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Influence of Drying Methods on Total Phenolic Content, Antioxidant Activity, and Colour Characteristics of *Olea europaea* L. cv. Koroneiki Leaves

Mahshad Tajik [1]✉

[1] M.Sc. Student, Department of Food Science and Engineering, Damghan Branch, Islamic Azad University, Damghan, Iran

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✉ ***Correspondence to:***
Mahshad Tajik

Email:
mahshadnim@gmail.com

A B S T R A C T

Objective: Olive (Olea europaea L.) leaves are a valuable source of bioactive phytochemicals, particularly oleuropein, which is largely responsible for many of their therapeutic properties. They also contain abundant phenolic compounds that contribute substantially to their antioxidant capacity. Owing to their high moisture content, freshly harvested olive leaves must be dried before phenolic compounds can be efficiently extracted and utilised. This study aimed to determine the drying method that best preserves the physicochemical properties, phenolic constituents, antioxidant activity, and colour quality of olive leaves.

Methods: Fresh Olea europaea L. cv. Koroneiki leaves were dried using three methods: hot-air oven drying, fluidized-bed drying, and microwave-assisted drying combined with either a hot-air oven or a fluidized-bed dryer under various temperature and microwave power conditions. Total phenolic content (TPC), DPPH radical-scavenging activity, and colour parameters (L, a, and b) were evaluated. All experiments were performed in triplicate, and the data were analysed using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test, with statistical significance set at $P < 0.05$.

Results: Drying method and processing conditions significantly influenced the total phenolic content (TPC), antioxidant activity, and colour characteristics of Olea europaea L. cv. Koroneiki leaves ($P < 0.05$). The highest TPC (5125.47 ppm) was achieved using oven drying at 35°C combined with a 360 W microwave pretreatment, whereas the lowest value (663.57 ppm) was observed following fluidized-bed drying at 75°C without microwave pretreatment. Increasing the drying temperature and microwave power progressively reduced phenolic retention and DPPH radical scavenging activity, while also inducing significant changes in colour parameters. Overall, mild drying conditions combined with moderate microwave power provided the most effective preservation of the bioactive compounds and colour quality of olive leaves.

Conclusion: Higher drying temperatures and microwave power levels likely reduced total phenolic content and antioxidant activity through the thermal degradation of phenolic compounds, while also adversely affecting leaf colour. Under the experimental conditions of this study and for Olea europaea L. cv. Koroneiki, microwave-assisted drying at lower temperatures appeared to better preserve bioactive compounds, antioxidant capacity, and colour quality. However, further studies involving other olive cultivars and a broader range of processing conditions are warranted before these findings can be generalized.

Keywords: Olea europaea L, Microwave-assisted drying, Fluidized-bed drying, Bioactive compounds, Phenolic retention, Antioxidant activity

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Introduction

The olive tree (Olea europaea L.), a member of the Oleaceae family, is an evergreen woody species of considerable agricultural, nutritional, and medicinal importance. Under natural conditions, wild olive trees typically reach a height of approximately 5 m, whereas cultivated trees grown under favourable environmental and agronomic conditions may

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attain heights of 12–15 m, with trunk circumferences of up to 3–4 m. Owing to its exceptional adaptability to diverse climatic conditions, O. europaea is widely cultivated throughout the Mediterranean Basin, North Africa, the Middle East, Southeast Asia, parts of China, and other temperate regions, including eastern Australia [1,2]. In Persian medicine, olive leaves and their preparations have long been used as natural remedies for hypertension, inflammation, and fever, as well as for their diuretic and general tonic effects. These traditional therapeutic uses have been largely attributed to their high content of phenolic compounds and other bioactive constituents with antioxidant and protective properties [3]. Olive leaves are arranged in opposite pairs along the stem and are characterised by their elongated elliptical shape, acute apex, and thick, leathery texture. Their upper (adaxial) surface is glossy dark green, whereas the lower (abaxial) surface is distinctly lighter, with a characteristic silvery-green appearance [4]. In traditional medicine, olive bark and leaves have long been used as diuretic, tonic, astringent, antipyretic, and antihypertensive remedies, with the antihypertensive effects being primarily attributed to the leaves [5]. Olive leaves contain a wide range of biologically active compounds, including phenolic constituents, terpenoids, lipid-soluble phytochemicals such as squalene, β-carotene, α-tocopherol, and β-sitosterol, together with long-chain aliphatic alcohols, α-amyrin, β-amyrin, carbohydrates, amino acids, vitamins, minerals, and numerous other secondary metabolites [6]. They are recognised as one of the richest natural sources of polyphenolic compounds, of which oleuropein is the predominant phenolic secoiridoid and the principal compound responsible for many of the pharmacological properties associated with olive leaves [7]. A growing body of experimental evidence indicates that the high concentration of phenolic compounds in olive leaves contributes substantially to their antioxidant, antimicrobial, and antifungal activities [8]. These biological properties have attracted increasing interest in the use of olive leaf extracts as functional ingredients in pharmaceutical, nutraceutical, food, and cosmetic applications.

Polyphenols constitute one of the largest and most widely distributed groups of secondary plant metabolites and represent an important component of the human diet. Over the past two decades, these compounds have received considerable attention because of their diverse biological activities and potential health benefits [9,10]. Chemically, polyphenols are characterised by one or more aromatic rings bearing hydroxyl (–OH) groups, a structural feature that underpins their strong antioxidant capacity. Depending on their molecular structure, polyphenols are classified into several major groups, including flavonoids, anthocyanidins, catechins, flavanones, flavones, flavonols, isoflavones, hydroxybenzoic acids, hydroxycinnamic acids, lignans, and tannins (proanthocyanidins) [11].

Preserving these bioactive constituents during post-harvest processing is essential because drying conditions strongly influence their stability and biological activity. Excessive temperatures and prolonged thermal exposure can accelerate the degradation of thermolabile phytochemicals, resulting in lower concentrations of phenolic compounds, diminished antioxidant capacity, and undesirable changes in product quality. Previous studies have shown that drying thyme and sage at 60°C leads to substantial losses of volatile constituents, primarily because of the degradation of non-oxygenated monoterpenes [12]. Similarly, although microwave drying produces rosemary leaves with acceptable visual quality, it is less suitable for preserving essential oils, as a considerable proportion of these volatile compounds is lost during the drying process [13]. Previous studies have demonstrated that drying methods influence the retention of bioactive compounds in olive leaves; however, comprehensive comparisons of oven, fluidized-bed, and microwave-assisted drying under comparable processing conditions remain limited. Moreover, the interactive effects of drying method, temperature, and microwave power on the phenolic content, antioxidant activity, and colour characteristics of *Olea europaea* L. cv. Koroneiki leaves have not yet been fully elucidated. Therefore, this study aimed to compare these drying techniques and determine the most suitable processing conditions for preserving the quality and bioactive properties of olive leaves.

Materials and Methods

Plant Material

Fresh leaves of the Koroneiki olive (*Olea europaea* L.) cultivar were harvested in May 2013 from commercial olive orchards in Valaghuz Village, Kurdkuy County, Iran. Immediately after harvesting, the leaves were transported to the laboratory, thoroughly cleaned to remove dust and other foreign materials, and processed according to the drying treatments described below.

Oven Drying

Conventional hot-air drying was performed using a laboratory oven (Binder, USA). Olive leaves were evenly spread in a single layer on drying trays to ensure uniform air

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circulation. Drying was conducted at 35, 55, and 75°C until a constant sample weight was achieved, indicating the completion of the drying process [14].

Fluidized-Bed Drying

Fluidized-bed drying was carried out using a laboratory-scale dryer designed and manufactured by the Department of Food Engineering, Gorgan University of Agricultural Sciences and Natural Resources. Samples were dried at air temperatures of 35, 55, and 75°C under a constant airflow rate until constant weight was attained [15].

Microwave-Assisted Oven Drying

For the combined microwave-assisted oven drying treatment, olive leaves were first exposed to microwave irradiation using a domestic microwave oven (Samsung CF3110N-5). Each 100 g batch of fresh leaves was treated for 2 min at one of three microwave power levels (360, 540, or 720 W). Immediately afterwards, the samples were transferred to the hot-air oven and dried at 35, 55, or 75°C until constant weight was reached [16].

Microwave-Assisted Fluidized-Bed Drying

The microwave pretreatment protocol described above was applied prior to fluidized-bed drying. Following microwave exposure at 360, 540, or 720 W for 2 min per 100 g of fresh leaves, the samples were dried in the fluidized-bed dryer at 35, 55, or 75°C until constant weight was obtained.

Preparation of Olive Leaf Extracts

The dried leaves were ground into a fine powder and extracted with 80% methanol using a solvent-to-solid ratio of 10:1 (v/w). The extraction mixture was stirred continuously at room temperature for 24 h, after which it was filtered through Whatman No. 1 filter paper. The resulting filtrate was used immediately for the determination of total phenolic content.

Determination of Total Phenolic Content

Total phenolic content (TPC) was determined using the Folin–Ciocalteu colorimetric assay. Briefly, 1 g of powdered sample was mixed with 75 mL of distilled water and heated in a boiling water bath (100°C) for 30 min. After cooling to room temperature, the extract was brought to the desired volume with distilled water and filtered. An aliquot (1 mL) of the filtrate was mixed with 0.5 mL of Folin–Ciocalteu reagent, 1 mL of 20% sodium carbonate solution, and 7.5 mL of distilled water. After thorough mixing, the reaction mixture was incubated at room temperature for 30 min, and absorbance was measured at 760 nm using a UV–Vis spectrophotometer.

Determination of DPPH Radical-Scavenging Activity

Antioxidant activity was evaluated using the DPPH radical-scavenging assay according to Arabshahi and Urooj (2007) [17]. Methanolic extracts were prepared at concentrations of 50, 100, 150, 200, 500, and 1000 ppm. One millilitre of 1 mM DPPH solution in methanol was added to 3 mL of each extract solution, followed by vortex mixing. The mixtures were incubated in the dark at room temperature for 30 min before absorbance was measured at 517 nm. Radical-scavenging activity was calculated from the reduction in absorbance relative to the control.

Colour Measurement

Colour characteristics were evaluated using a digital image analysis system under controlled illumination conditions. Samples were placed inside a custom-designed imaging chamber that provided uniform lighting from all directions, and digital images were captured using a Panasonic digital camera. Image analysis was performed with ImageJ software to obtain the colour coordinates L* (lightness), a* (red–green), and b* (yellow–blue) [18].

Experimental Design and Statistical Analysis

The experiment was conducted as a factorial arrangement within a completely randomized design (CRD). Four drying methods were evaluated: (i) oven drying (OD), (ii) fluidized-bed drying (FBD), (iii) microwave-assisted oven drying (MOD), and (iv) microwave-assisted fluidized-bed drying (MFBD).

For OD and FBD, one experimental factor, drying temperature, was evaluated at three levels (35, 55, and 75°C), resulting in three treatments for each drying method. For MOD and MFBD, two experimental factors, drying temperature (35, 55, and 75°C) and microwave power (360, 540, and 720 W), were evaluated in a 3 × 3 factorial

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arrangement, resulting in nine treatments for each microwave-assisted drying method. In total, 24 drying treatments were investigated (3 OD, 3 FBD, 9 MOD, and 9 MFBD).

Each treatment was performed with three independent replicates, yielding a total of 72 experimental units. For each replicate, a separate batch of fresh olive leaves was prepared and analysed independently.

Statistical analyses were conducted separately for each drying method. Data from OD and FBD were analysed using one-way analysis of variance (ANOVA), with drying temperature considered the fixed effect. Data from MOD and MFBD were analysed using two-way factorial ANOVA to evaluate the main effects of drying temperature and microwave power, as well as their interaction.

Results are presented as the mean ± standard deviation (SD). All statistical analyses were performed using SAS software (version 9.1.3; SAS Institute Inc., Cary, NC, USA). When ANOVA indicated significant differences, treatment means were compared using Duncan's multiple range test. Statistical significance was set at $P < 0.05$. Graphs were prepared using Microsoft Excel 2010.

Results

Combined drying technologies integrate two or more conventional or advanced drying methods in either simultaneous or sequential processes to enhance heat and mass transfer during dehydration. The effects of drying temperature and microwave power on the total phenolic content of olive leaves are presented in Figure 1.

As shown in Figure 1, microwave-assisted drying at 360 W combined with a drying temperature of 35°C resulted in the highest retention of total phenolic compounds. In contrast, progressive increases in either drying temperature or microwave power significantly reduced total phenolic content. The lowest phenolic concentrations were observed in samples dried at 75°C in combination with the highest microwave power (720 W), indicating that more intensive drying conditions adversely affected the preservation of phenolic constituents.

Analysis of variance showed that drying temperature, microwave power, and the interaction between these two factors all had significant effects on total phenolic content ($P < 0.05$). These findings indicate that phenolic retention was influenced not only by each processing variable individually but also by their combined effects, demonstrating the importance of optimising both drying temperature and microwave power to minimise phytochemical losses during processing.

The observed reduction in total phenolic content under more intensive drying conditions is consistent with previous reports describing thermal degradation of heat-sensitive phytochemicals during drying. Similarly, Omidbaigi and co-workers reported that increasing microwave power during rosemary drying resulted in substantial losses of essential oils owing to the release of volatile constituents from plant tissues. Although phenolic compounds differ chemically from essential oils, the present results likewise suggest that excessive microwave energy may compromise the preservation of valuable bioactive constituents during drying.

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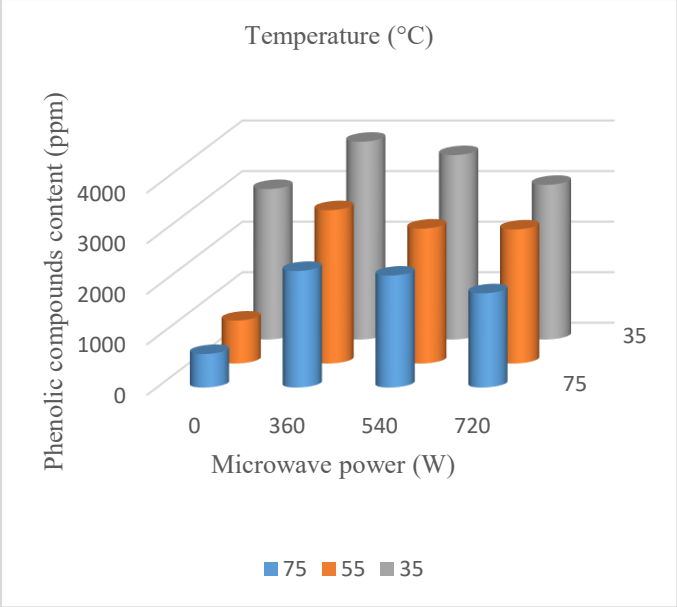


Figure 1: Effect of fluidized-bed–microwave drying on total phenolic content of olive leaves

As illustrated in Figure 1, the combination of a microwave power of 360 W and a drying temperature of 35°C resulted in the highest retention of total phenolic compounds, indicating that these processing conditions had the least detrimental effect on phenolic stability. In contrast, progressive increases in either drying temperature or microwave power significantly reduced the concentration of extractable phenolic compounds. The decline observed under more intensive drying conditions is likely attributable to the thermal degradation of heat-sensitive phenolic constituents and the disruption of their chemical structure during microwave-assisted drying, which ultimately reduced their recovery in the final extract.

Analysis of variance showed that drying temperature, microwave power, and the interaction between these two factors all had significant effects on total phenolic content ($P < 0.05$). These findings indicate that phenolic retention was influenced not only by each processing variable individually but also by their combined effects, highlighting the importance of optimizing both drying temperature and microwave power to maximize phenolic retention while minimizing thermal degradation during combined fluidized-bed–microwave drying.

Table 1: Effects of drying method, temperature, and microwave power on total phenolic content of olive leaves

Drying Method	Drying Temperature (°C)	Microwave Power (W)0	360	540	720
Oven	35	2756.42l	5125.47a	4806.42b	3680.23e
	55	1142.14q	4454.04c	3582.61fg	3537.38g
	75	704.04s	3449.28h	3349.28i	3089.76j
Fluidized-Bed	35	2975.47k	3911.19d	3646.90ef	3058.80j
	55	849.28r	3032.61jk	2668.33m	2651.66m
	75	663.57s	2306.42n	2213.57o	1863.57p

Note: Values represent the mean total phenolic content (ppm). The 0 W treatment indicates drying without microwave pretreatment. Within the table, values followed by different superscript letters differ significantly according to Duncan's multiple range test ($P < 0.05$).

The total phenolic contents of olive leaves under the different drying treatments are presented in Table 1. Significant differences in phenolic retention were observed among the drying methods ($P < 0.05$). Overall, microwave-assisted oven drying preserved the highest levels of total

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phenolic compounds, outperforming conventional oven drying, fluidized-bed drying, and microwave-assisted fluidized-bed drying.

Among all treatment combinations, microwave pretreatment at 360 W followed by oven drying at 35°C resulted in the highest total phenolic content. In contrast, progressively increasing either the drying temperature or microwave power reduced phenolic retention regardless of the drying method employed. These findings indicate that mild drying conditions combined with moderate microwave power are more effective in preserving phenolic compounds during olive leaf processing than more intensive drying conditions.

Table 2: ANOVA of drying temperature and microwave power effects on total phenolic content of olive leaves

Source of variation	Degrees of freedom (df)	Sum of squares (SS)	Mean square (MS)	F-value
Treatment	24	203,931,323.2	8,497,138.5	1,141.0**
Experimental error	49	36.5	0.7	—
Total	73	203,931,359.7	—	—

Note: ** indicates statistical significance at $P < 0.01$.

The effects of drying temperature and microwave power on the L value (lightness) of *Olea europaea* L. leaves are presented in Figure X (or Table X). The L value increased progressively with increasing drying temperature and microwave power in both the oven-dried and microwave-assisted oven-dried samples, indicating that more intensive drying conditions produced lighter-coloured leaves.

Analysis of variance revealed that drying temperature, microwave power, and the interaction between these factors significantly affected the L value ($P < 0.05$). These results demonstrate that both processing variables, individually and in combination, influenced the lightness of dried olive leaves.

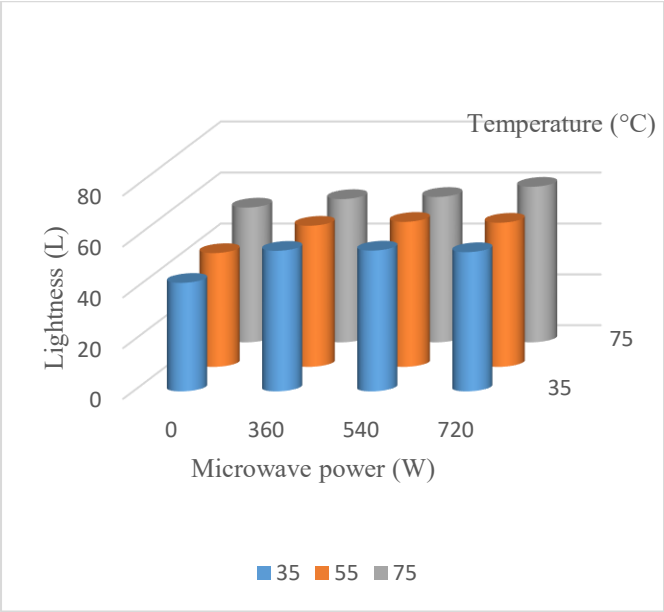


Figure 2: Effect of drying temperature and microwave power on L value of olive leaves

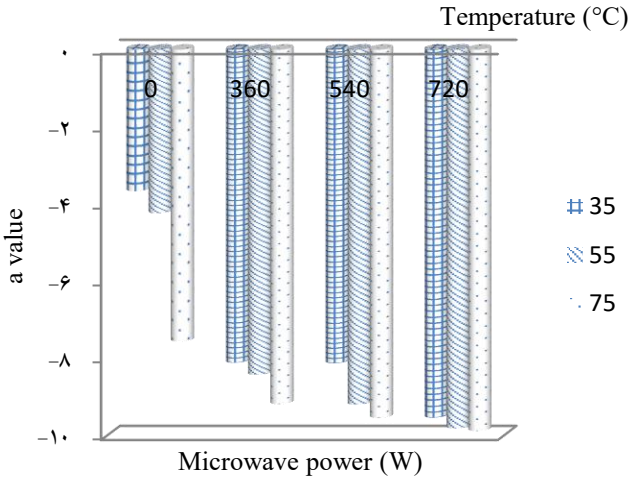


Figure 3: Effect of drying temperature and microwave power on a value of olive leaves

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The effects of drying temperature and microwave power on the a* (redness–greenness) value of *Olea europaea* L. leaves are presented in Figure 3. Both processing variables significantly influenced the a* value during drying. Specifically, increasing the drying temperature and microwave power resulted in a progressive decline in the a* value, indicating a reduction in the green colour intensity of the dried leaves.

Among all treatments, oven drying at 35°C without microwave pretreatment produced the highest a* value, indicating the greatest retention of the original leaf colour. Conversely, the combination of 75°C and 720 W resulted in the lowest a* value, reflecting the greatest change in colour. Analysis of variance confirmed that drying temperature, microwave power, and the interaction between these factors significantly affected the a* value ($P < 0.05$), demonstrating that both processing variables contributed to changes in the colour characteristics of dried olive leaves.

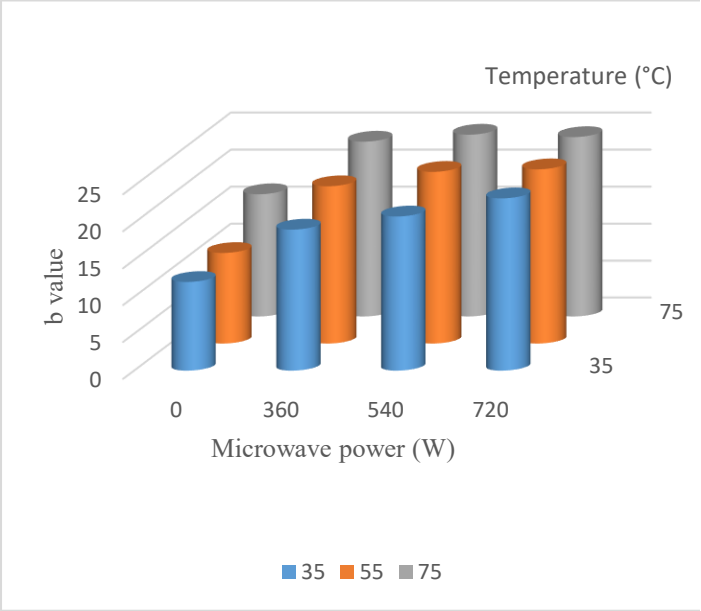


Figure 4: Effect of drying temperature and microwave power on b value of olive leaves

The effects of drying temperature and microwave power on the b* (yellowness–blueness) value of *Olea europaea* L. leaves are presented in Figure 4. The b* value increased progressively with increasing drying temperature and microwave power, indicating a greater degree of yellowness under more intensive drying conditions.

Analysis of variance showed that drying temperature, microwave power, and the interaction between these factors significantly affected the b* value ($P < 0.05$). As illustrated in Figure 4, the highest b* value was recorded for samples dried at 75°C with 720 W microwave power, whereas the lowest value was observed in leaves dried at 35°C without microwave pretreatment. These results demonstrate that increasing drying temperature and microwave power produced significant changes in the colour characteristics of dried olive leaves.

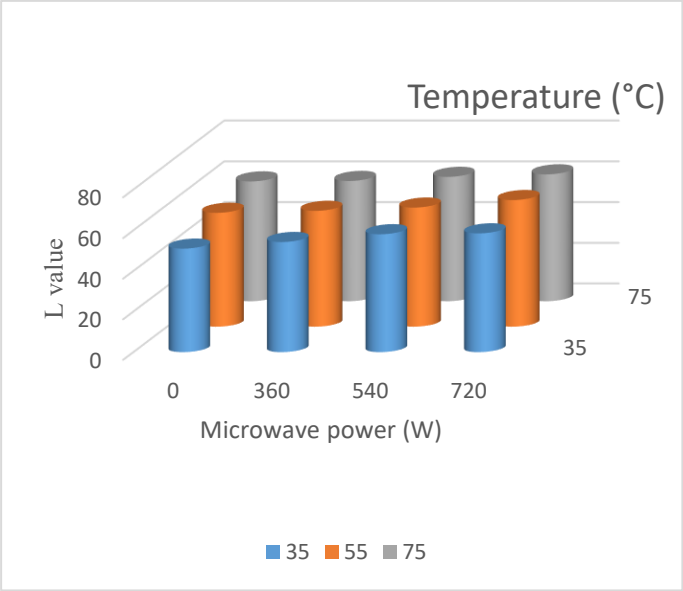


Figure 5: Effects of drying conditions on L value of olive leaves during microwave–fluidized-bed drying

The effects of drying temperature and microwave power on the L* (lightness) value of *Olea europaea* L. leaves during microwave-assisted fluidized-bed drying are presented in Figure 5. The L* value increased progressively with increasing drying temperature and microwave power, indicating that more intensive drying conditions produced lighter-coloured leaves. The highest L* value was recorded for samples dried at 75°C with 720 W microwave power.

Analysis of variance showed that drying temperature, microwave power, and the interaction between these factors significantly affected the L* value ($P < 0.05$). These findings demonstrate that both processing variables, individually and in combination, significantly influenced the lightness of dried olive leaves during microwave-assisted fluidized-bed drying.

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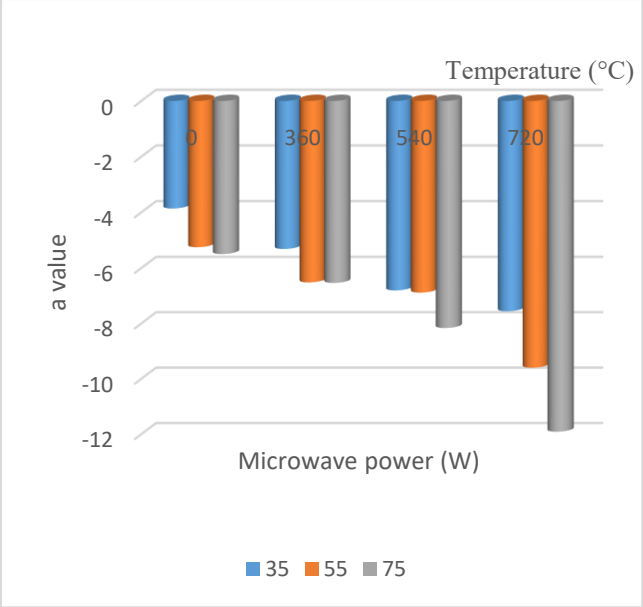


Figure 6. Influence of drying temperature on olive leaf redness/greenness (a) during fluidized-bed drying

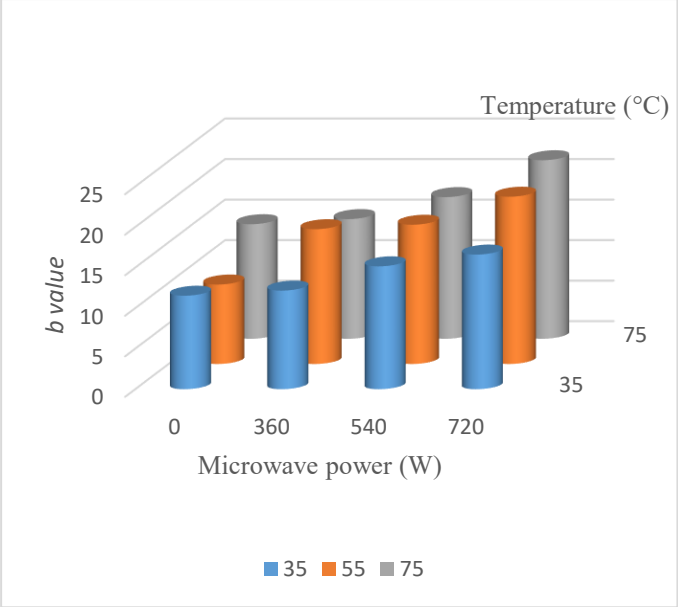


Figure 7: Influence of drying temperature on olive leaf yellowness/blueness (b) during fluidized-bed drying

The effects of drying temperature and microwave power on the a* (redness–greenness) value of dried *Olea europaea* L. leaves are presented in Figure 6. Both processing variables significantly influenced this colour parameter during drying. The a* value decreased progressively with increasing drying temperature and microwave power, indicating a reduction in green colour intensity under more intensive drying conditions.

The lowest a* value was observed in samples dried at 75°C with 720 W microwave power, whereas the highest value was recorded for leaves dried at 35°C without microwave pretreatment. Analysis of variance confirmed that drying temperature, microwave power, and their interaction significantly affected the a* value ($P < 0.05$). These findings demonstrate that drying conditions strongly influenced the redness–greenness characteristics of dried olive leaves.

The results obtained from the measurement of the b* color parameter under different drying temperatures and microwave power levels are presented in Figure 7. The results demonstrate that the b* value increased throughout the drying process, indicating an increase in yellowness of the dried olive leaves under more intensive drying conditions.

The analysis of variance and mean comparison revealed that drying temperature, microwave power, and their interaction had significant effects on the b* value ($P < 0.05$). According to Figure 7, the treatment involving 75°C drying temperature combined with 720 W microwave power exhibited the highest b* value. This increase may be attributed to enhanced pigment degradation and the conversion of green pigments into yellowish compounds under high thermal and microwave energy exposure.

The measurement of free radical scavenging activity is a reliable, accurate, simple, cost-effective, and highly reproducible approach widely used to evaluate the antioxidant activity of plant extracts under *in vitro* conditions (Singh and Singh, 2008). DPPH is a stable, hydrophilic free radical with a deep purple colour and a maximum absorbance at approximately 515–517 nm. Upon accepting an electron or hydrogen atom from reducing compounds, such as phenolic constituents, DPPH radicals are converted into the corresponding colourless hydrazine form, resulting in a reduction in absorbance intensity.

Free radical scavenging represents one of the major mechanisms by which antioxidant compounds inhibit lipid

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oxidation. In this assay, antioxidant activity is expressed as the percentage reduction in DPPH absorbance in the presence of the extract compared with the control DPPH solution without extract. The effects of different drying methods on DPPH radical scavenging activity are presented in Figure 8.

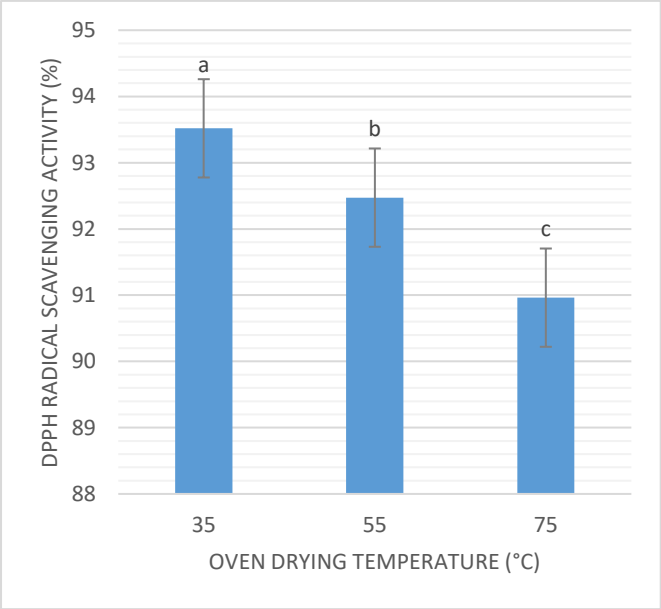


Figure 8: Effect of different drying methods on DPPH radical scavenging activity of olive leaf extracts

To comprehensively evaluate the effects of drying methods, the results were compared across all treatments, including oven drying, fluidized-bed drying, microwave-assisted oven drying, and microwave-assisted fluidized-bed drying. Significant differences were observed among the drying methods in terms of total phenolic content, antioxidant activity, and colour characteristics ($P < 0.05$). Microwave-assisted oven drying exhibited greater potential for preserving bioactive compounds compared with conventional drying methods, whereas higher drying temperatures and microwave power levels generally promoted greater degradation of phenolic compounds and alterations in colour parameters. These findings indicate that both the drying method and processing conditions play important roles in determining the quality attributes of dried olive leaves.

Discussion

The present study demonstrated that drying technology and processing conditions, particularly drying temperature and microwave power, substantially affected the retention of phenolic compounds and colour characteristics of olive leaves. The application of combined microwave-assisted drying techniques improved dehydration efficiency by reducing processing time; however, the extent of their effects on product quality depended strongly on the applied operating conditions. These results highlight the importance of optimising drying parameters to preserve bioactive compounds and maintain desirable visual properties in dried olive leaves.

Phenolic compounds represent a major group of secondary metabolites in olive leaves and contribute significantly to their antioxidant potential and biological activities [19]. In the present study, the highest total phenolic content was obtained using microwave pretreatment at 360 W followed by drying at 35°C. In contrast, increasing microwave power to 540 and 720 W, particularly when combined with higher drying temperatures, resulted in considerable reductions in phenolic content. Although microwave-assisted drying can accelerate moisture removal, the observed decrease in phenolic content at higher processing intensities may not be attributed solely to thermal degradation. Other contributing mechanisms, including enhanced oxidative reactions, activation of endogenous oxidative enzymes, disruption of cellular structures, and alterations in the accessibility and extractability of phenolic compounds, may also influence the final phenolic concentration.

The observed reduction in phenolic content at higher processing intensities is consistent with previous findings. Omidbaigi and co-workers reported that increased microwave intensity during rosemary drying resulted in greater losses of essential oils and reduced retention of valuable phytochemicals [20]. Similarly, several studies have demonstrated that excessive heat exposure can promote oxidative reactions and degradation of phenolic compounds in medicinal plants, leading to decreased antioxidant potential [21,22]. However, the extent of phenolic losses during drying depends on multiple interacting factors, including plant matrix characteristics, drying kinetics, oxygen availability, and the stability of individual phenolic compounds. Therefore, the reduction observed in the present study should be interpreted as a combined effect of processing conditions rather than a direct consequence of microwave energy alone.

Therefore, the use of moderate microwave power combined with low-temperature drying appears to provide a suitable

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approach for reducing processing time while limiting the degradation of heat-sensitive constituents [23]. In the current study, microwave pretreatment at 360 W followed by oven drying at 35°C represented the most favourable condition for preserving phenolic compounds in olive leaves.

In addition to phytochemical composition, colour is an important quality attribute of dried plant materials because it reflects changes in pigments and chemical constituents during processing [24]. In this study, colour characteristics were evaluated using the CIE Lab* system, which provides quantitative measurements of lightness (L*), redness–greenness (a*), and yellowness–blueness (b*) and is widely used for colour evaluation in food and plant-based products. Compared with RGB-based image analysis, the Lab* system provides a more standardized approach for detecting subtle colour variations.

The L* value increased with increasing drying temperature and microwave power in both oven-dried and fluidized-bed-dried samples, indicating greater lightness under more intensive drying conditions. Similar increases in L* values have been reported during the drying of other plant materials. Afshari and colleagues observed increased lightness during the drying of Mozafati dates at elevated temperatures, suggesting that thermal processing can significantly influence colour development in plant tissues [25]. The increase in lightness observed in the present study may be associated with complex structural modifications, moisture reduction, pigment transformation, and changes in surface characteristics induced by drying conditions.

In contrast, the a* value decreased as drying temperature and microwave power increased, indicating a reduction in green colour intensity. Similar changes have been reported in other dried plant products, where increased thermal exposure resulted in decreased a* values. This reduction may be related to chlorophyll degradation, oxidative reactions, and the formation of secondary colour compounds during drying; however, further pigment-specific analyses would be required to confirm these mechanisms.

The b* value showed an increasing trend with increasing drying temperature and microwave power, with the highest values observed at 75°C combined with 720 W microwave power. Similar increases in yellowness have been reported during thermal processing of plant materials and are generally associated with changes in pigment composition and the development of yellow-brown compounds. The comparable response observed in both oven and fluidized-bed drying indicates that processing intensity, particularly temperature and microwave power, plays a major role in determining colour changes in olive leaves.

The colour changes observed in this study are consistent with previous investigations, although variations among plant species have been reported. Nindo et al. (2003) observed decreased L* values accompanied by increased a* and b* values during asparagus drying [26]. These differences may be attributed to variations in plant matrix composition, pigment profile, moisture content, drying conditions, and the characteristics of the applied drying technology. Therefore, colour responses during drying should be interpreted according to the specific properties of each plant material and processing system.

Overall, the findings indicate that mild microwave-assisted drying conditions are more effective for maintaining the phenolic content and colour quality of olive leaves. The combination of microwave pretreatment at moderate power (360 W) and low-temperature drying (35°C) provided favourable conditions for preserving valuable phytochemicals while achieving efficient dehydration. Nevertheless, the effects of microwave treatment on phenolic retention appear to be influenced by several simultaneous mechanisms, and further studies involving enzyme activity assays, oxidative markers, and individual phenolic profiling are recommended to better elucidate the underlying processes.

This study has some limitations. Individual phenolic compounds, such as oleuropein, were not identified or quantified, and drying kinetics and energy consumption were not evaluated. In addition, the experiments were performed at laboratory scale using only *Olea europaea* L. cv. Koroneiki leaves; therefore, further studies with different cultivars and larger-scale systems are required to confirm the practical applicability of the findings.

Conclusion

This study evaluated the effects of different drying strategies, including conventional oven drying, fluidized-bed drying, and combined oven–microwave and fluidized-bed–microwave treatments, under various temperature and microwave power conditions on the quality characteristics of olive leaves. Following drying, the total phenolic content, antioxidant activity (DPPH radical-scavenging capacity), and colour attributes of *Olea europaea* L. cv. Koroneiki leaves were assessed. The results demonstrated that increasing drying intensity, particularly through higher temperatures, led to significant reductions in phenolic content and antioxidant activity across the evaluated drying

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methods. Microwave pretreatment improved the retention of phenolic compounds compared with conventional drying; however, excessive microwave power negatively affected their preservation, which may be associated with increased thermal stress, oxidative reactions, structural alterations, and changes in the extractability of heat-sensitive bioactive constituents. A similar trend was observed for DPPH radical-scavenging activity, indicating a close association between phenolic compound retention and antioxidant capacity. Among the evaluated treatments, microwave-assisted oven drying at 35°C with 360 W microwave power resulted in higher retention of phenolic compounds and antioxidant activity in Olea europaea L. cv. Koroneiki leaves compared with the other tested conditions. Colour analysis based on digital imaging further demonstrated that intensive drying conditions altered the visual characteristics of olive leaves, with higher temperatures and microwave power levels producing greater changes in colour parameters. Overall, mild microwave-assisted drying conditions may be considered a suitable option for preserving the phytochemical quality and visual properties of olive leaves under the experimental conditions investigated. However, further studies involving different olive cultivars, larger-scale processing systems, and industrial validation are required before broader conclusions can be drawn regarding the optimal drying strategy for olive leaves.

Statements and Declarations

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Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Author contributions

MT: Conceptualization, investigation, methodology, formal analysis, writing original draft preparation, writing review and editing, supervision, and project administration. All authors have read and approved the final version of the manuscript.

Declaration of Artificial Intelligence (AI) Use

The authors declare that this manuscript was written entirely by the authors. No artificial intelligence (AI) tools were used for content generation, data analysis, or interpretation of results. AI assistance was used solely for English language editing to improve the clarity, readability, and linguistic quality of the manuscript. The authors take full responsibility for the content and integrity of the article.

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