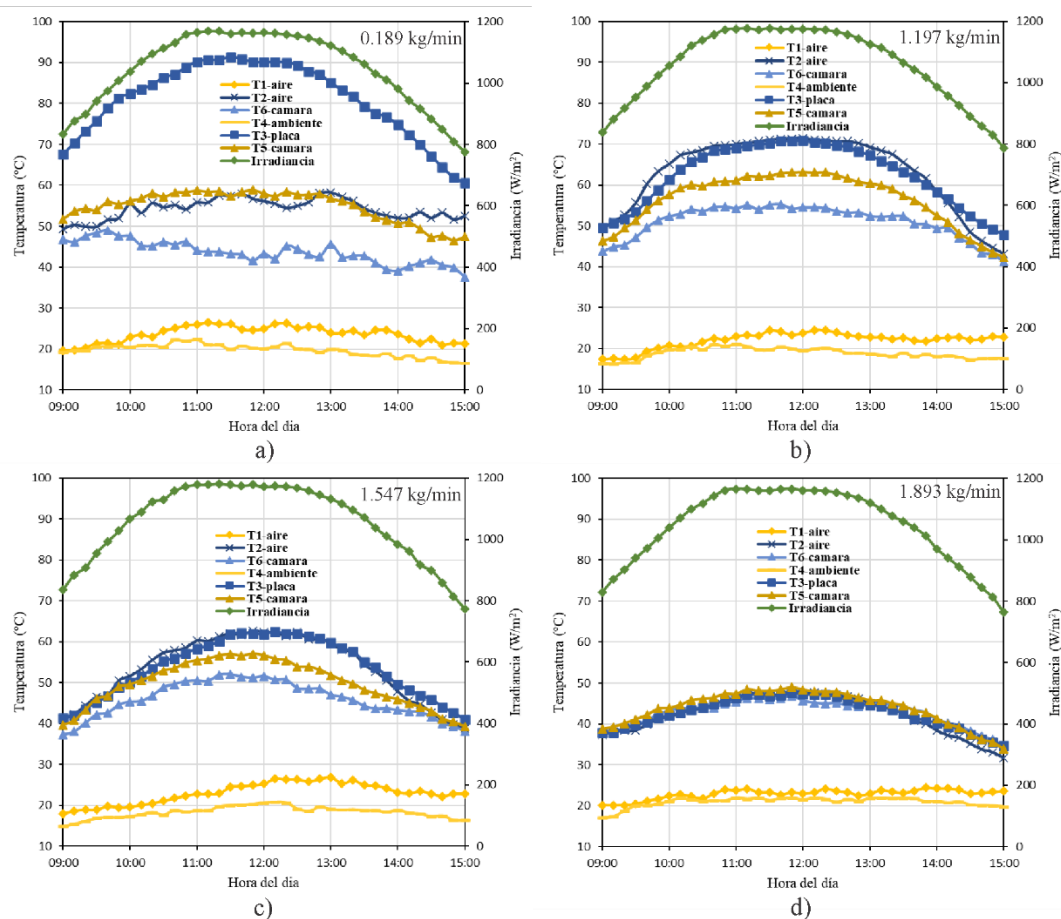
In Figure 3, the variations of the air temperature at the collector inlet (T1-air), the air temperature at the collector outlet (T2-air), the temperature of the absorber plate (T3-plate), the ambient temperature (T4-ambient), the temperature of the drying chamber (T5-chamber), the temperature of the drying chamber outlet (T6-chamber) and the irradiance are shown during the four days of testing for the following mass flows: 0.189 kg/min, 1.197 kg/min, 1.547 kg/min and 1.893 kg/min. The solar radiation varied from 763.9 to 1181.7 W/m² with an average intensity of the solar radiation that varied between 1042.78 and 1055.94 W/m², reaching the maximum value at noon, during the days that the experiment lasted. The ambient temperature was between 14.94 and 21.99 °C having low temperatures in the early hours of the day, the average ambient temperature was between 18.31 and 20.92 °C. The average temperature of the absorber plate for the mass flows of 0.189 kg/min, 1.197 kg/min, 1.547 kg/min and 1.893 kg/min, were 80.90 °C, 62.30 °C, 53.45 °C and 42.69 °C respectively, reaching the maximum temperature of 91.40 °C for a flow of 0.189 kg/min at noon. The average temperatures in the drying tray for the mass flows of 0.189 kg/min, 1.197 kg/min, 1.547 kg/min and 1.893 kg/min



were 54.95 °C, 56.42 °C, 49.66 °C and 43.91 °C respectively, ranging between 34.73 °C and 91.39 °C.

Figure 3

Variation of temperatures and solar radiation over time for the four air flows.



From the results it can be seen that, at lower air flows, higher temperatures are reached in the drying chamber, so that a higher mass flow affects the temperature of the drying chamber as occurs with the flow rate of 1,893 kg/min having the lowest temperature in the drying chamber of 43.91 °C. It should also be noted that, when the solar collector reaches higher temperatures, greater heat losses occur. In addition, from Figure 3, it can be deduced that the incoming air is progressively heated until it enters the drying chamber, where the temperature continues to increase, although to a lesser extent, except in the case with a mass flow of 1,197 kg/min.

Figure 4 shows the variation in the thermal efficiency of the air heating solar collector during the daylight hours for the four mass flows obtained with equation (1). The average thermal efficiency of the collector for the mass flows of 0.189 kg/min, 1.197 kg/min, 1.547



kg/min and 1.893 kg/min were 9.42%, 77.38%, 74.00% and 58.20% respectively. The lowest average thermal efficiency was reached when the flow was by natural convection, while the highest efficiency was reached for the forced flow of 1.197 kg/min. The low efficiency in the case of natural convection was mainly affected by the inclination angle of the solar collector which was 15°. On the other hand, the higher the mass flow, the lower the thermal efficiency of the collector among the forced flow cases.

Figure 4

Thermal efficiency of the solar air heater collector during the day for the four flows.

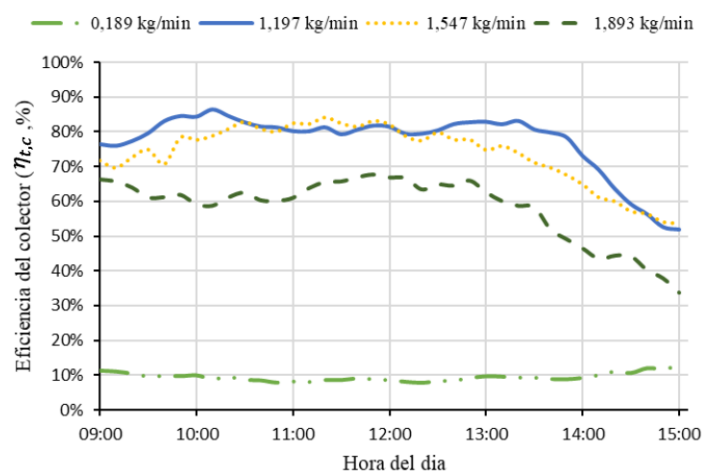
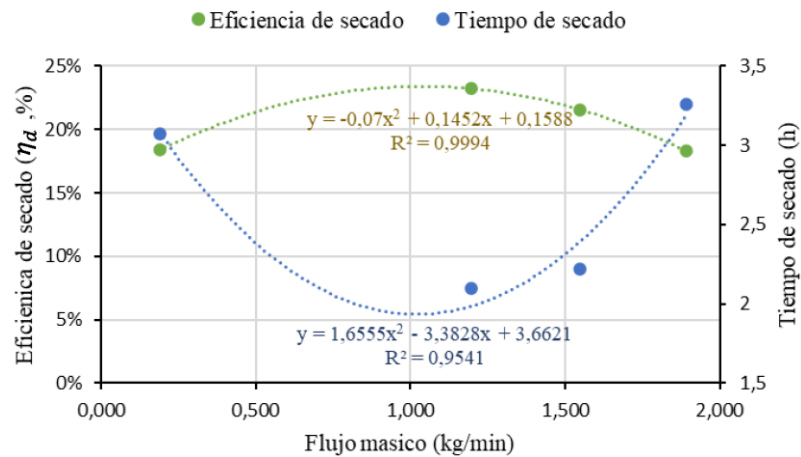


Figure 5 shows the variation of the average overall drying efficiency of the mixed solar dryer obtained by equation (2) with respect to the mass flow, the drying time with respect to the air mass flow and their respective fitting curves where there is a good fit. The maximum average overall efficiency achieved was 23.28% and the minimum drying time was 2.1 hours, achieved for a flow of 1.197 kg/min, with an average drying temperature of 56.42 °C. The fitting curve of the overall drying efficiency indicates that the overall drying efficiency will not be significantly higher than 23.28%, and the fitting curve of the drying time reveals that it will be very close to 2.1 hours. In addition, the maximum overall efficiency and the minimum drying time are achieved when the mass flow is 1.02 kg/min. In the case of open sun drying, the drying time was 5.82 hours. When comparing the drying time in the open sun with the minimum drying time in the forced case, a reduction in drying time of up to 68% is observed for drying quinoa at a flow rate of 1,197 kg/min, with the average drying temperature being 56.42 °C.

**Figure 5**

Correlation of overall drying efficiency and drying time with respect to mass flow.



In the mixed type dryer, solar radiation is used both directly and indirectly, so that the air in the drying chamber is heated in both ways. In this research it was observed that the thermal efficiency of the solar collector depends mainly on solar radiation, mass flow and drying temperature. For an average solar irradiance of 1055 W/m^2 , the average thermal efficiency of the solar collector was 77 % and the overall drying efficiency was 23 %, for a mass flow of 1.197 kg/min and an average temperature of the drying chamber of 56 °C. The efficiencies obtained for the solar dryer are within the acceptable range, and in some cases the efficiency obtained exceeds other similar works carried out by (Mbakuop et al., 2023), (Ekka et al., 2021), (Reddy Mugi & Chandramohan, 2021), (Gupta et al., 2024), (A. Lingayat et al., 2020) and (Kumar et al., 2024). The high efficiency is due to the artificial roughness installed on the absorbent plate, as pointed out by (Kumar et al., 2019). Finally, drying in the open sun has multiple disadvantages that affect the final product, while indirectly drying food has significant advantages that significantly improve drying time and protect the final dried product. An important aspect is that, by using the polycarbonate cover with UV filter in the drying process, the nutritional value of the dried product is preserved (Nair et al., 2020; Rodríguez-Ramírez et al., 2021).

5 CONCLUSION

In the present work, a mixed-type solar dryer constructed with a single-flow flat plate solar collector with a multiple arc-shaped ribbed artificial roughness attached on the top of the absorber plate was experimentally tested and the drying characteristics of quinoa were



investigated. The performance, the effect of air mass flow rates, drying temperatures, drying time and drying kinetics for forced and natural convection were compared and compared with open sun drying. The test mass flow rates were 0.189 kg/min, 1.197 kg/min, 1.547 kg/min and 1.893 kg/min. The artificial roughness installed on the absorber plate increased the performance of the solar collector, so the maximum average thermal efficiency of the solar collector was 77 % for an average solar irradiance of 1055 W/m^2 , a mass flow of 1.197 kg/min and an average temperature of the drying chamber of 56 °C. The maximum average overall efficiency achieved was 23.28 % and the minimum drying time was 2.1 hours, which was achieved for a flow of 1.197 kg/min. The designed mixed solar dryer would have maximum efficiency for a forced flow of 1.02 kg/min, and the drying time for quinoa would be reduced by 68% compared to open sun drying. Drying in the mixed solar dryer has significant advantages, as it reduces the drying time by more than half and protects the final product, increasing the quality of the product. In addition, by using the polycarbonate cover with UV filter, the nutritional value of quinoa is preserved.

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