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ORIGINAL ARTICLE

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Thermal evaluation of solar dryers and the effect on the antioxidant and some physicochemical properties of *Agastache mexicana* and *Rosmarinus officinalis*

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Abstract: Lemon balm (*Agastache mexicana*) and rosemary (*Rosmarinus officinalis*) were dried using a mixed-mode solar dryer. A 2^3-factorial design was carried out: operation mode (mesh shade and direct irradiance), airflow (natural convection and forced convection), and type of flat plate solar collector cover (polycarbonate and glass). The drying kinetics of lemon balm and rosemary ranged from 4.5 to 6.5 h and 4 to 7 h, respectively, according to the operation mode of the solar dryer. The highest percentage of antioxidant activity in the 2,2-diphenyl-1-picrylhydrazil tests was lemon balm, with values between 88% and 93% (100 µg/mL), and rosemary, 88% and 92% (100 µg/mL). When forced convection was applied, solar collector thermal efficiency increased from 3.97%–5.11% to 17.20%–24.75%, dryer efficiencies ranged from 4.78% to 6.05%, and drying efficiencies between 14.17% and 44.23%. The lowest color difference (6.01) for lemon balm was shown with the mesh shade, forced convection, and glass cover collector, and for rosemary, the lowest color difference (12.87) resulted from using the mesh shade and natural convection; according to the analysis of variance, the cover collector did not affect significantly the color difference. Dehydrated lemon balm and rosemary could be used as an additive for medicinal, gastronomic, and food preservative applications.

KEYWORDS

antioxidant activity, aromatic herbs, solar drying, solar energy, thermal evaluation

Practical Application: The results are significant for designing dryers for community centers in areas where the production and losses of fruits, vegetables, aromatic herbs, and edible flowers are high. The novelty of this research is to introduce a new product for the consumer; in this case, the traditional dried

rosemary and lemon balm in powder form as a nutritional source, both for the preparation of remedies and for direct consumption in dishes, powders, or healthy pills and food supplements.

1 | INTRODUCTION

Usage of medicinal plants to treat some diseases or modify nonpathological states has been a common practice worldwide. Lara et al. (2019) reported that about 80% of people worldwide depend on traditional medicine. In Mexico, medicinal plants play an essential role in public health among the local communities as a first alternative due to many drugs being expensive or unavailable locally. Among the wide variety of medicinal and aromatic plants, *Rosmarinus officinalis* and *Agastache mexicana* are important species that are considered sources of nutrients and benefits to human health. *R. officinalis*, commonly known as rosemary, is an aromatic plant with medicinal properties used as spice and herbal tea mixtures (Gonzáles et al., 2020). This plant presents biological activities, including antioxidant, antibacterial, hypoglycemic, anticancer, hepatoprotective, anti-inflammatory, and antithrombotic effects (Brindisi et al., 2020). These pharmacological properties are attributed to rosemary's chemical constituents, including flavonoids such as carnosol, carnosic, and rosmarinic acid, and volatile oils (Cheung & Tai, 2007).

Conversely, *A. mexicana, also known as lemon balm or bee balm, is a perennial herb traditionally used to treat* headaches, gastrointestinal diseases, and anemia and as a sedative for depression, psychosis, and hysteria symptoms (Miraj et al., 2017). Studies have revealed that this plant contains volatile compounds, triterpenoids, phenolic acids, and flavonoids, which provide anxiolytic, antiviral, and antispasmodic effects for consumers (Shakeri et al., 2016). As can be seen, medicinal plants can be part of the markets for pharmaceuticals, food, cosmetics, and perfumery, which makes it necessary to implement postharvest conservation methods that increase their shelf life and ensure the quality and quantity of the active ingredients in the product (Rocha et al., 2011). In this sense, medicinal plants should be dried as soon as possible after harvesting to prevent losses of their valuable components due to their perishable nature and the high levels of moisture and microorganisms that plants contain. Over the years, drying techniques have been developed to provide new possibilities to increase the drying process's quality and efficiency and give some advantages over conventional methods.

Drying is a complex process that involves simultaneous heat and mass transfer mechanisms as the product is heated and then the moisture is removed (Mennouche et al., 2014). Sun drying is an antique method where fresh products are placed on well-ventilated drying racks and exposed directly to the sunlight. This solar drying method is abundantly available, inexpensive, and an environment-friendly energy source. The growing popularity of solar energy in the agricultural sector is attributed to increased global energy demand. Most of this increase has been covered by fossil fuels, and consequently, significant CO_2 emissions have occurred (Ahmadi et al., 2021). Although some studies in herbs, such as *Acorus calamus* L. (Kumar et al., 2016), *Coriander sativum* L. (Pirbalouti et al., 2017), and *Cymbopogon citratus* (Hanaa et al., 2012), have demonstrated to be a suitable technique to preserve herbs, it is known that these are sensitive to drying conditions or pretreatments used, giving as a result different colors and chemical compositions of drying foodstuffs. Moreover, it is essential to mention that the type of plants, the season of harvesting, and planting sites may impact the drying quality of dried foodstuffs; therefore, the process needs to be adequately studied. Solar dryers are classified according to the drying air circulation to natural and forced convection dryers and in direct, indirect, or mixed modes. For this research, a cabinet-type mixed-mode solar dryer was used, combining direct (integral)-type and indirect (distributed)-type solar dryers. A combined system was used to dry herbs. Solar radiation incidents on herbs and air preheated in a flat plate solar collector. Studies on the drying process (particularly the sun drying) of rosemary and lemon balm are scarce in the literature, so the objective of this study was to evaluate the effect of sun drying on the quality of herbs under different working conditions. This article provides an alternative to preserve medicinal plants and their antioxidant constituents. Moreover, this research shows that solar drying methods are an excellent option because the rosemary and lemon balm could maintain and even enhance their quality and properties, with the value added of a sustainable process that improves the production and consumption practices in the food and pharmaceutical industry.

2 | MATERIALS AND METHODS

2.1 | Sample preparation

Fresh medicinal plants were obtained from a local market in Cuernavaca, Morelos, Mexico (18°55′33.66″

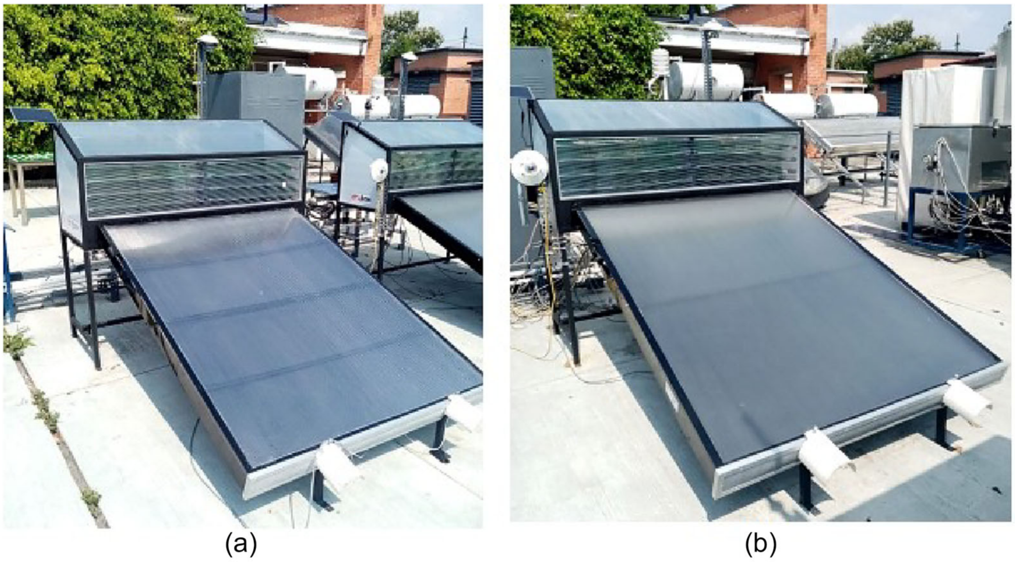

FIGURE 1 Cabinet solar dryers with solar collector: (a) collector with polycarbonate cover, (b) collector with glass cover.

Latitude, 99°13′58.01″ Longitude at 1100 mamsl). Samples were washed and disinfected, and the samples were immersed in a disinfectant detergent solution (SWIPE VEGGIEFRUIT WASH 1:100) for 15 min. Then, they were drained. The samples (100 g) were placed in a Teflon mesh and introduced into the solar dryer.

2.2 | Drying

The drying process was carried out in a cabinet-type mixed-mode solar dryer that contains a drying chamber with 10 trays (0.63 × 0.43 m) in 5 levels; each tray has multiple perforations of 0.0025 × 0.007 m, a photovoltaic fan, and a flat plate solar collector. Two different covers were used for the solar collector: polycarbonate (Figure 1a) and glass covers (Figure 1b). A photovoltaic panel was used to operate a fan that extracted the humid air inside the drying chamber, and a shade mesh can be placed on the drying chamber to decrease solar radiation and the temperature inside the dryer.

2.3 | Instrumentation

Each dryer was instrumented with two pyranometers (Kipp & Zonen, CM11; 0–1400 W/m^2 ± 2%, Netherlands) (one inclined in the plane of the collector and another vertical for the front of the drying chamber to measure the solar irradiance on drying days). Sixteen temperature sensors (RTD PT 1000, −50 to 750 ± 0.2°C) were placed in different sections: 2 at the inlet, 2 at the outlet of the 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-34972A) every 30 s (Figure 2). The air velocity was measured with two anemometers: a digital hot fin anemometer (Dwyer model 473B, ± 0.1 m/s) to measure fan air velocity and a hot wire anemometer (Dwyer model 471B, ± 0.1 m/s) for the air velocity at the outlet grilles; the tilt angle was 21°.

2.4 | Experimental design

A 2^3-factorial method was employed, and the use of mesh shade (X_1), fan (X_2), and collector cover types (X_3) were established as factors. The levels of the factors were called "low" when no mesh shade and fan were used and when cellular polycarbonate was used; on the other hand, the factors were called "high" when the mesh shade and the fan were used, and the cover collector was glass material. Eight experimental tests were assessed, and the experimental analysis was conducted in triplicate.

2.5 | Statistical analysis

Statistical analysis was performed using analysis of variance (ANOVA). The data were analyzed using MINITAB 16 with a significance level of $\alpha = 0.05$. The response variables were moisture content, water activity (aw), color parameters, collector thermal efficiency, dryer efficiency, drying efficiency, and antioxidant activity for lemon balms and rosemary herbs. Table 1 shows the factors and levels used.

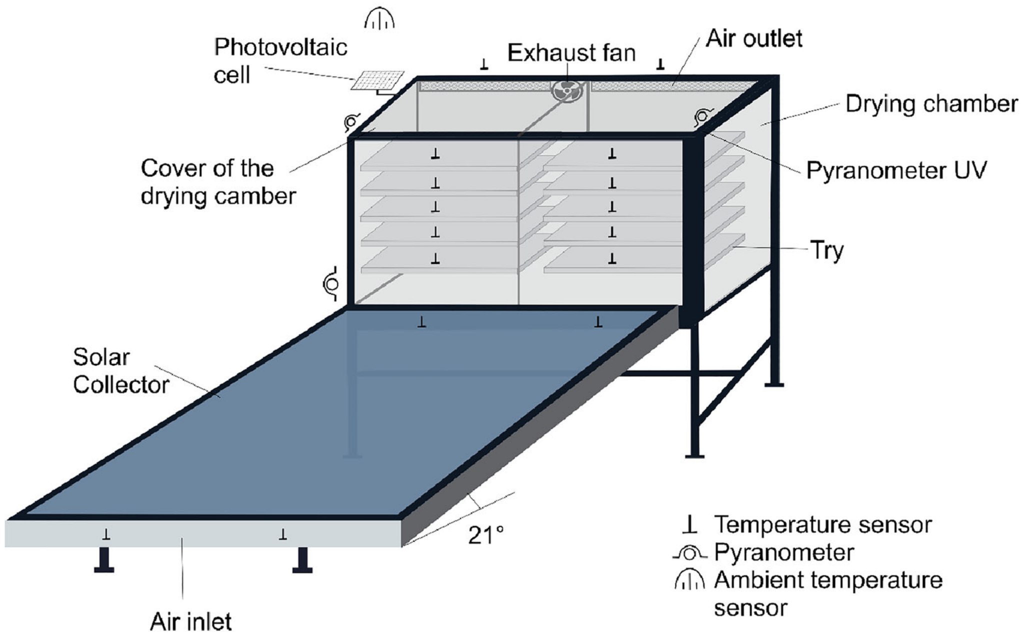

FIGURE 2 Instrumented cabinet solar dryer.

TABLE 1 Experimental design.

Factor	Low level (−1)	High level (+1)
Mesh shade (X_1)	Without mesh	With mesh
Fan (X_2)	Without fan	With fan
Collector cover type (X_3)	Cellular polycarbonate	Glass

Experimental test			
Test	**Mesh shade**	**Air flow**	**Type of cover**
1	−1	−1	−1
2	+1	−1	−1
3	−1	+1	−1
4	+1	+1	−1
5	−1	−1	+1
6	+1	−1	+1
7	−1	+1	+1
8	+1	+1	+1

2.6 | Color

The sample color was measured by a portable colorimeter (NR60CP*). A representative sample 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 calculated the color difference between the fresh and dried samples (ΔE), chroma, and hue angle:

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

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

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

2.7 | Moisture content and water activity

The moisture content was obtained using a thermobalance (OHAUS, MB45, with a readability of 0.001 g) at 105°C; around 3 g of the sample was placed and distributed uniformly on an aluminum pan inside the equipment. aw was determined with a Rotronic aw meter (Higrolab C1) at 25°C, where the disposable sample cup was covered entirely and introduced inside the kit for 20 min. The equipment was calibrated using Rotronic verification standards.

2.8 | Antioxidant activity

Distilled water was added to 20 g of the sample, and the mixture was heated without boiling. Subsequently, samples were cooled down and filtered. After that, solids were frozen with liquid nitrogen, freeze-dried, and saved in vials for analysis. The antioxidant activity of the extracts was determined using the 2,2-diphenyl-1-picrylhydrazil (DPPH) free radical scavenging activity method, described by Chaves et al. (2020), with some modifications. 1.5–2 mg

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TABLE 2 Physicochemical analysis of lemon balm and rosemary.

Analysis	Lemon balm Mean values	Rosemary
Moisture content (%)	77 ± 0.81	67 ± 0.70
Water activity	0.98 ± 0.01	0.96 ± 0.01
L	37.86 ± 0.21	47.31 ± 0.87
a	−8.52 ± 0.24	−5.24 ± 0.11
b	16.56 ± 0.99	12.50 ± 0.46
c	18.67 ± 0.64	13.61 ± 0.13
h	117.53 ± 0.53	113.09 ± 0.72
Antioxidant activity (%)	63 ± 0.01	91 ± 0.01

Note: L (lightness), *a* (green–red), *b* (yellow–blue), *c* (chroma), *h* (hue).

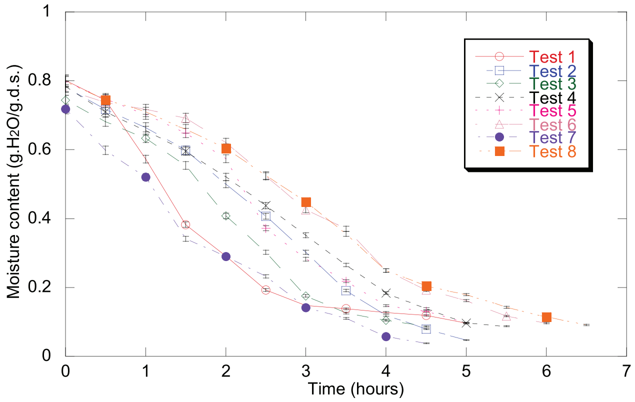

FIGURE 3 Drying kinetics of lemon balm.

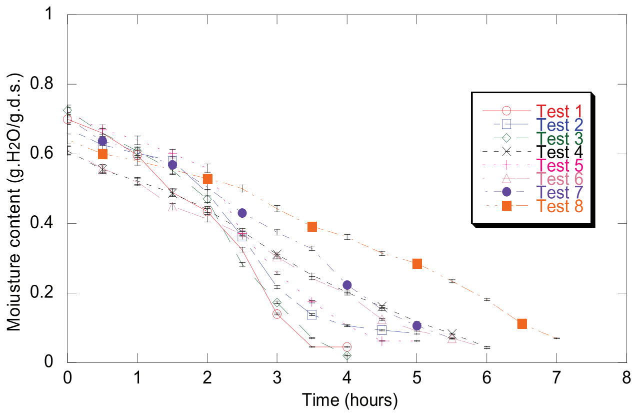

FIGURE 4 Drying kinetics of rosemary.

of samples were weighed and dissolved in deionized water to determine antioxidant activity to obtain a 20 mg/mL concentration. The assay was performed on 96 healthy plates. In these wells, 50 µL of the solution was placed at increasing concentrations from 1 to 100 µg/mL. Subsequently, 150 µL of 133 µM ethanolic DPPH solution (final concentration 100 µM) were added. The plate was incubated for 30 min at 37°C in the dark and under constant stirring. The absorbance of each well was measured at 515 nm in a microplate reader (Bio-Tek, Elx-808). The activity on DPPH is expressed as a percentage reduction and calculated with the following equation:

$$\% \text{ reduction} = \left(\frac{C - E}{C}\right) \times 100$$

where C = OD (optical density) of DPPH 100 µM, E = OD (optical density) of the DPPH mixture 100 µM + mixture.

2.9 | Instantaneous thermal efficiency of the solar collector

The instantaneous thermal efficiency in the solar collector was calculated by applying the following equation:

$$\eta_c = \frac{\dot{m}_{da} Cp_{da} \left(T_{out,C} - T_{in,C}\right)}{A_C I_T}$$

where $\dot{m}_{da}$ is the air mass flow rate, Cp_{da} is the specific heat of air at constant pressure at an average temperature between the inlet and outlet of the solar collector, $T_{out,C}$ and $T_{in,C}$ is the outlet and inlet temperature of the collector, respectively. Although I_T is the incident solar radiation on the solar collector plane, A_C is the gross solar collector area.

2.9.1 | Thermal efficiency of the dryer

In a solar dryer, energy efficiency describes the energy used to evaporate moisture contained in foodstuffs at a given temperature, with the entire energy supplied to the dryer (López et al., 2020). The energy efficiency of the dryer was calculated by applying the following equation:

$$\eta_E = \frac{m_w h_{fg}}{(A_C \times I_{PI}) + A_{G_T}(I_{PI} \times F_{EI}) + A_{G_V}(I_{PV} \times F_{EI}) + W_{vent}}$$

where m_w is the water evaporated mass, h_{fg} is the latent heat of vaporization of water, A_C is the gross solar collector area, A_{G_T} is the inclined area of the drying chamber corresponding to the roof, and I_{PI} is the irradiance in the collector plane. A_{GV} is the vertical area of the chamber corresponding to the front multiplied by I_{PV} that is the irradiance in the vertical plane, W_{vent} is the fan power, and F_{EI} is the fraction of incident energy. F_{EI} refers to the solar

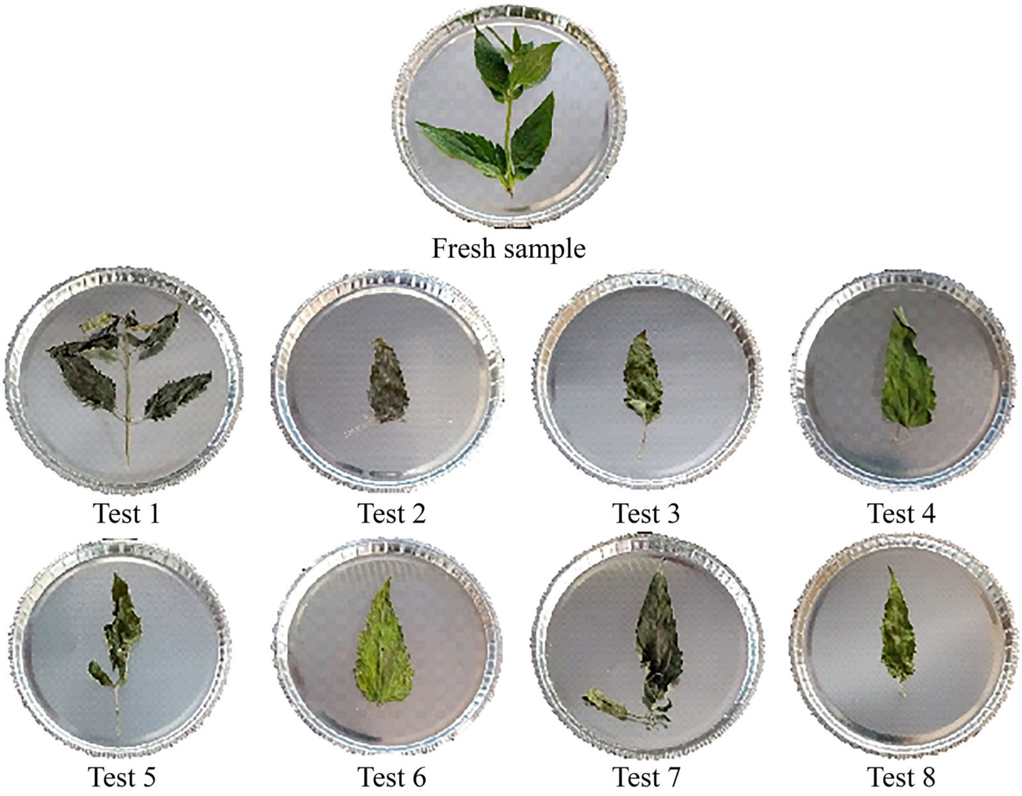

FIGURE 5 Lemon balm fresh and dried at different drying conditions.

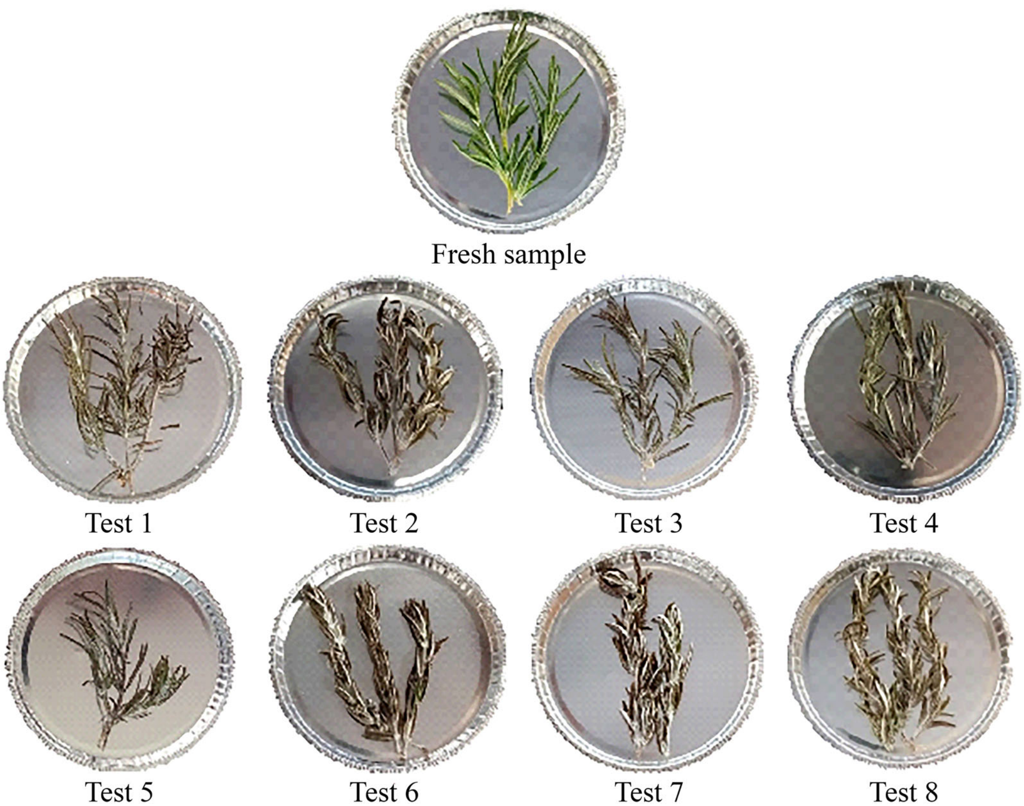

FIGURE 6 Rosemary fresh and dried at different drying conditions.

TABLE 3 Average ambient conditions of the test days.

Test	Average inclined plane solar irradiance (W/m^2)	Average vertical plane solar irradiance (W/m^2)	Insolation (MJ)	Average ambient relative humidity (%)	Average ambient temperature (°C)	Average dryer temperature (°C)
1	880	508	2164	57	30	50
2	851	616	2133	39	30	46
3	882	615	2203	48	30	49
4	815	625	2055	47	30	44
5	861	680	2144	41	28	48
6	812	607	2042	37	30	45
7	851	585	2123	44	29	46
8	708	564	1793	45	29	40

radiation incident on the drying chamber when the shade mesh was used; this value was 0.3 because the shade mesh was 70%. However, when the shade mesh was not used, the value was 1.

2.9.2 | Thermal efficiency of the drying

The thermal efficiency of the drying is related to the energy applied to heat the fresh material and evaporate its contained moisture with the energy provided to the drying system. It is calculated with the following equation:

$$\eta_D = \frac{m_p Cp_p \left(T_{p,t+dt} - T_{p,t}\right) + m_w h_{fg}}{\left(A_C \eta_C \times I_{PI}\right) + \left(I_{PI} \times F_{EI}\right)\left(A_{G_T} \tau_G\right) + A_{G_V}\left(I_{PV} \times F_{EI}\right)\tau_G}$$

where m_p and Cp_p are mass and specific heat of the material. $T_{p,t+dt}$ is the temperature of the product in the next time step, $T_{p,t}$ is the temperature at that moment, η_C is the solar collector's thermal efficiency, and τ_G is the transmittance of the drying chamber cover.

3 | RESULTS AND DISCUSSION

3.1 | Characterization of lemon balm (*Agastache mexicana*) and rosemary (*Rosmaninus Officinalis*)

The initial moisture content of lemon balm and rosemary was 77% and 67 %, respectively. Shamekhi et al. (2018) reported values close to 80% for fresh lemon balm (*Melissa officinalis*), and Mulinacci et al. (2011) reported 60% for rosemary. The moisture content and quality of herbs depend on the growth stage at collection, geographical origin, postharvest handling, and the species. Due to the high level of aw for lemon balm (0.98) and rosemary (0.96), herbs are highly perishable and tend to decompose (Table 2).

The shelf life of herbs after the postharvest is 3 weeks at 0°C and 2 weeks at 5°C, depending on the storage method. Lopresti and Tomkins (1997) reported that the best storage temperature is 0°C. Under these conditions, herbs maintained excellent visual quality over 10–14 days (Lopresti & Tompkins, 1997). The antioxidant activity of lemon balm and rosemary was 63% and 91%; this property is defined as the capacity of a substance to prevent or delay the oxidation of easily oxidizable materials, such as fats (Miguel, 2010). The colorimetric analysis in the lemon balm showed a lightness value of 37.86 and a negative value in *a* parameter (−8.52); according to the Hunter system, the greenness is represented by −*a* on the negative side.

On the other hand, the lemon balm showed a hue angle of 117.53°. The color passes from yellow to green when the hue angle oscillates from 90° to 180°. The colorimetric analysis of the rosemary showed a lightness value of 47.31, the a negative value (−5.24), and a hue angle (113.09).

3.2 | Drying kinetic

The solar drying process of lemon balm and rosemary was carried out from October 25th to November 30th, 2022. The experiments took place from 10:00 to 17:00 h. Environmental conditions are shown in Table 3.

The drying temperature ranged from 44 to 50°C with the cellular polycarbonate collector, whereas the drying temperature ranged from 40 to 48°C with the glass collector. Müller and Heindl (2006) reported that to protect sensitive active compounds in herbs and medicinal plants, low drying temperatures from 30 to 50°C are recommended. The drying temperature inside the dryers was controlled using an exhaust fan and a mesh shade to reduce the solar irradiance. Figure 3 shows the drying kinetics of lemon balm (each point shows its error bar due to the experimental measurements); the drying duration ranged from 4.5 to 6.5 h according to each operation mode of the drying system; usually, the drying duration is comparably long at low drying temperatures. Shamekhi et al. (2018) in an indirect solar dryer system, the reported drying times of lemon balm leaves were from 3.5 to 5.5 h at 50°C.

Figure 4 shows the drying kinetic of rosemary (each point shows its error bar due to the experimental measurements); in this case, the drying time ranged from 4 to 7 h. Similar results were reported by Karami et al. (2021) in the solar drying of rosemary by using a hybrid solar dryer; according to their results, the drying time ranged from 4 to 8 h depending on the drying temperature (40–70°C) and the airflow (1–2 m/s). Ali et al. (2020) reported the convective drying of rosemary at 50, 60, and 70°C; in this report, the drying time was 5.5, 3, and 2 h, respectively.

3.3 | Moisture content and water activity

The average moisture percentage of lemon balm and rosemary was 77% and 67%, respectively (Table 2). As seen in Table 4, the final moisture content ranged from 3.8% to 9.6%; these values are close to the results obtained by Vallino et al. (2022), who obtained final moisture in lemon balm lower than 12% in an oven drying at 40°C for 24 h. Ali et al. (2020) reported a final moisture content in rosemary of about 12% in a hybrid solar dryer.

The ANOVA for lemon balm (Table 5) drying showed that the use of mesh shade, type of convection, and the collector cover type, as well as the interactions, significantly affected ($p < 0.05$) the moisture content of the product. According to the ANOVA, the lowest moisture content can be obtained without mesh shade and when forced convection and polycarbonate cover in the collector were used. As seen in Table 4, the final moisture content of lemon balm ranged from 3.8% to 9.6%, and the aw values varied from 0.349 to 0.535. These values of aw mean that reactions of a chemical or biological nature will not come about.

The cover collector, the mesh shade's interaction effect, and the convection type affected the aw significantly. The aw values were low when the glass cover collector was used (Table 4). The final moisture content of rosemary ranged from 2% to 8.3% (Table 6); the ANOVA (Table 7) revealed that the independent variables (mesh shade, type of convection, and the collector cover type) significantly affected ($p < 0.05$) this response variable.

According to the results, the lowest moisture content can be obtained when no mesh shade was used, with forced convection, and when the collector with polycar-

TABLE 4 Results obtained for the response variables in lemon balm.

Test	Factors			Response variables			Color parameters					
	X_1	X_2	X_3	Drying time (hours)	Final moisture content (%)	Final water activity	L	a	b	c	h	ΔE
1	−1	−1	−1	5	9.6	0.535 ± 0.01	22.29 ± 1.03	−1 ± 0.20	6.29 ± 0.45	6.38 ± 0.46	98.45 ± 1.46	16.76 ± 2.6
2	+1	−1	−1	5	4.7	0.374 ± 0.01	26.51 ± 0.26	0.33 ± 0.05	10.36 ± 0.20	10.37 ± 0.20	88.15 ± 0.3	17.86 ± 0.02
3	−1	+1	−1	4.5	8.7	0.389 ± 0.02	26.56 ± 0.15	−3.56 ± 0.07	9.87 ± 0.09	10.49 ± 0.06	109.85 ± 0.50	13.35 ± 0.74
4	+1	+1	−1	5.5	8.7	0.495 ± 0.0	38.56 ± 0.02	−2.36 ± 0.03	16.8 ± 0.01	16.96 ± 0.01	98.00 ± 0.08	7.94 ± 0.01
5	−1	−1	+1	5	9.7	0.405 ± 0.05	28.11 ± 0.75	−2 ± 0.32	10.31 ± 0.51	10.51 ± 0.56	100.96 ± 1.19	16.18 ± 0.10
6	+1	−1	+1	6	9.6	0.383 ± 0.01	31.14 ± 0.31	−4.2 ± 0.05	17.3 ± 0.16	17.81 ± 0.17	103.63 ± 0.03	8.23 ± 0.01
7	−1	+1	+1	4.5	3.8	0.349 ± 0.04	18.44 ± 0.94	0.25 ± 0.46	4.15 ± 1.45	4.20 ± 1.37	85.18 ± 8.91	21.34 ± 1.12
8	+1	+1	+1	6.5	9.1	0.357 ± 0.02	28.88 ± 0.12	−4.53 ± 0.04	14.3 ± 0.03	15.01 ± 0.03	107.75 ± 0.16	6.01 ± 0.02

Note: L (lightness), a (green–red), b (yellow–blue), ΔE (color difference), X_1 = mesh shade, X_2 = fan, X_3 = collector cover type.

TABLE 5 Analysis of variance of response variables of lemon balm.

Responses					
Y_1 = moisture content					
Factor	DF	Sum of squares	Mean squares	F-ratio	Prob. level
X_1	1	0.034	0.0337	6.12	0.024*
X_2	1	4.084	4.0838	740.52	0.000*
X_3	1	0.094	0.0937	17.00	0.001*
$X_1 \times X_2$	1	39.784	39.7837	7214.12	0.000*
$X_1 \times X_3$	1	38.254	38.2538	6936.68	0.000*
$X_2 \times X_3$	1	33.844	33.8437	6137.00	0.000*
Error	17	0.094	0.0055		
Total	23	116.186			
Y_2 = water activity					
X_1	1	0.001751	0.001751	0.94	0.345
X_2	1	0.004347	0.004347	2.34	0.145
X_3	1	0.033675	0.033675	18.11	0.001*
$X_1 \times X_2$	1	0.032930	0.032930	17.71	0.001*
$X_1 \times X_3$	1	0.000610	0.000610	0.33	0.574
$X_2 \times X_3$	1	0.001190	0.001190	0.64	0.435
Error	17	0.031614	0.001860		
Total	23	0.106117			
Y_3 = color difference					
X_1	1	310.392	310.392	156.38	0.000*
X_2	1	31.809	31.809	16.03	0.001*
X_3	1	10.653	10.653	5.37	0.033*
$X_1 \times X_2$	1	60.579	60.579	30.52	0.000*
$X_1 \times X_3$	1	152.258	152.258	76.71	0.000*
$X_2 \times X_3$	1	114.188	114.188	57.53	0.000*
Error	17	33.743	1.985		
Total	23	713.623			
Y_4 = antioxidant activity					
X_1	1	6.000	6.0000	1.89	0.187
X_2	1	6.000	6.0000	1.89	0.187
X_3	1	6.000	6.0000	1.89	0.187
$X_1 \times X_2$	1	6.000	6.0000	1.89	0.187
$X_1 \times X_3$	1	24.000	24.0000	7.56	0.014*
$X_2 \times X_3$	1	6.000	6.0000	1.89	0.187
Error	17	54.000	3.1765		
Total	23	108.000			

Note: "*" Indicates significant differences at $\alpha = 0.05$.

bonate cover was used. Mulinacci et al. (2011) reported a final moisture content of rosemary of 5% after drying at room temperature in the dark for several days. The aw values ranged from 0.341 to 0.574; with these values, it is possible to ensure that the drying process inhibits the growth of microorganisms due to contamination that causes food spoilage as well as contributes to suspending enzymatic or nonenzymatic browning reactions, and according to literature, the minimum activity water at which microorganisms can subsist is 0.60 (Alp & Bulantekin, 2021).

3.4 | Colorimetric analysis

Color is one of the most critical food characteristics that require evaluation, and this quality parameter determines market acceptance (Jin et al., 2016). In this sense, the main

TABLE 6 Results obtained for the response variables in rosemary.

	Factors			Response variables			Color parameters					
Test	X_1	X_2	X_3	Drying time (hours)	Final moisture content (%)	Final water activity	*L*	*a*	*b*	*c*	*h*	Δ*E*
1	−1	−1	−1	4	4.5	0.5 ± 0.01	28.1 ± 0.06	0.72 ± 0.02	8.7 ± 0.02	8.73 ± 0.02	85.27 ± 0.15	23.17 ± 0.78
2	+1	−1	−1	5	8.3	0.389 ± 0.03	26.3 ± 0.24	1.2 ± 0.16	8.44 ± 0.46	8.53 ± 0.47	81.88 ± 0.82	17.89 ± 0.81
3	−1	+1	−1	4	2	0.323 ± 0.04	32.1 ± 0.25	−0.19 ± 0.02	7.08 ± 0.04	7.08 ± 0.05	91.56 ± 0.15	23.52 ± 0.14
4	+1	+1	−1	6	4.5	0.535 ± 0.00	30.6 ± 0.1	0.27 ± 0.03	12.51 ± 0.07	12.52 ± 0.06	88.76 ± 0.14	18.88 ± 0.04
5	−1	−1	+1	5	6.2	0.370 ± 0.02	27.8 ± 0.09	−0.78 ± 0.03	9.89 ± 0.02	9.92 ± 0.03	94.53 ± 0.11	25.44 ± 0.61
6	+1	−1	+1	6	4	0.309 ± 0.01	38.0 ± 2.2	0.91 ± 0.06	6.84 ± 0.09	6.90 ± 0.10	82.40 ± 0.39	12.87 ± 0.07
7	−1	+1	+1	5.5	6.9	0.574 ± 0.01	31.9 ± 1.5	1.3 ± 0.19	5.81 ± 0.88	5.95 ± 0.90	77.40 ± 0.22	30.15 ± 1.75
8	+1	+1	+1	7	7	0.341 ± 0.08	38.48 ± 0.09	1.63 ± 0.07	10.2 ± 0.28	10.41 ± 0.28	81.00 ± 0.13	14.94 ± 0.32

Note: L (lightness), *a* (green–red), *b* (yellow–blue), Δ*E* (color difference), X_1 = mesh shade, X_2 = fan, X_3 = collector cover type.

point was to find the drying conditions that maintained natural color in dried food products as much as possible to maintain an excellent visual appearance. During the drying process of lemon balm, the initial lightness (37.86) decreased to values that ranged from 18.44 to 37.56; the decrease in *a* parameter means that the lemon balm tends to be less green, as seen from Table 4. The *a* parameter increases from −8.52 to values that ranged from −4.53 to 0.33. An increase in *b* parameter means that the lemon balm inclines to the yellow color; this behavior can be observed with the decrease in hue angle from an initial value of 117.53 to values from 85.18° to 109.85°. Orphanides et al. (2016) reported that chlorophyll is transformed into pheophytins during the drying process, converting green color to olive brown due to high temperatures; therefore, drying temperature below 50°C is recommended. Vallino et al. (2022) reported that cold drying of lemon balm leaves at 20°C for 72 h preserved higher brightness and a greater tendency to green color than the lemon balm leaves dehydrated at 40°C in traditional drying. The total color difference (Δ*E*) is the variation observed between raw and dried materials. As shown in Table 4, Δ*E* took values from 6.01 to 17.86; this means a perceptible difference compared to the standard (Figure 5). In this case, the lowest color difference was obtained when the drying system operated with the mesh shade, forced convection, and glass cover collector (Test 8).

In Table 5, the color parameters of rosemary were reported; the initial lightness (47.31) decreased to values that ranged from 26.33 to 38.48, which means that the sample turned dark, and the *a* parameter dropped from −5.24 to values that went from −0.78 to 1.63; therefore, the sample will be less green (Figure 6). The Hue angle decreased from 113.09 to values between 77.40 and 94.53; thus, the color passed from green to yellow. Similar values in *L*, *a*, and *b* were reported by Arslan and Özcan (2008) during the evaluation of drying methods (electric oven at 50°C during 12 h, sun drying, and microwave). The lowest color difference resulted from using the mesh shade and natural convection (Tests 5 and 6); according to the ANOVA, the cover collector did not significantly affect ($p > 0.05$) the color difference (Table 7).

3.5 | Antioxidant activity

Due to many bioactive compounds as antioxidants that may degrade during solar drying, the study of the drying process in several conditions was the key to obtaining the best quality dried product. The lemon balm sample had an initial antioxidant activity of 63%; however, when it was subjected to the solar drying process, the percentage increased to values that ranged from 88.53% to 93.08%

TABLE 7 Analysis of variance of response variables of rosemary.

Response variables					
Y_1 = moisture content					
Factor	DF	Sum of squares	Mean squares	F-Ratio	Prob. level
X_1	1	6.6150	6.6150	23.14	0.000*
X_2	1	2.5350	2.5350	8.87	0.008*
X_3	1	8.6400	8.6400	30.22	0.000*
$X_1 \times X_2$	1	0.3750	0.3750	1.31	0.268
$X_1 \times X_3$	1	26.4600	26.4600	92.56	0.000*
$X_2 \times X_3$	1	37.5000	37.5000	131.17	0.000*
Error	17	4.8600	0.2859		
Total	23	86.9850			
Y_2 = water activity					
X_1	1	0.013968	0.013968	2.12	0.163
X_2	1	0.015759	0.015759	2.40	0.140
X_3	1	0.008778	0.008778	1.34	0.264
$X_1 \times X_2$	1	0.008400	0.008400	1.28	0.274
$X_1 \times X_3$	1	0.058905	0.058905	8.96	0.008*
$X_2 \times X_3$	1	0.027001	0.027001	4.11	0.059
Error	17	0.111764	0.006574		
Total	23	0.244576			
Y_3 = color difference					
X_1	1	535.532	535.532	510.84	0.000*
X_2	1	25.400	25.400	24.23	0.000*
X_3	1	0.008	0.008	0.01	0.930
$X_1 \times X_2$	1	1.670	1.670	1.59	0.224
$X_1 \times X_3$	1	118.415	118.415	112.95	0.000*
$X_2 \times X_3$	1	10.653	10.653	10.16	0.005*
Error	17	17.822	1.048		
Total	23	709.499			
Y_4 = antioxidant activity					
X_1	1	0.3750	0.3750	17.00	0.001*
X_2	1	3.3750	3.3750	153.00	0.000*
X_3	1	30.3750	30.3750	1377.00	0.000*
$X_1 \times X_2$	1	3.3750	3.3750	153.00	0.000*
$X_1 \times X_3$	1	0.3750	0.3750	17.00	0.001*
$X_2 \times X_3$	1	3.3750	3.3750	153.00	0.000*
Error	17	0.3750	0.0221		
Total	23	41.6250			

Note: "*" Indicates significant differences at $\alpha = 0.05$.

(Figure 7, each test shows its error bar due to experimental measurements). According to the results, the solar drying process greatly benefits antioxidant activity, which can represent a great advantage compared to other drying techniques.

According to Kwaśniewska and Mostowski (2021), this behavior can be attributed to the fact that when an aromatic herb is subjected to a drying process, it causes the release of additional active compounds, increasing the antioxidant activity in the dried samples. On the other hand, Zielińska and Matkowski (2014) reported a high flavonoid content during the initial flowering period of lemon balm. Flavonoids are mainly responsible for the antioxidant activity of plants; therefore, the high values reported for antioxidant activity in this study may be related to the presence of these flavonoids. The ANOVA

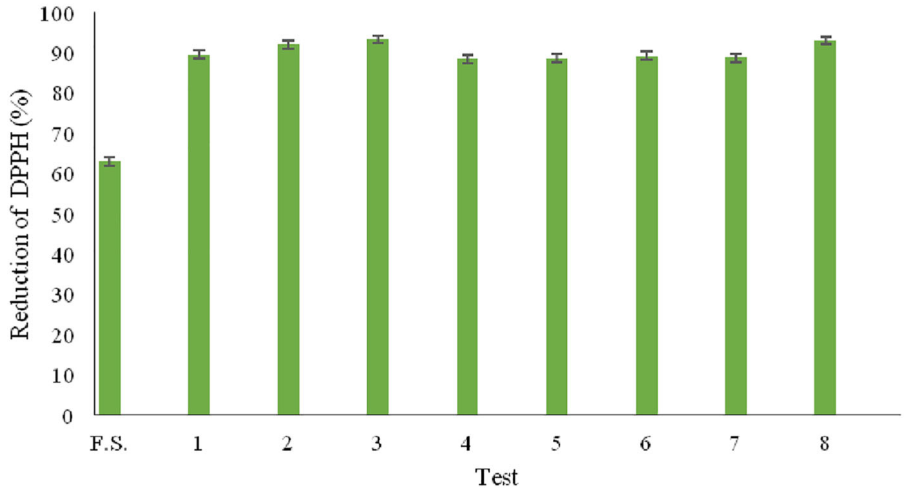

FIGURE 7 Antioxidant activity of lemon balm at different drying conditions.

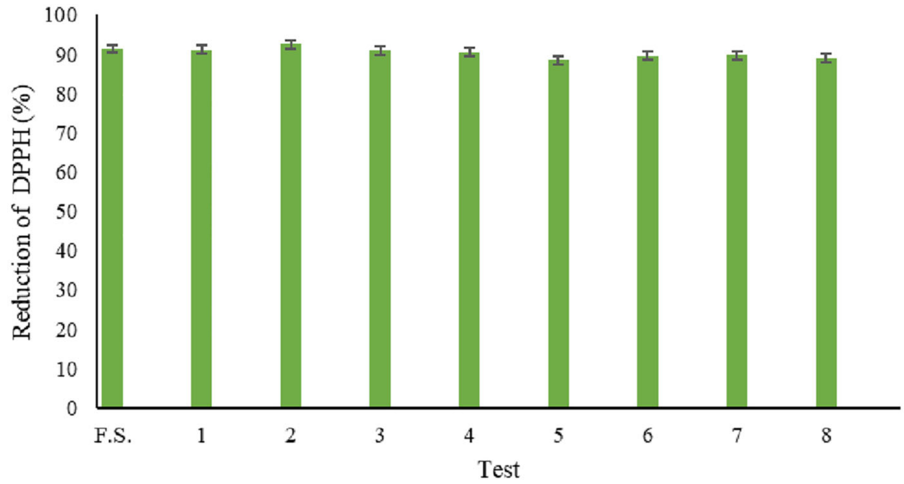

FIGURE 8 Antioxidant activity of rosemary at different drying conditions.

(Table 5) showed that the interaction effect of mesh shade and type of cover collector significantly affected ($p < 0.05$) antioxidant activity. High antioxidant activity was obtained using mesh shade and the glass cover collector or the polycarbonate cover collector without mesh shade.

Figure 8 shows the antioxidant activity of rosemary (each test shows its error bar due to experimental measurements); as seen from the figure, the initial antioxidant activity was 91%; this value ranged from 88.48% to 92.48%. According to the results, the solar drying process did not affect the antioxidant activity; the drying condition used mesh shade, natural convection, and polycarbonate cover collector to preserve the antioxidant activity.

Kwaśniewska and Mostowski (2021) reported that polyphenols determine the antioxidant activity of herbs; these compounds are released during the drying process. According to their results, freeze-drying removes more polyphenols than the convective drying at 30°C. In this case, the antioxidant activity of rosemary at different drying conditions was close to the initial value. The best drying conditions for high antioxidant activity are mesh shade, natural convection, and polycarbonate collector. Antioxidants are such important components that help to maintain human health because they are able to diminish the overproduction of free radicals, which are considered a significant cause of aging and carcinogenesis (Lambert & Yang, 2003). Moreover, increases in antioxidant capacity after solar drying may be related to the Maillard reactions that can be formed because of the heat treatment or prolonged storage, which generally exhibit strong antioxidant properties.

TABLE 8 Thermal efficiency of lemon balm and rosemary.

Lemon balm						
				Efficiency (%)		
Test	X_1	X_2	X_3	Collector	Dryer	Drying
1	−1	−1	−1	4.04	4.79	17.41
2	+1	−1	−1	3.97	6.05	44.23
3	−1	+1	−1	17.20	4.78	18.63
4	+1	+1	−1	18.05	5.87	23.86
5	−1	−1	+1	4.87	4.79	16.56
6	+1	−1	+1	5.11	5.29	35.70
7	−1	+1	+1	24.75	4.83	14.17
8	+1	+1	+1	21.79	5.62	18.80
Rosemary						
1	−1	−1	−1	4.04	5.15	18.72
2	+1	−1	−1	3.97	5.42	37
3	−1	+1	−1	17.20	5.35	20.65
4	+1	+1	−1	18.05	4.25	17.78
5	−1	−1	+1	4.87	4.42	15.29
6	+1	−1	+1	5.11	4.58	28.41
7	−1	+1	+1	24.75	3.91	10.82
8	+1	+1	+1	21.79	4.27	14.66

Note: X_1 = mesh shade, X_2 = fan, X_3 = collector cover type.

3.6 | Thermal performance evaluation

The dryer efficiency indicates thermal performance; this relates to the amount of energy necessary to remove water content from the foodstuffs and the energy supplied in the process (Table 8).

Eight experimental conditions were tested (Table 1). For the experiments where the mesh shade was not used, the energy was supplied to the system by the irradiance in the solar collector plane and the irradiance in the vertical plane of the drying chamber. On the other hand, when the mesh shade was used, the energy supplied to the system was similar; however, the solar radiation was attenuated by 70%; only 30% of the solar irradiance fell directly on the drying chamber. Table 8 shows lemon balm and rosemary; as seen from the results, the collector thermal efficiency increased from 3.97%–5.11% (at natural convection) to 17.20%–24.75% when the dryer was operated in forced convection. Essalhi et al. (2018) compared the thermal performance between two solar air collectors for an indirect solar dryer and observed that the efficiency increased when the dryer was operated in forced convection due to the increase in the mass flow rate of air and the width of the cylinders that constitute the absorber, and a more significant transfer of heat to the flowing air occurs, resulting in a high efficiency of the collector.

Additionally, collector efficiency improves by increasing the mass flow rate due to better heat transfer to the airflow. The dryer efficiencies ranged from 4.78% to 6.05%; the highest efficiency values were obtained when the mesh shade was used. The same behavior was observed for the drying efficiencies, which were between 14.17% and 44.23%. According to López et al. (2021), a high drying efficiency was observed when a cover was used in the drying chamber because the energy reached by the dryer was used in a more significant quantity than in the experiments that did not use a cover. Studies have been carried out on the thermal efficiency of different dryers. Kaur et al. (2023) reported an efficiency of 16.85% in indirect mode and 14.60% in direct mode during the drying process of coriander leaves using domestic solar dryers with natural convection. Mealla and Morales (2018) reported efficiencies of 1.8% and 18% during the thermal evaluation of solar dryers in direct and indirect modes, respectively; in this case, it was observed that the efficiencies increased when the dryer was operated in indirect mode. López et al. (2021) carried out an energy analysis of a mixed solar dryer for pear slices (*Pyrus communis* L); the dryer was operated under three conditions: mixed mode with natural convection, mixed mode with forced convection, and indirect mode with natural convection. The results indicated efficiencies of 6.6% and 14% for the dryer and drying process, respectively, when the dryer was operated in mixed mode with natural convection and efficiencies of 7.5% for the dryer and 11.6% for the drying process when the mixed mode with forced convection was used. Finally, the results indicated efficiencies of 8.2% for the dryer and 26.6% for the drying process by using the indirect mode with natural convection.

4 | CONCLUSIONS

In this study, the drying conditions that kept the physicochemical properties of lemon balm (as compared to fresh) were mesh shade, forced convection, and glass collector; at this drying condition, the lowest moisture content was 9.1%, aw 0.35, color difference of 6.01, and antioxidant activity of 93%. When the lemon balm was subjected to a drying process, it released additional active compounds, increasing the antioxidant activity in the dried samples. The best drying conditions for rosemary were achieved using the mesh shade, natural convection, and glass collector. The moisture content at these conditions was 4%, aw 0.309, color difference 12.87, and 92% of antioxidant activity. For lemon balm and rosemary, the collector efficiencies increased at forced convection due to increased air mass flow. The dryer efficiencies increased when the mesh shade was used because the energy that reached the dryer was used in a more significant proportion than the energy that reached the dryer when the mesh shade was not used.

AUTHOR CONTRIBUTIONS

Alfredo Domínguez-Niño: Investigation; writing—original draft; formal analysis. **Ana María Lucho-Gómez**: Investigation; methodology. **Rosa María Chávez-Santos**: Investigation; formal analysis. **Roberto Martínez**: Investigation. **Paulina Guillén-Velázquez**: Investigation; methodology; formal analysis. **Beatriz Castillo-Téllez**: Investigation; writing—review and editing. **Octavio García-Valladares**: Supervision; writing—review and editing; validation.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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