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Research article

Comparative effects of conventional and modern drying methods on drying time, energy consumption, and physicochemical properties of lavender (Lavandula stricta Del.)

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Abstract: Lavender is known as a natural antidepressant and sleep-promoting herbal medicine. In this study, we compared six distinct drying techniques: Refractance window drying (RW), freeze drying (FD), microwave drying (MW), infrared drying (IR), hot air drying (HA), and shade drying (SD), to evaluate their effects on drying time, energy and physicochemical and phytochemical properties of dried lavender. Moreover, we compared drying methods and their influence on water activity, rehydration ratio, total phenolic content, flavonoid content, antioxidant activity, color, and essential oil. RW and MW drying illustrated short-term drying processes with energy saving. All dried lavender samples demonstrated water activity levels within acceptable limits (less than 0.6). The results showed that FD and RW could preserve the total phenolic and total flavonoid contents compared to other techniques. In addition, there was no significant difference ($p < 0.05$) between RW and frozen samples regarding essential oil yield and rehydration ratio. The total antioxidant capacity of the fresh sample was significantly higher than that of dried samples, but FD significantly preserved the antioxidant content better than other treatments. Moreover, SD-dried samples had the lowest physicochemical and bioactive properties, which were attributed to oxidation reactions and long drying times. The RW sample showed the least color difference. Among the studied methods, FD and RW are recommended due to their superior ability to preserve bioactive compounds and increase the rehydration ratio. In addition, the RW drying method can provide a suitable alternative to FD by providing less time and energy consumption, practical preservation of physicochemical properties, and fewer color changes.

Keywords: drying techniques; Refractance window drying; physicochemical properties; essential oil yield; rehydration ratio

1. Introduction

Medicinal plants are critical in the food and pharmaceutical industries due to their therapeutic and nutritional properties. [1]. Among these, lavender (Lavandula stricta Del.) is widely recognized for its essential oils, antioxidants, and phenolic compounds used in perfumes, herbal remedies, and functional foods [2,3]. However, to preserve these bioactive components, postharvest processing such as drying is essential [4]. Like many medicinal plants, lavender contains a high moisture content (60–80%), making it prone to microbial spoilage. Therefore, drying is crucial to maintain product quality and extend its shelf life by reducing moisture content to 10–12%. However, the choice of drying method significantly influences the retention of essential oils, antioxidants, color, and texture, which are key quality indicators [5,6]. For this reason, the drying process significantly impacts the economic value and physical and chemical properties of medicinal plants, and it is better to choose the appropriate method to reduce the loss of aromatic compounds and save costs [7].

The choice of the appropriate drying method, temperature, and time depends on the desired final purpose. Sun drying is one of the oldest traditional methods for drying medicinal and agricultural products. It involves placing materials in direct sunlight, usually on open trays or surfaces, to evaporate moisture naturally. This method is particularly valued for its low cost, simplicity, and eco-friendliness, as it requires no specialized equipment or external energy sources, making it especially suitable for rural and resource-limited settings. However, sun drying also has notable disadvantages. It is time-consuming and heavily dependent on weather conditions, leading to delays and inefficiency. Additionally, prolonged exposure to sunlight and air can cause significant degradation in product quality, including loss of color, aroma, and essential bioactive compounds due to oxidation and enzymatic reactions [5]. The method also carries a high risk of contamination from dust, insects, and microorganisms, and often results in uneven drying due to a lack of temperature and humidity control. As a result, while sun drying is accessible and sustainable, its limitations usually make it unsuitable for high-quality or sensitive medicinal plant processing. Therefore, a careful study of the drying methods and process parameters on food quality is essential. Individual food drying methods each have unique advantages and disadvantages. For example, hot air drying (HA) is valued for its simplicity, availability, and scalability, making it suitable for industrial and small-scale operations. The method offers faster drying times than sun drying and enables better control over drying parameters such as temperature and airflow. However, its disadvantages include low energy efficiency and possible degradation of heat-sensitive compounds, such as essential oils, antioxidants, and pigments. Prolonged exposure to hot air can lead to texture shrinkage, loss of flavor, and reduced rehydration ratio, making the dried product less desirable for high-value applications [8]. On the other hand, freeze drying (FD) is an advanced technique that removes water by sublimating ice under low pressure and temperature. This method is highly effective for preserving sensitive bioactive compounds, including essential oils, antioxidants, phenolics, and color pigments, making it ideal for high-quality pharmaceutical and food products. Its significant advantages include minimal structural damage, high product porosity, excellent rehydration ability, and superior retention of nutritional and sensory properties. However, FD is time-consuming, energy-intensive, and expensive, requiring specialized equipment and longer processing times, which limits its use mainly to high-value products. [9]. The next method is microwave drying (MW), which uses electromagnetic radiation to rapidly heat and evaporate moisture within plant tissues. It offers significantly reduced drying time, uniform heating, and better energy efficiency than conventional HA. However, disadvantages include the risk of overheating or localized burning, uneven drying if not optimized properly, and partial loss of volatile components due to the rapid heating process. [10]. In the case of infrared drying (IR), infrared radiation is used to heat the surface of plant materials directly. This method offers rapid heat transfer, shorter drying times, and higher thermal efficiency than conventional HA, as the energy is absorbed directly by the product without needing to heat surrounding air. IR drying is especially suitable for thin-layer drying. However, overexposure can cause surface overheating, leading to quality deterioration, such as discoloration or loss of volatile compounds [11].

It is important to note that the drying process, regardless of the method used, can lead to substantial losses of essential oils, as these volatile compounds are often removed from plant tissues during the drying stage [12,13]. Therefore, other methods are sought. One of the new methods is refractance window drying. This technique utilizes hot water circulating under a transparent polymer film (typically Mylar) to transfer thermal energy to the product through conduction and radiation, all under atmospheric pressure [14,15]. One of its key advantages is that the product temperature remains below that of the water, which helps retain aroma, color, flavor, and bioactive compounds. Compared to conventional methods such as hot air or IR, refractance window drying (RW) offers shorter drying times, lower energy consumption, and higher energy efficiency. Studies have shown that dried products with this method, including dragon fruit, pomegranate juice, and *Centella asiatica*, exhibit better nutrient retention, higher yields, and improved physical and sensory qualities [16–18]. Additionally, RW minimizes overdrying and thermal degradation, enhancing essential oil retention, antioxidant capacity, and color stability [1]. The method is also cost-effective, has a relatively simple setup, causes less tissue damage, and improves rehydration properties and microbiological safety [19]. These advantages make the refractance window a promising alternative to FD, particularly for processing medicinal plants where maintaining quality is critical.

Despite the growing use of these modern techniques, there is limited comparative research on their relative effectiveness in preserving lavender's physicochemical and phytochemical qualities, particularly Lavandula stricta Del., which has been less studied than other lavender species. Moreover, most researchers focus on individual parameters or specific drying methods without offering a holistic evaluation of drying performance across multiple techniques. We aim to fill this gap by conducting a comparative analysis of six drying methods such as shade drying (SD), FD, HA, IR, RW, MW, evaluating their effects on drying time, energy consumption, water activity, rehydration ratio, antioxidant activity, total phenolic and flavonoid content, color changes, and essential oil yield in lavender. The novelty of this research lies in providing an integrated assessment that informs optimal method selection for retaining the functional and sensory qualities of dried lavender in food and pharmaceutical applications.

2. Materials and methods

2.1. Material

Lavender leaves were collected in mid-August from the medicinal plant farm of Urmia Agricultural Research Center, Iran, when 70% of the florets had opened. For the experiment, they were stored in a refrigerator at +3 °C. The initial moisture content of the sample was obtained by oven drying. A total of 10 g samples were placed in an oven at 105 °C and dried. No weight change was observed between the two weightings. This was done in 3 replicates. Equation (1) was used to determine the initial moisture content on a dry basis. The initial moisture content of lavender was obtained as 2.63 kg/kg dry basis (d.b.).

$$MC = \frac{\left(M_t - M_d\right)}{M_d}. \tag{1}$$

Here, MC is the initial moisture content (g/g), m_t is the initial mass of lavender (g), and m_d is the dry matter mass of lavender (g).

2.2. Drying methods

Six types of dryers were used to conduct lavender drying experiments. The methods used and the materials required for each of the experiments are briefly explained below. All the technological processes were performed at least 3 times.

2.2.1. Natural method based on SD

The natural method was conducted on a tray based on SD. Lavender samples were placed on the surface of a tray covered with aluminum foil after washing with distilled water. After 72 hours at room temperature (25°C) and reaching constant weight, the samples were placed in air-tight zipper bags and stored in a freezer (−18°C) until the extraction operation.

2.2.2. HA

The lavender drying process was carried out by a hot air dryer (Grok Engineering and Design Company) at a speed of 1 m/s at a temperature of 50°C. In general, medicinal plants are usually dried at about 50°C because this temperature level is usually more suitable for preserving essential oils, antioxidant activity, and polyphenols, and the texture of the samples is not destroyed.

2.2.3. MW

A household microwave (Sharp R-I96T, Thailand) with a maximum power output of 900 W, equipped with a rotating tray, digital power adjustment, and time, was used. A total of 100 g of lavender leaf samples were spread evenly on the tray to absorb microwave energy evenly. The power was set to 200 W, and the weight of the samples was recorded every 10 s until the weight stabilized.

2.2.4. FD

The lavender samples were placed at −40°C for 12 hours to freeze free water. Then, they were dried by a freeze-dryer (FD-5003-BT, Dena Vacuum, Iran) for 24 hours at −40°C.

2.2.5. RW

A pilot-scale window refractometer dryer was used at the Urmia Agricultural Research Center to dry lavender [9]. The practical dimensions of the dryer, which consisted of a Mylar plate with a thickness of 0.26 mm, were designed as 200 × 50 cm^2. A tank filled with distilled water was under the Mylar plate. A centrifugal pump circulated the water. Moreover, the water in the tank was heated by two heaters, and a thermostat controlled its heating. A total of 100 g of samples were placed in a single layer on the Mylar plate. The water temperature was set at 90 ± 0.5°C based on preliminary experiments. Excess moisture was removed by two fans above the Mylar plate and one fan at the end of the path. The weight loss of the samples was measured and recorded at specified time intervals, every 5 minutes.

2.2.6. IR

A laboratory infrared dryer (Grok Engineering and Design Company) equipped with eight infrared lamps of 250 W (total 2000 W) was used. The height of the lamps was adjustable from the sample surface, vertically, and at a distance of 15 cm from the samples. A suction fan was used to move air and remove moisture from the drying chamber, and two vents were created above the suction fan. This dryer used a 500 W lamp intensity to conduct the experiments. Changes in lavender moisture content were measured at 5-minute intervals using a digital scale with an accuracy of 0.01 g.

2.3. Determination of thermal properties

2.3.1. Drying time

The drying time of the samples was continued until their weight reached a moisture content of 0.1% on a dry weight basis (or 10% on a wet weight basis). The drying time in each dryer was counted using a timer.

2.3.2. Specific energy consumption

The specific energy consumption during the drying process of lavender under different methods (FD, RW, MW, IR, HA, and SD) was estimated using the technique of Polat et al. [20] and Eq (2).

$$ECR = \frac{E_t}{M_w}. \tag{2}$$

Here, E_t is the total energy supplied in the drying process (kW h) and M_w is the amount of water removed during drying (kg).

2.4. Determination of physicochemical properties

2.4.1. Water activity

The water activity (a_w) of lavender samples dried by different methods was measured directly using a water activity meter (Novasina, Switzerland) at 20°C and according to the method described by Li et al. [21]. The analysis was conducted in 3 repetitions.

2.4.2. Color

The color values (L*, a*, and b*) of fresh and dried lavender were measured using a colorimeter (model CR 400 made by Konica Minolta, Japan) in five repetitions. A standard white paper was used to calibrate the colorimeter. The amount of color change (ΔE) was defined using Eq (3) [8]:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}. \tag{3}$$

Here, ΔL is the brightness changes before and after drying, Δa is the redness and greenness changes before and after drying, and Δb is the yellowness and blueness before and after drying.

2.4.3. Rehydration ratio (RR)

The rehydration ratio was determined according to the method of Ji et al. [22]. Accordingly, 2 g of dried lavender was immersed in special kits containing 50 ml of distilled water for 2 hours at 30°C. The analysis was conducted in 3 repetitions. Then, the surface water of the samples was removed with filter paper. Based on Eq 4, the amount of RR in the samples was calculated:

$$RR = \frac{W_r}{W_d}. \tag{4}$$

Here, RR is the rehydration ratio of lavender leaves, Wr is the weight of the sample at the time of collection (g), and Wd is the weight of the lavender leaves before rehydration (g).

2.5. Determination of phytochemical and essential oil assessment

2.5.1. Antioxidant activity

The DPPH (2,2-diphenyl-1-picrylhydrazyl) kit was used to measure the antioxidant activities of lavender. The determination of antioxidant activity was carried out according to the method of Hu et al. [23]. Accordingly, 0.1 ml of diluted lavender sample extracts was added to 4 ml of 0.14 m mol/L DPPH methanol solution in a plastic kit. The solution was kept in a dark room for 30 minutes, and then the absorbance was measured at a wavelength of 517 nm. The analysis was conducted in 3 repetitions.

The percentage of radical scavenging was calculated using Eq 5:

$$I(\%) = \frac{(A_i - A_t)}{A_i} \times 100. \quad (5)$$

Here, A_i indicates the absorption value of the reference blank, and A_t indicates the absorption of the sample extract.

2.5.2. Total phenol content

According to the method of Demircan et al. [24], Folin-Ciocalteu reagent (5 ml, 0.1 M) was mixed into 1 ml of powdered extract in a plastic kit. Then 4 mL of 7.5% Na_2CO_3 was added to the mixture and vortexed for 10 minutes. The prepared solutions were kept in the dark for 30 minutes. Then, the absorbance was measured at a wavelength of 760 nm using a spectrophotometer. The analysis was conducted in 3 repetitions.

2.5.3. Total flavonoid content

To measure the flavonoid content, the extracts were estimated using the method of Mahmoudi et al. [5]. The extracts were prepared at a concentration of 0.5 g/mL in methanol, and 200 µL of the extract was added to 200 µL of aluminum chloride (2% methanol solution) in a plastic kit. All solutions were read after 30 min in the dark at a wavelength of 420 nm using a spectrophotometer. The analysis was conducted in 3 repetitions.

2.5.4. Essential oil

Dried lavender samples were ground as much as possible. Then, coarse pieces were separated from the powder by a sieve. Essential oil extraction was performed using the method of Nazari et al. [10] with slight modifications. According to their operation, about 50 g of dry powder was produced with one liter of distilled water for 3 h by water distillation in a Clevenger apparatus with 3 replicates. This experimental process was repeated 3 times, and Eq (6) was used to calculate the essential oil (EO):

$$EO(\%) = \frac{m_i}{m_j} \times 100 \quad (6)$$

where, m_1 and m_2 represent the weight of dry lavender powder in g and the volume of essential oil obtained in mL, respectively.

2.6. Statistical analysis

The effect of different drying methods on thermal, physicochemical, phytochemical, and essential oil properties of lavender was investigated based on a completely randomized experimental design with 3 replicates using one-way analysis of variance (ANOVA) in SPSS software.

3. Results and Discussion

3.1. Drying time and specific energy consumption during the drying process

The results of the effect of different drying methods on drying time and specific energy consumption are shown in Figures 1 and 2, respectively. Figure 1 shows a significant difference between the drying time in different drying methods ($p < 0.05$). The drying period for RW, MW, IR, HA, FD, and SD was determined as 90, 40, 186.66, 320, 1440, and 1800 minutes, respectively. Moreover, the specific energy consumption for RW, MW, IR, HA, and FD was 5.04, 2.40, 9.11, 16.62, and 45.24 kWh/kg, respectively. The longest drying time was for SD drying, followed by the FD dryer. In addition, the highest energy consumption was recorded for FD. When comparing different drying methods, the production of dried samples was not suitable for SD because it required a longer time. It was more sensitive to external factors such as dust and bird attacks. On the other hand, the prolonged use of freezing equipment resulted in higher energy consumption and cost. The shortest drying time and energy consumption were for RW and MW drying ($p < 0.05$). There was no significant difference between these. It is worth noting that Dadhaneeya et al. [25] and Leiton-Ramírez et al. [26] also reported similar results on the effect of drying methods on the drying time of banana and guava, respectively. According to Nahar et al. [27], electromagnetic radiation by polar molecules during MW drying leads to significant water evaporation from the lavender matrix. Therefore, rapid removal of water vapor reduces drying time.

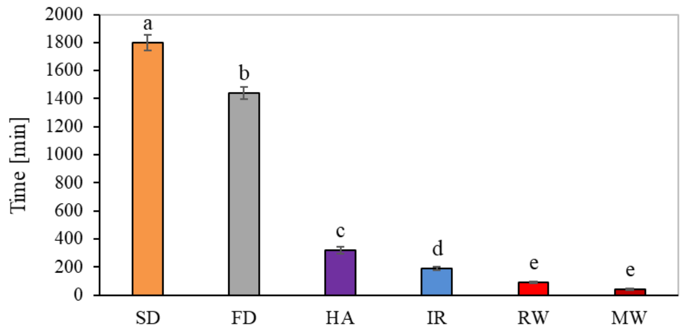

Figure 1. Results of drying time of dried lavender leaves under different drying methods (SD–shade drying, FD–freeze drying, HA–hot air drying, IR–infrared drying, RW–refractance window drying, MW–microwave drying). Values represent mean ± SD (n = 3). The different letters in the columns show the significant differences between the samples ($p < 0.05$).

According to Figure 2, the treatments dried in the RW method required less time and energy for drying than FD, HA, and IR. The high drying rate using RWD is the result of high mass transfer and moisture evaporation due to the continuous circulation of hot water under the Mylar plate by convection, radiation, and conduction mechanisms during food drying, reducing drying time and energy consumption compared to other dryers [26]. Dadhaneeya et al. [16] observed that applying RW drying was more effective in reducing the drying time during dehydration of dragon fruit than FD, HA, and vacuum drying. Furthermore, Baeghbali et al. [18] and Baeghbali et al. [15] illustrated that FD requires more specific energy consumption than the refractance window and HA for pomegranate and apple drying, respectively.

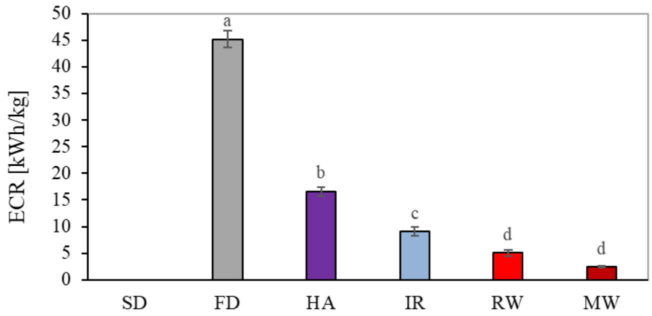

Figure 2. Effects of different drying methods on the energy consumption ratio (ECR) of dried lavender leaves (SD–shade drying, FD–freeze drying, HA–hot air drying, IR–infrared drying, RW–refractance window drying, MW–microwave drying). Values represent mean ± SD (n = 3). The different letters in the columns show the significant differences between the samples ($p < 0.05$).

3.2. Physicochemical characteristics

3.2.1. Water activity

Water activity (a_w) can contribute to a product and food's shelf life and stability [24]. Values of a_w less than 0.6 can significantly inhibit microbial and biochemical reactions [28]. The aw values under different drying methods, as presented in Table 1, ranged from 0.265 to 0.385, and statistically significant differences were identified between the methods. The lowest aw values were observed in FD samples (0.265), and the FD method had higher stability and better storage potential. The SD method recorded the highest values (0.385), likely due to the prolonged drying duration and less effective moisture removal. Similar findings were also reported by Li et al. [21]. Moreover, compared to HA, IR, MW, and vacuum methods, the aw values of *Bletilla striata* dried using the FD method were significantly reduced [29].

Table 1. Results of water activity (a_w) and rehydration ratio (RR) of lavender samples under different drying methods.

Drying methods	a_w [-]	RR [-]
Fresh	0.959 ± 0.021^{a}	-
SD	0.385 ± 0.017^{b}	1.27 ± 0.09^{d}
FD	0.265 ± 0.008^{e}	2.56 ± 0.12^{a}
HA	0.354 ± 0.011^{bc}	1.68 ± 0.08^{bc}
IR	0.322 ± 0.013^{cd}	1.93 ± 0.08^{bc}
RW	0.285 ± 0.008^{de}	2.42 ± 0.06^{a}
MW	0.292 ± 0.010^{de}	2.11 ± 0.05^{b}

Note: Values represent mean ± SD (n = 3). The different letters in the columns show the significant differences between the samples ($p < 0.05$); (SD–shade drying, FD–freeze drying, HA–hot air drying, IR–infrared drying, RW–refractance window drying, and MW–microwave drying).

3.2.2. Rehydration ratio (RR)

One of the significant indicators of the quality of the dried product for evaluating the chemical and physical transformations is the RR. Thus, the higher the hydration ratio, the fewer structural changes and cellular disorders, and the better the product quality [30]. As shown in Table 1, different drying techniques significantly differ in the RR value of lavender ($p < 0.05$). Samples dried with the FD (2.56) and RW (2.42) techniques achieved the highest RR values, while samples dried in SD (1.27) recorded the lowest values. The RR values for FD, RW, MW, IR, HA, and SD were 2.56, 2.42, 2.11, 1.93, 1.68, and 1.27, respectively. According to Alolga et al. [30], the lowest RR values of samples dried in the SD method may result from collapse and destruction of cell structure and significant shrinkage of samples during long drying time, which leads to reduced water retention ability. On the other hand, the highest RR values of lavender samples dried in the FD and RW methods were obtained ($p < 0.05$). This evaluation showed that the FD method causes fewer changes in cell structure, better preservation of capillary paths, and porous structure of samples due to ice crystal formation compared to other thermal drying techniques [20]. Higher RR was found for FD compared to MW, IR, and HA techniques in apricot [31] and *Gastrodia elata* [32]. Moreover, Baeghbali et al. [15] showed that the RR value for apple drying using the FD method was higher than that of the HA and RW methods. On the other hand, there was no significant effect between the values obtained from the RW and FD samples ($p < 0.01$). Therefore, RW dried samples generally have a higher potential for water absorption than samples dried using other thermal methods. Reports have shown that samples dried under high temperatures have reduced porosity and experienced significant shrinkage compared to RW [33,34]. Therefore, as Table 1 shows, the RR rate follows the order FD > RW > MW> IR > HA > SD.

3.2.3. Color

In dried products, color is one of the major indicators of quality, and it is essential to prevent excessive color change or burning of the product. The color component L* indicates the brightness of the dried lavender. The results showed that the brightness (L*) in the RW and FD methods in lavender is significantly higher than in other methods ($p < 0.05$) (Table 2). The lowest brightness value was also recorded for the SD method. The decrease in brightness in samples dried using the SD technique is probably due to the increase in the rate of enzymatic and non-enzymatic browning reactions (Maillard). The effect of drying methods on the green-redness (color component a*) of dried lavender, in contrast to changes in brightness, reduced the redness in the samples. The blue-yellowness of the b* component decreased in all samples after drying.

Altay et al. [4] investigated the color parameters of basil obtained by different methods (FD, MD, SD, and HA). They showed that FD samples had higher values of b* and a* parameters. Caparino et al. [35] reported that the RW-dried product had a light green color, indicating that most chlorophyll pigments were greener after the process than after HA, spray, and FD. Topuz et al. [36] The L* color changes in FD and RW samples may be related to less carotenoid degradation and/or less formation of undesirable pigments due to mild drying conditions. As shown in Table 2, the ΔE values for the dryers (FD, RW, MW, IR, HA, and SD) were determined to be 11.92, 6.71, 14.53, 11.25, 17.92, and 22.41, respectively. The lowest color changes were obtained in the RW, while the highest were in the SD. The lower color changes in the RW method indicated better color retention, prevention of oxidation and pigment degradation, and a slight browning reaction during evaporation of the product surface on the

Mylar sheet [14]. Leiton-Ramírez et al. [26] noted that the shadow method has the highest color changes because the samples are exposed to light for a long time, which causes deterioration of the visual quality of the sample, which is similar to this study.

Table 2. Color measurement of fresh and dried lavender leaves.

Drying methods	L*	a*	b*	ΔE
Fresh	2.19 ± 0.10^{cd}	4.45 ± 0.22^{a}	4.12 ± 0.25^{a}	-
SD	1.97 ± 0.08^{d}	1.99 ± 0.18^{e}	1.29 ± 0.11^{f}	22.41 ± 0.09^{a}
FD	3.11 ± 0.12^{a}	3.93 ± 0.15^{b}	2.88 ± 0.21^{cd}	11.92 ± 1.71^{bc}
HA	2.34 ± 0.09^{c}	2.34 ± 0.16^{d}	1.56 ± 0.12^{ef}	17.92 ± 0.16^{ab}
IR	2.77 ± 0.07^{b}	3.07 ± 0.14^{c}	2.45 ± 0.22^{d}	11.25 ± 1.45^{bc}
RW	3.21 ± 0.12^{a}	3.64 ± 0.10^{b}	3.27 ± 0.19^{b}	6.71 ± 2.33^{c}
MW	2.97 ± 0.10^{ab}	2.99 ± 0.12^{c}	2.23 ± 0.18^{de}	14.53 ± 2.42^{b}

Note: Values represent mean ± SD (n = 3). The different letters in the columns show the significant differences between the samples ($p < 0.05$). L*–brightness, a*–green-redness, b*–blue-yellowness, ΔE–total color change, SD–shade drying, FD–freeze drying, HA–hot air drying, IR–infrared drying, RW–refractance window drying, and MW–microwave drying.

3.3. Phytochemical contents and essential oil

3.3.1. Antioxidant activity (AA)

The results of lavender AA tests for fresh and dry samples varied by an average of 54.01 to 91% (Figure 3). AA values of dry lavender samples were significantly lower than those of their fresh sample ($p < 0.05$), which corresponds to the results obtained by Altay et al. [4] in basil leaves. The maximum AA was determined as 82% in the FD. Therefore, the FD sample recorded the strongest antioxidant activities. While this value was recorded for RW (77%) in the MW (73.06%), IR (69%), HA method (67.01%), and in SD (54.01%). On this basis, it can be concluded that dried lavender under different drying methods shows a trend: FD> RW> MW> IR> HA> SD.

According to Hu et al. [23], FD has a low-temperature environment, which reduces the decomposition of antioxidants by light, heat, and oxygen, as well as the heat destruction of heat-sensitive compounds during the drying process. Similar results have been reported by Demircan et al. [24] and Sarkar et al. [7]. The lowest AA was also related to the SD (54.01%) because, at room temperature (about 25℃), it decreased due to the prolongation of the drying process of phenol compounds, which in turn reduced the AA. In line with this study, Tran et al. [37] demonstrated that in the study of Roots Dan Sam regarding AA, the FD method was the most appropriate, while the SD method had the least AA. The AA values of the RW samples were higher than those of other drying methods. This demonstrates that RW treatment can effectively maintain the AA of the lavender sample. Dadhaneeya et al. [25] illustrated that after the FD drying, the RW method can better maintain the antioxidant properties of bananas than other techniques. Moreover, the maintenance of AA in the RW method has been reported in the study of Kaveh et al. [9] for rose flowers. In addition, the maintenance of AA in MW was greater than IR and HA because penetrating microwave heating can accelerate the dissolution of active materials inside the cell.

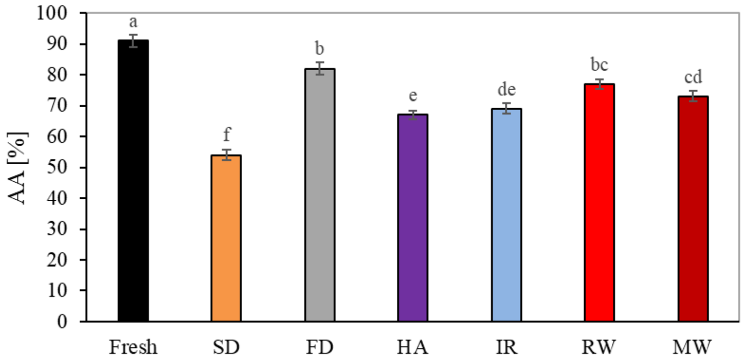

Figure 3. Antioxidant activity (AA) of lavender leaves as affected by different drying methods (SD–shade drying, FD–freeze drying, HA–hot air drying, IR–infrared drying, RW–refractance window drying, and MW–microwave drying). Values represent mean ± SD (n = 3). The different letters in the columns show the significant differences between the samples ($p < 0.05$).

3.3.2. Total phenolic content (TPC) and total flavonoid content (TFC)

Table 3 presents the average values evaluated for total phenolic and flavonoid content in samples dried under different drying methods. Since phenolic content is sensitive to heat, different drying methods can significantly affect its content. In general, thermal drying methods (HA, MW, and IR) and SD reduced more phenolic compounds in the lavender drying process than FD and RW. Therefore, the TPC in the FD sample was significantly ($p < 0.05$) higher than that in HA, MW, IR, and SD samples, while no significant difference in TPC was found with the RW method (Table 3). The highest TPC (44.37 mg GAE/g d.w) and (58.36 mg GAE/g d.w) were found in FD and RWD samples, respectively. The phenol content in FD was 11%, 40.8%, 24.9%, and 44.1% higher than that of MW, HA, IR, and SD samples, respectively. On the other hand, the phenol content for RW was 8.5, 37.6, 22, and 40.8% higher than that of MW, HA, IF, and SD, respectively. Studies have shown that freeze-drying, due to minimal heat treatment (low temperature) and oxygen-free conditions (reduced oxidation of phenols) [24,29] as well as the formation of ice crystals in the matrix of the samples, leads to further disruption of the cellular structure, which is why the extraction of active ingredients and total phenolic content increases [38]. The decrease in TPC during MW and IR drying compared to FD and RW can be attributed to the oxidative destruction of active components due to high temperature and short drying time of the samples, which aligns with other studies [5,23].

Furthermore, prolonged exposure to SD and HA leads to a decrease in drying efficiency and an increase in the surface area exposed to oxygen, thus significantly increasing the loss of polyphenols [39]. Eapen et al. [17] pointed out that the positive effects of the RW drying method on phenolic compounds may be due to the type of heat transfer that occurs through water circulating under the Mylar sheet. This heat transfer through radiation and conduction leads to a better preservation of phenolic content than other thermal dryers, as reported in the studies of Minuye et al. [40], Hernández-Santos et al. [41], and Núñez et al. [42].

Table 3. Results of total phenolic content (TPC) and total flavonoid content (TFC) of lavender samples under different drying methods.

Drying methods	TPC (mg GAE/g DW)	TFC (mg QE/g DW)
Fresh	49.27±1.84[a]	35.47±1.80[a]
SD	25.98±1.09[d]	14.65±1.13[e]
FD	37.44±1.23[b]	28.20±1.30[b]
HA	26.58±1.39[d]	16.82±0.73[de]
IR	29.97±0.90[cd]	19.16±0.94[cd]
RW	36.58±1.30[b]	26.17±1.07[b]
MW	33.71±1.25[bc]	22.25±0.73[cd]

Note: Values represent mean ± SD (n = 3). The different letters in the columns show the significant differences between the samples ($p < 0.05$), SD–shade drying, FD–freeze drying, HA–hot air drying, IR–infrared drying, RW–refractance window drying, and MW–microwave drying.

Flavonoid content of lavender was also affected by different dryers ($p < 0.05$). The results in Table 3 show that the SD method had the lowest TPC (14.65 mg QE/g d.w.). In the next stage, the two methods, HA and IR, characterized by 16.82 mg QE/g d.w. and 19.16 mg QE/g d.w., respectively, recorded statistically higher TPC than the SD method. According to Bhat et al. [43], the loss of TPC during the drying process may be due to high temperatures, direct contact with oxygen, and long-term process. FD (28.2 mg QE/g d.w) and RW (26.17 mg QE/g d.w) recorded statistically the highest extraction efficiency of flavonoid compounds among all methods. The higher extraction of these compounds in the FD method is due to the lower temperature and better preservation of cell structure and polyphenol oxidase activity [44]. These results are consistent with the findings of Ji et al. [22] for drying winter jujube and Sobatinasab et al. [13] for drying Ajowan. Furthermore, similar to the FD method (no statistical difference), the number of flavonoid compounds in the RW combined dryer was higher than in other dryers. The moderate heat (from the Mylar plate), leading to softening, accelerates the disruption of plant tissue, decomposes cellular components, and thus facilitates the extraction of flavonoids. Dadhaneeya et al. [16] and Martínez-Sanchez et al. [8] concluded in a study that the efficiency of flavonoid compounds in dragon and beets, respectively, is higher in the RW dryer compared to HA and vacuum methods.

3.3.3. Essential oil (EO)

According to the results of Figure 4, there was a significant difference between the different drying treatments on the EO ($p < 0.05$). Fresh samples had an EO (v/w on a dry weight basis) of 2.19%, while the highest EO (3.21% and 3.11%) was obtained in the samples dried in the RW and FD, respectively, and the lowest EO (1.97%) was obtained in the SD method. There was no significant difference between the EO obtained from the plant materials dried in the RW and FD. Pirbalouti et al. [45] pointed out that the increase or decrease in the extraction efficiency of the active compounds of the plants depends on the temperature, time, and drying method before extraction. In the FD method, low temperature improved the performance of the EO. The results are consistent with those reported for thyme [11], coriander [46], and *Dracocephalum moldavica* [47]. The lower EO in the SD method can be attributed to its longer drying time. Drying of plant materials in the SD takes two days, so the loss of EO components by their diffusion into the atmosphere is higher in the SD method. The adverse effect of SD on EO is shown in the study by Rahimmalek and Goli [12] in thyme and Nazari et al. [10] in Shirazi thyme. On the other hand, the EO in the RW was higher than in the other thermal methods. According to Zamani et al. [1], rapid and gentle drying by RW leads to reduced thermal degradation and oxidation, maximizing the aroma and flavor of the product. Kaveh et al. [9] also noted that the essential oil yield of rose drying by RW is higher than that of IR and HA. Addiotionally, more cell wall and plasma membrane decay occurs in samples dried under high temperatures, which may affect the permeability of the plasma membrane [48]. Therefore, high temperatures in MW, IR, and HA dryers compared to FD and RW can lead to a decrease in EO content due to accelerated evaporation of volatile compounds, decomposition of EO components, and damage to glandular trichomes [49].

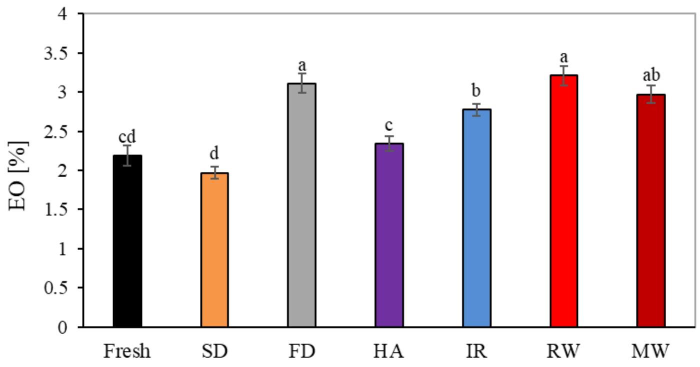

Figure 4. Effects of different drying techniques on essential oil (EO) of dried lavender samples (SD–shade drying, FD–freeze drying, HA–hot air drying, IR–infrared drying, RW–refractance window drying, and MW–microwave drying). The different letters in the columns show the significant differences between the samples ($p < 0.05$).

4. Conclusions

We examined the time of drying, energy, physicochemical properties, and phytochemical and essential oil efficiencies during the drying process of lavender samples in six different methods of drying (RW, FD, MW, IR, HA, and SD). The findings show that MW and RW have the fastest drying speed and the least energy consumed. In contrast, the longest drying time is recorded for the SD, and the FD illustrates the highest amount of energy consumed. In terms of preserving the contents of the total phenol and flavonoid, the rehydration ratio, essential oil of FD, and RW drying methods are more favorable. However, in reducing water activity, FD is significantly better than the others. However, by comparing the statistical analysis for dried lavender under six drying methods, the color level of the RW samples undergoes fewer changes. The RW method, due to less energy consumption, shorter drying time, improved physical and phytochemical properties, and better maintaining color changes, can be a promising technology for drying medicinal herbs such as lavender. In addition, despite the more extended period of time, the quality of FD samples was significantly higher than MW, IR, HA, and SD. Therefore, SD and RW drying are recommended as the preferred methods for obtaining high-quality dried herbs. Further studies on the impact of different pretreatments before the RW method can entail the potential applications of these new techniques in the development of functional foods and nutrients.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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