



Evaluation of solar drying techniques for preserving avocado leaves (*Persea americana*): physicochemical and bioactive compound analysis

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Abstract

A mixed-mode solar dryer (direct/50% mesh shade) was used to evaluate the impact of solar drying on the physicochemical properties and bioactive compounds of avocado leaves (*Persea americana* var. *drymifolia*). Also, oven drying at 50 °C and open sun drying were performed. Fresh avocado leaves moisture was 55.6% and water activity 0.96. Color parameters were as follows: lightness (L^*) 31.12, a^* -7.91, b^* 11.45, *chroma* 5.10 and *hue angle* 124.63°. The flavonoid content was 5.26 mg QE/g db (quercetin equivalents/g dry basis), total phenols 27.57 mg GAE/g db (gallic acid equivalents/g dry basis), ascorbic acid 62.79 mg/100 g, and antioxidant activity of 92.32%. After drying antioxidant activity remained unchanged (89.04 to 94.27% $p > 0.05$). Flavonoids decreased (1.04–2.71 mg QE/g db, $p < 0.05$), and total phenols showed an increase with the open sun, oven, and mesh shade solar drying (28.53–30.88 mg GAE/g db $p < 0.05$). Ascorbic acid was better preserved with mesh shade solar drying (52.71 mg/100 g). Mesh shade drying described the least color difference ($\Delta E = 6.98$). Page model better described the drying kinetics with an $R^2 \geq 0.994$. The study suggests that solar drying effectively preserves bioactive compounds in avocado leaves, offering an alternative for food and pharmaceutical use.

Keywords Avocado leaves · Antioxidants · Bioactive compounds · Solar drying · Solar energy

Introduction

Over the years, it has been demonstrated that a high level of bioactive ingredients, including phenolic compounds, are commonly found in medicinal herbs (Mustafa and Harbourne 2024). Several studies have focused on the report of

the essential bioactive molecules and chemical constituents present in plants such as alkaloids, flavonoids, tannins, and phenolic compounds, (Rajkumar et al. 2022; Dar et al. 2023), and their role in a healthy body contributing to the treatment of several diseases that are considered difficult to cure. Leaves of fruit trees have been also studied in recent years for their medicinal properties. Huynh et al. (2025) reported the bioactive compounds from guava leaves (*Psidium guajava* L.); Ali et al. (2020) studied mango leaves (*Mangifera indica*) phytopharmacological compounds founding secondary metabolites such as alkaloids, flavonoids, tannins, saponins, total phenol and cardiac glycosides and Sharma et al. (2022) reported papaya leaves bioactives and its anti-proliferative activity on cancerous cells along with immune modulatory effects. In this sense, “Criollo” avocado leaves (*Persea americana* var. *drymifolia*) have been traditionally used not only in cooking but also to treat conditions like influenza, bronchitis, menstrual pain, diabetes, and rheumatism (Kendir and Köroglu 2018); these beneficial and biological properties may be related to the presence of polyphenolic compounds and the presence of phenolic acids, flavonoids, and procyanidins (Yamassaki et al. 2017). Nevertheless,

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worldwide avocado leaves are mostly not used or commercialized. In fact, the increasing industrial processing of avocados generates substantial residues (including seeds, peels, and leaves) from seasonal pruning in both summer and winter, which contribute to environmental issues such as greenhouse gas emissions and water contamination (Féliz-Jiménez and Sánchez-Rosario, 2024). These residues can be valorized by the industry for the extraction of bioactive compounds such as flavonoids, antioxidants, and phenolic compounds, as well as pigments, proteins, lipids, and carbohydrates, with potential applications in various industrial processes. *Persea americana* var. *drymifolia* is a highly relevant variety in Mexico, between 2012 and 2022, the global area cultivated with avocado expanded at an average annual rate of 6.7%, reaching 884,000 hectares in 2022, with average yields of 10.2 tons per hectare. That year, 55.1% of the harvested area was concentrated in five countries: Mexico, Colombia, Peru, the Dominican Republic, and Chile (FAO, 2022). In Mexico, avocado leaves hold an importance due to their medicinal background; however, despite its vast availability, the interest in studying avocado leaves has not been fully harnessed, particularly in urban and rural communities. Lately, by-products such as tree leaves have attracted growing attention from the industry due to their nutritional value and beneficial effects on health (Eyiz and Tontul 2022). Leaves remain fresh and in good condition when stored in a cool, dry place, lasting about 1 to 2 weeks after harvest without wilting; after this period, decomposition reactions take place (Pérez-Álvarez et al. 2015). For this reason, various methods have been developed to extend their useful life such as air, sun, oven, microwave, and freeze drying. These methods remove as much water as possible to prevent microbial growth on the leaves (Loh and Lim 2018). Nevertheless, in recent years, the development of sustainable drying methods has become a major challenge. Solar drying is considered a major application of solar energy. A solar dryer is a device that utilizes solar energy, heating the product while extracting moisture to maintain its quality. Solar

drying contributes significantly to reduce energy consumption compared to other drying methods and is considered highly efficient due to its low production and operational costs (Hage et al. 2018). This research utilized a hybrid active solar drying system, integrating both direct and indirect drying methods. Direct solar dryers feature a transparent chamber, permitting sunlight to penetrate throughout the drying process. In contrast, indirect dryers operate with an enclosed, non-transparent chamber, in which air is heated by a solar collector and then circulated to effectively dry the product. This indirect method helps to preserve the product physical properties by preventing direct radiation from altering certain characteristics (Prakash and Kumar 2017). While previous studies have evaluated drying effects on avocado leaves or other medicinal plants with similar healing effects to avocado leaves (Karami et al. 2021; Loh and Lim 2018; Yamassaki et al. 2017) this work integrates drying kinetics, detailed color analysis using the Hunter system, and comprehensive quantification of key bioactive compounds, including flavonoids, total phenols, ascorbic acid, and antioxidant activity. Accordingly, this study aimed to evaluate the effects of solar drying on the physicochemical properties and bioactive compounds of avocado leaves (*Persea americana* var. *drymifolia*), and to compare these results with those obtained from conventional methods, such as oven drying, in order to identify sustainable alternatives for their preservation.

Materials and methods

Sample preparation

Fresh avocado leaves were obtained from a local plantation in Hueyapan, Morelos, Mexico (18°51'54.82" Latitude, 98°42'1.357" Longitude at 2000–2500 mams). The leaves were separated from the stems, washed and disinfected before drying by immersing in a disinfectant detergent solution (SWIPE VEGGIEFRUIT WASH 1:100) for 15 min and consequently drained to eliminate excess of water. The samples were placed in 10 plastic meshes with 50 g of sample each one and introduced into the dryer.

Drying

The drying process was carried out in a cabinet-type mixed-mode solar dryer (Fig. 1a) that contains a drying chamber with ten trays (0.63×0.43 m) in five levels; each tray has 0.0025×0.007 m perforation, a small photovoltaic fan, and a flat plate solar collector (with a tilt angle of 21°). A photovoltaic panel operated on a fan and the natural convection helped to extract the humid air inside the drying chamber.



Fig. 1 Mixed-type solar dryer used in the drying process of avocado leaves **a)** without mesh shade and **b)** with mesh shade

Another drying condition was developed by covering the drying chamber with a mesh shade (50%) to decrease solar irradiance and the temperature inside the solar dryer (Fig. 1b). On the other hand, electric oven drying (Model RIOSA HCFD-48×48) at 50 °C and open sun drying were carried out to compare the effect on the physicochemical characteristics of avocado leaves in several conditions. The open sun drying method was carried out by exposing the samples directly to sunlight in a shade-free area on a table.

For each drying condition, the samples were evenly distributed on plastic meshes, with each mesh containing 50 g of avocado leaves. All experiments were conducted in duplicate to ensure reliability and consistency of results. During the drying process, the samples were periodically weighed until a constant mass was achieved.

Instrumentation

Each solar dryer was equipped with two pyranometers Kipp & Zonen, CM11; 0–1400 W/m²±2%, Netherlands (one inclined in the plane of the solar collector and another vertical to the drying chamber to measure the solar irradiance on drying days). Sixteen temperature sensors (RTD PT 1000, –50 to 750 °C±0.2 °C, Mexico) were placed in different sections: 2 at the inlet, 2 at the outlet of the solar collector, 10 in the trays inside the dryer, and 2 at the outlet of the drying chamber. Measurements were registered automatically by a data acquisition system (Agilent-34972 A) every 30 s.

Mathematical modeling fitting

The drying kinetics of avocado leaves were evaluated by applying mathematical models to the experimental moisture ratio data collected during the drying process. The Moisture Ratio (MR) was determined according to the following equation:

$$MR = \frac{M - Me}{Mo - Me}$$

M denotes the moisture content, Me represents the equilibrium moisture, and Mo refers to the initial humidity. The equilibrium moisture content (Me) was calculated using the equation shown below:

$$Me = \frac{W_1 Mo + W_f W_1}{W_1 (1 - M)}$$

W_1 represents the starting weight, Mo indicates the initial moisture content of the avocado leaves and W_f refers to

the sample weight at Me . Mathematical models assessed are the following:

$$MR = \exp(-kt^n) \text{ (Page).}$$

$$MR = a \exp(-kt) \text{ (Henderson-Pabis).}$$

$$MR = a \exp(-kt) + c \text{ (Logarithmic).}$$

$$MR = \exp(-kt) \text{ (Newton).}$$

Goodness of fit was assessed based on three descriptors: coefficient of determination (r^2), reduced chi-squared coefficient (χ^2), and Root Mean Square Error ($RMSE$). A better fit is indicated by lower χ^2 and the $RMSE$, ideally near zero, representing deviation between experimental and predicted values. r^2 , χ^2 , and $RMSE$ descriptors were calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N}}$$

$$r^2 = \frac{\sum_{i=1}^N (MR_1 - MR_{pre,i}) \sum_{i=1}^N (MR_1 - MR_{exp,i})}{\sqrt{\left[\sum_{i=1}^N (MR_1 - MR_{pre,i})^2 \right] \left[\sum_{i=1}^N (MR_1 - MR_{exp,i})^2 \right]}}$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - Z}$$

where N is the total number of data values, Z is the number of drying constants, $MR_{exp,i}$ is the experimental moisture ratio value, and $MR_{pre,i}$ is the predicted moisture ratio value.

Statistical analysis

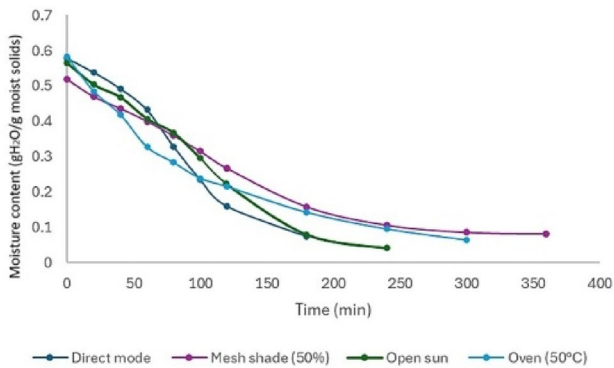
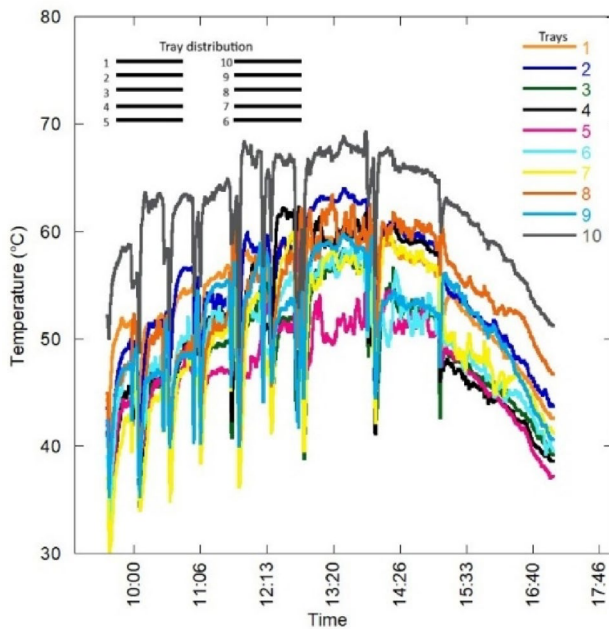
A one-factor experimental design comprising the four drying conditions was established. The mean value and standard deviation for each experimental dataset were calculated from three independent replicates. The data significance was determined through ANOVA and Dunnett test at 95% confidence level using Minitab 2019 software with a significance level of $\alpha=0.05$. The response variables were moisture content, water activity, color parameters, total flavonoid content, total phenols content, ascorbic acid, and antioxidant activity for avocado leaves, each determination was made by triplicate.

Moisture content and water activity

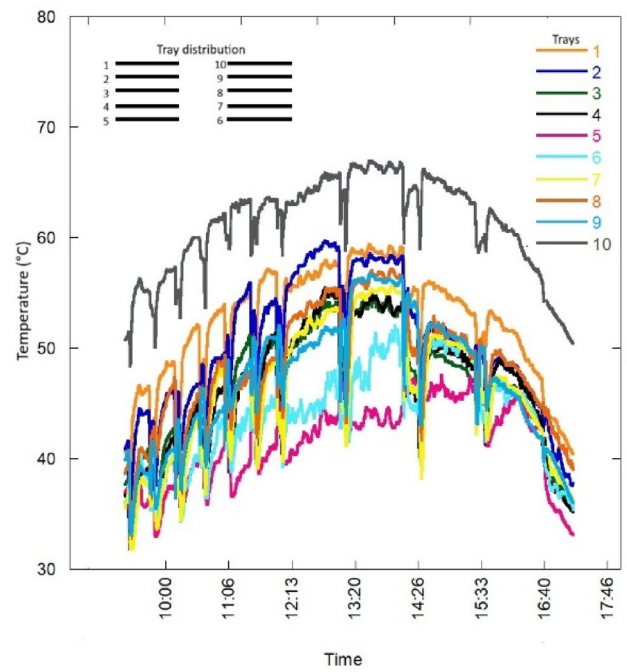
The moisture content was obtained using a thermobalance (OHAUS, MB45, Switzerland, with a readability of 0.001 g) at 105 °C; the determination was made by taking and distributing uniformly 3 g of the sample on an aluminum pan inside the equipment. Water activity (a_w) was

Table 1 Average solar irradiance (global and UV), ambient temperature and drying time

Date	Global solar irradiance (W/m ²)	UV irradiance (W/m ²)	Ambient temperature (°C)	Drying time (min)
October 11, 2024	859.207	28.985	29.946	240
October 25, 2024	785.119	26.506	31.069	360
November 19, 2024	713.142	22.815	33.597	240

**Fig. 2** Drying kinetics of avocado leaves dried in different conditions**Fig. 3** Trays temperatures during the direct solar drying process

determined by a Rotronic water activity meter (Higrolab C1, USA) at 25 °C, where the disposable sample cup was covered entirely and introduced inside the kit for 20 min. The moisture content was reported in wet basis units.

**Fig. 4** Trays temperatures during the solar drying with 50% mesh shade process

Color

The color of avocado leaves was measured by a portable colorimeter (NR60CP*, USA). A sample representative of each plant was taken at the beginning and the end of the test. Values were expressed as L* (luminosity), a* (red-green), b* (yellow-blue), H* (hue angle), and C* (chromatic saturation). These results were used to calculate the color difference between the fresh and dried samples (ΔE), chroma (C), and hue angle (H) according to the equations reported by Domínguez-Niño et al. (2024) and Mustafa and Harbourn (2024) as shown below:

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{\frac{1}{2}}$$

$$C = \sqrt{(a)^2 + (b)^2}$$

$$H = \arctan\left(\frac{b}{a}\right)$$

The following parameters were reported and represents:

ΔL =changes in lightness (positive values indicate lighter samples).

Δa =the shift from green (−) to red (+).

Δb =the shift from blue (−) to yellow (+).

ΔC =changes in chroma or color saturation.

ΔH =the change in hue angle.

Table 2 Mathematical models parameters and coefficients

Model	Parameters				R^2	RMSE	χ^2
	k	n	a	c			
Direct mode							
Page	0.7158	1.6464			0.9940	0.0248	0.0009
Henderson–Pabis	0.8634		1.0702		0.9469	0.0735	0.0076
Logarithmic	0.8634		1.0702	0.0000	0.9469	0.0735	0.0094
Newton	0.8007				0.9369	0.0801	0.0075
Mesh shade (50%)							
Page	0.5659	1.1802			0.9945	0.0239	0.0007
Logarithmic	0.6301		1.0215	0.0000	0.9885	0.0345	0.0017
Henderson–Pabis	0.6301		1.0215		0.9885	0.0345	0.0015
Newton	0.6145				0.9877	0.0356	0.0014
Open sun							
Page	0.6774	1.1906			0.9887	0.0317	0.0013
Henderson–Pabis	0.7327		1.0189		0.9812	0.0408	0.0022
Logarithmic	0.7327		1.0189	0.0000	0.9812	0.0408	0.0027
Newton	0.7167				0.9805	0.0416	0.0020
Oven (50 °C)							
Page	1.0746	0.8623			0.9981	0.0131	0.0002
Logarithmic	1.1659		0.9480	0.0404	0.9969	0.0166	0.0004
Henderson–Pabis	1.0402		0.9766		0.9940	0.0230	0.0007
Newton	1.0679				0.9932	0.0246	0.0007

ΔE =the total color difference between fresh and dried samples.

Total flavonoid content

Aluminum chloride colorimetric method reported by (Pourmorad et al. 2006) was used for flavonoid determination. The extraction process involved weighing 1 g of avocado leaves and dissolving them in 10 mL of 80% methanol. The sample was then heated to 70 °C and subsequently centrifuged at 3500 rpm. Each plant extract was separately mixed with 1.5 mL of methanol, 0.1 mL of 10% aluminum chloride, 0.1 mL of 1 M potassium acetate, and 2.8 mL of distilled water. It remained at room temperature for 30 min; the absorbance of the reaction mixture was measured at 415 nm. The calibration curve was prepared by preparing quercetin solutions at concentrations of 20 to 100 mg/mL in methanol.

Total phenols content

The Folin-Ciocalteu method was used to determine the total phenols of avocado leaves. Methodology reported by (Barimah et al. 2017) was developed. Avocado leaf extraction was performed by weighing 250 mg of dried sample, followed by the addition of 10 mL of acetone (70/30 v/v). The mixture was heated to 70 °C, allowed to cool to ambient temperature, and then centrifuged at 3500 rpm. The phenol content determination was carried out by adding 0.5 mL of

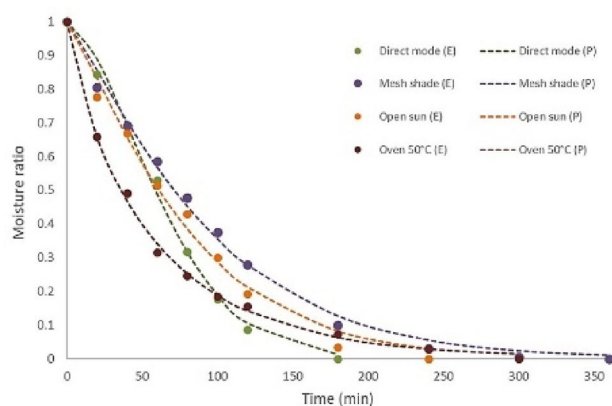


Fig. 5 Experimental (E) and Predicted (P) by Page model moisture ratio values of avocado leaves

the extraction and 0.5 mL of Folin-Ciocalteu (2 M) reagent. It was well mixed and then left to stand for 10 min after which 1.5 mL of 20% sodium carbonate solution was added. The solution was mixed and incubated at room temperature in the dark. Afterwards, the absorbance was read at 760 nm. The total phenolic contents were expressed in terms of gallic acid equivalent (mg GAE/g of dry mass), a common reference compound. Distilled water was used as blank.

Ascorbic acid content

Ascorbic acid quantification was performed using the iodometric titration method outlined by Medina Meza and

Barbosa-Cánovas (2015) and García et al. (2022) with minor adjustments. A 10% metaphosphoric acid solution was added to a 10 g sample, which was subsequently dissolved and filtered. The filtrate was transferred to a 100 mL volumetric flask and brought to volume with distilled water. A 10 mL aliquot of this extract was combined with 10 drops of 1% starch solution as an indicator. Titration was conducted using 0.01 N iodine until the appearance of a blue coloration signaled the endpoint. Ascorbic acid content, expressed in mg/100 g, was determined using the following equation:

$$Aa \left(\frac{mg}{100 g} \right) = \frac{(i) (0.8806) (V_t)}{(V_f) (m)} \times 100$$

Where i represents the volume of iodine used (mL), V_t represents the volume of extract (mL) and V_f represents the volume of the aliquot (mL).

Antioxidant activity

The antioxidant content was determined following the methodology proposed by Kailey et al. (2019) with slight modifications. The DPPH radical (2,2-diphenyl-1-picrylhydrazyl) inhibition capacity was measured by adding 25 mL of 80% methanol to a 0.5 g sample of the dehydrated herbs. The mixture was left to stand for 40 min, after which a 0.1 mL aliquot was taken and combined with 3.9 mL of DPPH radical solution. The test tube was kept in darkness for 30 min, and absorbance was measured at 517 nm using a spectrophotometer. A blank was prepared using 80% ethanol. The DPPH free radical inhibition (%) was calculated using the following equation:

$$\% \text{Inhibition} = \frac{\text{Control absorbance} - \text{Sample absorbance}}{\text{Control absorbance}} \times 100$$

Results and discussion

Drying process and kinetics

The drying of avocado leaves under each condition began at 9:00 a.m. and was terminated once a constant weight was reached. Table 1 presents the drying times for each experiment, together with the corresponding average global and UV irradiance, as well as ambient temperature measurements. The drying kinetics of avocado leaves are shown in Fig. 2. Figures 3 and 4 illustrate the temperature profiles recorded in the trays within the drying chamber. Trays 1 and 10, positioned at the top of the cabinet, experienced higher temperatures compared to those located on the lower levels.

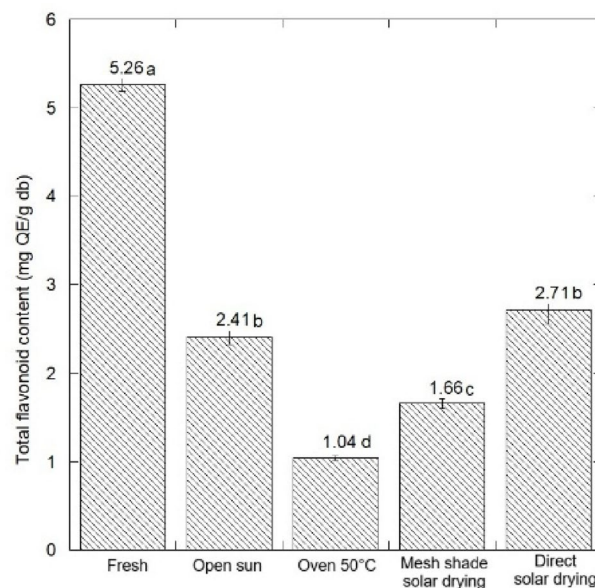


Fig. 6 Total flavonoid content of fresh and dried avocado leaves

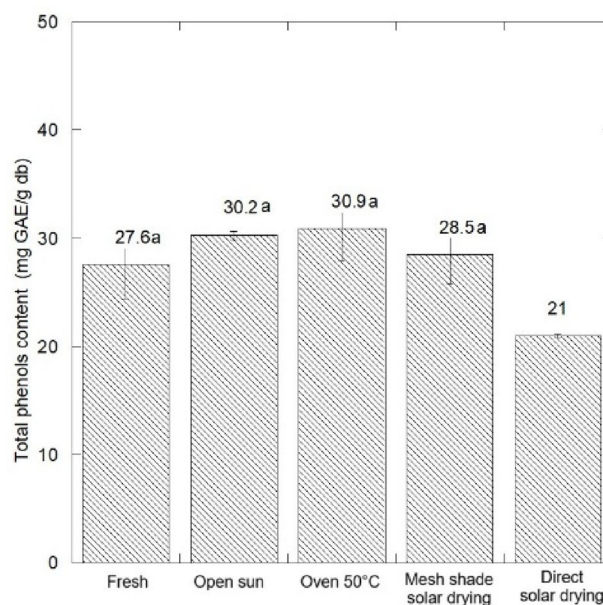


Fig. 7 Total phenols content of fresh and dried avocado leaves

In contrast, trays 5 and 6 described the lowest temperatures. To guarantee the uniformity of the drying process and temperatures, the meshes containing the samples were rotated and randomized along the drying process. Direct mode was carried out on October 11, 2024, using a mixed-mode solar dryer. The initial moisture content began at 57.81% and finished at 7.47%. The maximum drying temperature was 59.92 °C, and the maximum solar irradiance was 1095.49 W/m². The initial water activity was reduced from 0.922 to 0.413. A 50% mesh shade (October 25, 2024) was used in

drying kinetics to reduce the solar irradiance and decrease the drying temperature. The initial moisture content began at 51.92% and finished at 8.09%, and the initial water activity was reduced from 0.980 to 0.484. The average drying temperature in the solar dryer cabinet was 54.69 °C, and the maximum solar irradiance was 1041.39 W/m². It is important to notice that the presence of the mesh shade resulted in a solar irradiance level of 520.69 W/m² within the solar drying chamber. Domínguez et al. (2024) reported the use of mesh shades to reduce the solar irradiance in the drying kinetics of *Agastache Mexicana* and *Rosmarinus officinalis* according to their results, the drying kinetics reported a drying time between 4.5 and 6.5 h and 4 to 7 h, respectively, according to the operation mode of the solar dryer. Castillo et al. (2023) reported the convective drying of stevia leaves; according to their report, the drying time was affected by the temperature (65 °C) and air velocity (4 m/s). Loh and Lim (2018) reported a decrease in water activity during the drying of avocado leaves (*Persea americana*) by using different drying methods. Their results showed that the most significant decrease in water activity was observed in the oven drying at 50 °C, 100 °C, and freeze drying, followed by microwave drying. Mghazli et al. (2017) studied the drying kinetics of rosemary leaves in an indirect active solar dryer; according to their report, the air temperature (50 °C to 80 °C) and air flow rate (150 and 300 m³/h) influenced the drying kinetics of rosemary a higher drying rate was observed at higher drying temperature and flow rate. For drying kinetics of avocado leaves using an electric oven at 50 °C the initial moisture content began at 58.37% and finished at 6.35%, and the water activity was reduced from 0.973 to 0.523. Finally, the drying of avocado leaves in open

sun drying (November 9, 2024) started at a moisture content of 56.49% and finished with a value of 4.15%. The water activity was reduced to values of 0.56.

Fitting to mathematical models

Table 2 describes the mathematical model parameters and coefficients obtained. Figure 5 shows the comparison between experimental and predicted values (Page model) of moisture ratio, where E describes experimental moisture ratio and P represents predicted values by the model. As seen, the Page model adequately described the drying kinetics under all evaluated conditions ($r^2 \geq 0.994$). The drying constant k ranged from 0.374 to 0.801, indicating notable differences in drying rates among conditions, while the exponent n varied between 1.240 and 1.879, reflecting changes in the curvature of the drying profiles. The accuracy of medicinal leaves and plants varies across the mathematical models used. Elwakeel et al. (2025) in the direct solar drying of henna leaves found that the Lewis (Newton), Weibullian, and Page models were the most suitable drying models for henna leaves with thickness of 2, 4, and 6 cm, respectively. On the other hand, in the investigation reported by Cerezal-Mezquita et al. (2020) the three models that best represented indirect solar drying of lettuce leaves were Page, Midilli and Kucuk, and Weibull, which implied a strong correlation between the predicted humidity ratios from these models and the experimental data, supporting their effectiveness for modelling drying kinetics.

Characterization of fresh avocado leaves

Fresh avocado leaves had a moisture content of 55.6% and water activity of 0.96; according to the colorimetric analysis of the leaves, the lightness L^* was 31.12, a^* -7.91, b^* 11.45, chroma 5.10 and hue angle of 124.63°, as seen from the results, the greenness is represented by a in the negative side, and the yellowness is represented by b in the positive side, indicating a shift from bright green to dull green-yellow. According to the Hunter system when the hue angle ranges from 90° to 180°, the color passes from yellow to green; in this case, the hue angle (124.63°) is in the green zone (Wrolstad and Smith 2010). Recent reports of the color of herbs for their commercial acceptability are described by Al-Hamdani et al. (2022) for the mint and basil, also by Huang et al. (2021) describing the color of *Stevia rebaudiana* leaves. The flavonoid content of the fresh avocado leaves was 5.26 mg QE/g db, total phenols 27.57 mg GAE/g db, ascorbic acid 62.79 mg/100 g, and antioxidant activity of 92.32%.

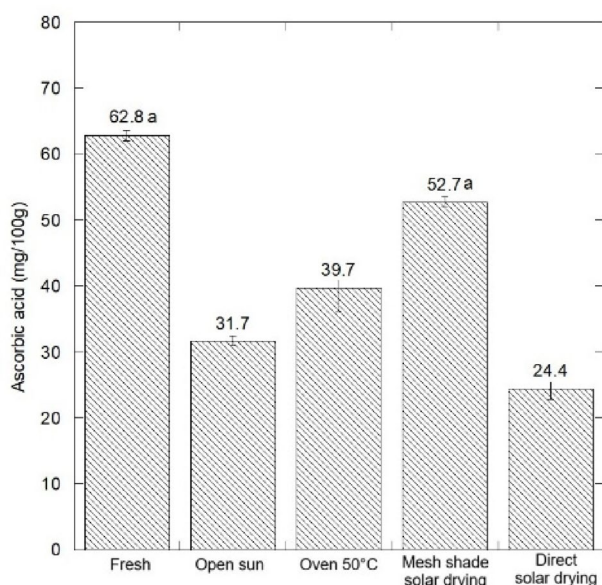


Fig. 8 Ascorbic acid of fresh and dried avocado leaves

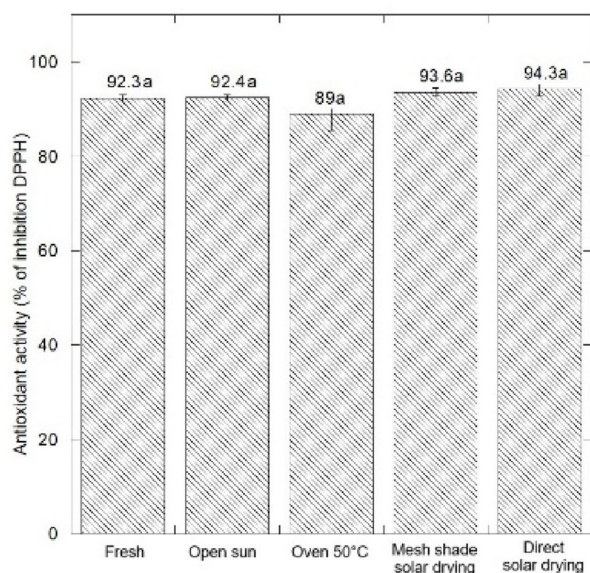


Fig. 9 Antioxidant activity of fresh and dried avocado leaves

Total flavonoid content

Flavonoid content of dried avocado leaves expressed in terms of quercetin equivalent was between 1.04 and 2.71 mg QE/g (Fig. 6). As observed, there was a significant decrease in flavonoid content after the drying process and as demonstrated by the Dunnett's test ($\alpha=0.05$, p value=0.00000068). When drying methods were compared, there was a significant difference between flavonoid content, showing a better retention for direct solar drying and open sun conditions. This behavior can be attributed to the shorter times of avocado leaves to heat exposure. As shown in the investigation reported by Yilmaz et al. (2021) in the drying of thyme plant at different conditions, shorter drying times led to the highest levels of flavonoids and flavonoids measured in conventional and natural drying methods, where airflow is dominant and drying time is very long decreased significantly its content.

Total phenols content

According to the results, total phenols content for avocado leaves described a range between 20.99 and 30.88 mg GAE/g (Fig. 7). The study demonstrated that there was a slight increase in these compounds when open sun, oven,

and mesh shade solar drying were applied compared to fresh avocado leaves (Fig. 7). The release of these compounds after drying was reported by García et al. (2021). In this research, *Urtica dioica* L. leaves were evaluated, finding that it could have occurred a release of bound antioxidant substances such as phenolic compounds because of the disrupting cell structure and obtaining a natural extraction for the analysis, as the formation of new antioxidants such as Maillard reaction products resulting from thermal chemical reaction and the suppression of oxidation by thermal inactivation of oxidative enzymes of antioxidants such as polyphenol oxidase. According to the findings of Hussein et al. (2011), the degradation of certain high-molecular-weight components and changes in their solubility within the tested solvents led to an increased concentration of phenolic compounds. Sultana et al. (2012) observed that, during the drying process, phenolic compounds with higher molecular weights, such as those found in apricots, may be converted to simpler free forms through heat treatment, thereby increasing the total phenolic content in the samples. Concerning direct solar drying, there was a significant decrease in phenols content, demonstrated by Dunnett's test (p value=0.001) when compared to fresh sample. According to Barimah et al. (2017) direct solar drying may have caused chemical structure changes in polyphenols also, the cell structure may have ruptured as a result of thermal processing which leads to migration of these components, hence their loss. Also, Bahloul et al. (2009) reported that this reduction was possibly caused by the long exposure to the sunlight that produced oxidation of some phenolic substrates to corresponding quinones by enzymatic activity. In addition, Benjamin et al. (2022) in the study of bamboo leaves drying by several methods found that low-temperature drying techniques enhanced the retention of bioactive chemicals and in contrast, sun drying caused a decrease in phenolic compounds.

Ascorbic acid determination

Ascorbic acid is a compound that mainly contributes to the antioxidant activities of green leaves and fruits (Kumar et al. 2015). It is a parameter that may measure the damage caused by drying due to it being considered a highly thermolabile substance. After drying ascorbic acid went from 62.79 mg/100 g (fresh leaves) to a range between 24.44 and 52.71 mg/100 g (Fig. 8). The Dunnett test ($\alpha=0.05$, p

Table 3 Color differences of dried avocado leaves

Experiment	Color properties					
	ΔL^*	Δa^*	Δb^*	Δc^*	Δh^*	ΔE^*
Open sun	1.66 $\pm$ 0.117b	6.60 $\pm$ 0.47a	1.38 $\pm$ 0.10d	-0.38 $\pm$ 0.03c	-6.67 $\pm$ 0.47a	6.98 $\pm$ 0.49b
Oven	5.3 $\pm$ 0.37a	3.35 $\pm$ 0.24b	6.09 $\pm$ 0.43b	4.48 $\pm$ 0.38b	-5.42 $\pm$ 0.38a	9.17 $\pm$ 0.65a
Mesh shade solar drying	1.38 $\pm$ 0.09b	6.04 $\pm$ 0.43a	3.52 $\pm$ 0.25c	3.76 $\pm$ 0.27b	-6.87 $\pm$ 0.49a	7.28 $\pm$ 0.56b
Direct solar drying	1.60 $\pm$ 0.11b	3.80 $\pm$ 0.27b	8.14 $\pm$ 0.58a	5.76 $\pm$ 0.41a	-6.89 $\pm$ 0.49a	9.16 $\pm$ 0.65a

value=0.000044) indicated that only mesh shade did not show significant differences with the control (fresh leaves). It can be attributed to the protection against solar radiation and the low temperature in the drying chamber. The rest of the experiments showed a significant decrease in vitamin C content following the next order: mesh shade solar drying > oven 50 °C > open sun > direct solar drying. Similar results were obtained by Gwala and Padmavati (2015), where the pineapple slices were subject to tray drying, solar drying, and open sun drying, obtaining the highest retention when indirect solar drying was applied (31.20 mg/100 g). The authors pointed out that this was due to the indirect solar heating mechanism prevailing in the solar dryer, which protected the pineapples from direct sunlight.

Antioxidant activity

The DPPH scavenging activity presented in terms of percentage inhibition of DPPH of the avocado leaves extract was 89.04 to 94.27%, where the highest antioxidant activity was measured on direct and mesh shade drying as seen in Fig. 9. Nevertheless, statistical analysis indicated no significant differences between fresh and dried leaves (p value=0.175). Figure 9 shows all percentages obtained for every drying condition. Some investigations point out that antioxidants are substances that have the ability to neutralize free radicals or their actions. In the case of avocado leaves dried by different methods, it was possible to keep the high concentration of these components, allowing potential consumers to ingest a product that may cause benefits to their health such as prevention and treatment of complex diseases like atherosclerosis, stroke, diabetes, Alzheimer's disease (AD), Parkinson's disease and cancer (Devasagayam et al. 2004).

Color

Color can indicate quality changes caused by drying and is considered a quality parameter that affects acceptance by consumers. The main objective is to keep as much as possible the original color of fresh material. Hunter L^* , a^* , b^* space of color gives numerical values to the color change, as seen in Table 3. With respect to ΔL^* , which represents the change in luminosity parameter, changes were positive, so dried samples were more luminous than fresh avocado leaves. Among drying techniques carried out, oven drying at 50 °C, represented the more significant change in luminosity parameter. The Δa^* parameter that describes a red (+) or green (−) color change, resulting in positive values for all dried samples, which means that the color of the leaves tends to be less green after the drying process. It can be explained because of the degradation of chlorophylls by

the incidence of sunlight and high temperatures. Δb^* , which represents the color blue (−) or yellow (+), presented positive values; in this case, dried avocado samples tend to be yellow in color. On the other hand, Δc parameter showed positive values for all samples except open sun drying with a value of −0.376. Δc^* positive values for dried avocado leaves describe that samples are more saturated or have more intensity compared to the original standard. Δh^* negative values indicated a shift towards the opposite side of the color, in this case, to redness. Finally, ΔE^* , which represents the global color difference, showed values between 6.98 and 9.17. The drying conditions that presented the smallest color differences were the open sun and mesh shade drying. It could be attributed to the lower temperatures in comparison to the rest of the drying conditions that did not have a significant incidence or impact on the color and compounds of avocado leaves.

Conclusions

Avocado leaves are usually not known by their medicinal properties or food additive potential and considering the increase of avocado plantations around the world there is a potential field of application of the benefits of the leaves to different products. In this study, solar drying techniques were applied to preserve avocado leaves and a comparison with oven (50 °C) was made. Drying conditions lead to retention of the antioxidant activity of avocado leaves in the range of 89.04 to 94.27% with no changes against fresh leaves. Flavonoid decreased after drying with values between 1.041 and 2.71 mg QE/g db; with respect to total phenols, it was observed an increment when open sun, oven, and mesh shade solar drying were applied (28.53–30.88 mg GAE/g db), ascorbic acid content better preserved with mesh shade solar drying with a value of 52.71 mg/100 g and color presented the least ΔE with open sun and mesh shade drying (6.98, 7.28). The study demonstrated that solar drying can be an excellent alternative to traditional systems to keep antioxidants and even enhance phenolic compound content with the advantage of using a sustainable energy source to obtain products with high-quality parameters and benefits to the health of potential consumers.

Solar drying provides a cost-effective and scalable approach for processing avocado leaves, making it particularly suitable for rural and producing regions. Modular mixed-mode solar dryers require minimal investment and can be readily implemented at small to medium scales. Future research should focus on scale-up optimization, economic evaluation, extraction techniques, formulation development, and regulatory frameworks to further enhance their industrial and commercial potential.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval Ethics approval was not required for this study.

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