

Drying Behaviour and Quality Retention in Avocado (*Persea americana*) Leaves: A Comparison of Hot Air and Microwave Drying

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Abstract

Avocado (*Persea americana*) leaves are an underutilised plant material with potential applications as herbal teas and functional ingredients due to their phenolic and antioxidant compounds. However, limited information exists on suitable drying conditions to preserve their quality. This study investigated the effect of oven temperatures (50, 60 and 70°C) and microwave power levels (200, 500 and 700W) on the drying behaviour and quality attributes of avocado leaves. Leaves were dried in a hot air oven and a digital microwave oven until equilibrium moisture content was reached. Initial moisture content and water activity of fresh leaves averaged 1.40 g H₂O/g DM (58.34% wb) and 0.958, respectively. Increasing temperature and microwave power significantly reduced drying time, with microwave drying achieving comparable moisture reduction in substantially shorter times. Drying occurred predominantly in the falling rate period. Drying rate constants and effective diffusivity increased with both temperature and microwave power level, with higher values observed for microwave drying. Quality evaluation showed that microwave drying, particularly at 700W, resulted in significantly higher ($p \leq 0.05$) retention of total phenolic content, antioxidant capacity, flavonoids and condensed tannins compared to oven drying. Selected thin-layer models adequately described drying behaviour under both methods. The results indicate that microwave drying at 700W is an efficient method for rapid drying of avocado leaves while preserving key bioactive compounds.

Keywords: antioxidant capacity, drying rate constant, flavonoids, leaf dehydration, moisture diffusivity, tannins, thin-layer models

1. Introduction

The avocado (*Persea americana*) plant is widely known for its fruit, which is consumed globally and used in a variety of culinary and industrial applications. It belongs to the Lauraceae family and is the most commercially important species of the genus *Persea* (Yahia, 2012). The plant is classified into three botanical races (Mexican, Guatemalan and West Indian), each with distinct characteristics. The fruit is commonly utilised for pulp and oil production, particularly in the cosmetic industry (Duarte et al., 2016).

Avocado leaves have been reported to contain appreciable levels of protein (~25.5%), dietary fibre (~38.4%) and ash (~19.4%), along with bioactive phytochemicals such as flavonoids and phenolic compounds, contributing to their nutritional and functional value (Arukwe et al., 2012). They have also been used in traditional folk medicine because of their purported antioxidant, anti-inflammatory, antiviral, antidiabetic and hypoglycaemic properties, which are associated with the presence of these bioactive compounds (Yamassaki et al., 2017; Bhuyan et al., 2019). In particular, phenolic compounds and flavonoids contribute significantly to antioxidant activity (Arukwe et al., 2012), making avocado leaves of interest for applications such as herbal infusions and functional food ingredients.

As plant leaves are typically consumed in dried or heat-treated forms, understanding the effects of drying on the retention of bioactive compounds is important. For avocado leaves, drying would enable their use in loose-leaf infusions, powdered formulations and as additives in food and cosmetic products. Drying reduces water activity, thereby limiting microbial growth and extending shelf life, while also influencing the stability of bioactive compounds (Loh and Lim, 2018). The retention of phytochemicals such as phenolics, flavonoids and tannins

during drying is therefore critical to preserving their functional value.

Understanding the drying behaviour of plant materials is essential for optimising processing conditions and ensuring product quality. Drying kinetics describes moisture removal under specific conditions and provides insight into the mechanisms governing moisture transport (Antal, 2015). Analysis of drying behaviour enables the development of drying curves and predictive models for moisture content and drying rates, supporting process optimisation. Previous studies on avocado leaves have primarily examined the effects of drying on antioxidant activity, enzyme activity and phytochemical composition (Loh and Lim, 2018). These studies showed that drying conditions significantly influence phenolic retention and enzyme activity. For example, oven drying resulted in reductions in total phenolic content, while microwave drying showed minimal losses (approximately 3-4%), indicating better preservation of bioactive compounds. Enzymes such as polyphenol oxidase and peroxidase were largely inactivated during thermal and microwave drying. Yamassaki et al. (2017) also reported that higher drying temperatures ($\geq 70^{\circ}\text{C}$) resulted in significantly lower phenolic content and antioxidant activity compared to lower temperatures ($40\text{--}60^{\circ}\text{C}$), indicating increased degradation at elevated temperatures. Additional studies have confirmed the presence of bioactive compounds such as flavonoids, phenolics and tannins in avocado leaves and their contribution to antioxidant activity (Rahman et al., 2018; Castro-López et al., 2019).

These studies highlight the potential of avocado leaves as a source of bioactive compounds for functional and nutraceutical applications. However, there remains limited information on their drying behaviour, kinetics and modelling under controlled conditions. This study therefore investigates the drying behaviour and selected quality attributes of avocado (*Persea americana*) leaves using oven (hot air) and microwave drying, with emphasis on drying curves, moisture ratio analysis and the relationship between drying conditions and quality attributes.

2. Materials and Methods

2.1 Raw Material Handling and Preparation

Avocado leaves of the West Indian variety (Figure 1a) were handpicked from a single large tree and harvested in the early morning hours to limit moisture loss. The leaves, averaging 124.14 ± 4.80 , 69.20 ± 2.90 and 2.40 ± 2.00 mm (length x width x thickness) were stored at $4 \pm 0.5^{\circ}\text{C}$ until use (Soysal, 2005; Ramsumair et al., 2014; Loh and Lim, 2018). Only leaves that appeared healthy and without any insect bites, physical damage or imperfections were picked (Loh and Lim, 2018). The leaves were gently wiped with paper towels to remove any adhering dust before drying. Preliminary trials showed that leaves cut into transverse strips 20 mm wide reached approximately 60% weight loss within 80 min, compared to 220 min for whole leaves, representing a 2.74-fold reduction in drying time. Therefore, leaves were cut into strips (Figure 1b) for all subsequent experiments.

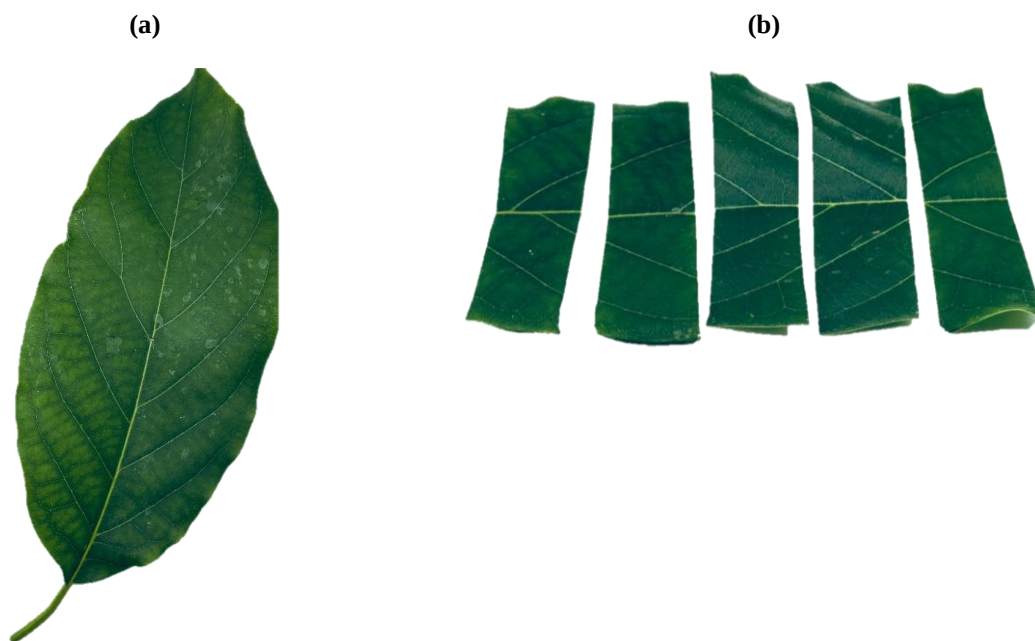


Figure 1. Fresh avocado leaves: (a) whole (b) cut into strips

2.2 Drying

For oven drying, leaves were dried in a 2.86 cu. ft. Digital Series Lab Oven (Model 40 AFE-LT Quincy Lab Inc., IL, USA) with a temperature range of ambient (room temperature) +8°C to 107°C, with an accuracy of ±0.5°C and a power rating of 800W. A circulating fan provided air circulation (<0.5 m/s) for improved uniformity. Approximately 10g of leaves were placed in a single layer on each of the three drying trays which were placed into the dryer. At 20-minute intervals, each tray was quickly removed from the oven and weighed using an Explorer Precision Balance (Model EX2202, Ohaus Corporation, New Jersey, USA). This procedure was repeated until equilibrium moisture content was reached, indicated by negligible change in sample weight. At each interval, the oven and sample surface temperatures were measured using an infrared thermometer (TP30, ThermoPro Inc., Shenzhen, China; −50 to 550°C range, ±1.5% accuracy). Drying was carried out at 50, 60 and 70°C based on the work previously reported by Loh and Lim (2018) for avocado leaves and for other leafy materials such as West Indian lemongrass (Mujaffar and John, 2018) and tea and ginger leaves (Chan et al., 2009).

Microwave-drying of leaves was carried in a 34L capacity Amana MCS 10TS MenuMaster Commercial Digital Microwave Oven (Accelerated Cooking Products, IA, USA) with a rated microwave power output of 1000 W and electrical specifications of 120 V, 60 Hz. The time as well as the different power levels were adjusted by using the digital panel situated in front of the microwave. Leaf samples were dried at 200, 500 and 700W (Soysal 2005; Mujaffar and Bynoe, 2019) until constant weight was achieved. Preliminary experiments revealed that the avocado leaves were easily scorched at higher power levels. The time interval used for weighing the leaves varied according to the power level. The drying run at each power level was repeated three (3) times. Following drying, the dried leaves were allowed to cool, placed in plastic bags which were sealed using a 200 mm impulse sealer (Metronic, Model FS-200, China), and placed in a laboratory desiccator until analysis (Mujaffar and Lee Loy, 2016).

2.3 Analytical Methods and Data Analysis

Moisture content of the fresh and dried leaves was determined using the oven method (AOAC Official Method 925.10; AOAC, 2005) at 105°C for minimum of 5 hours. The temperature used was based on previous studies on the drying of leaves as no previous research on avocado leaves reported a moisture determination method. Moisture content (wb) was calculated on a wet weight basis (Eqn 1). Moisture content on a dry weight basis (g H₂O/g DM) was determined using the dry mass of the leaves.

$$\text{Moisture content (\% wet basis)} = (\text{Mass of water} / \text{Mass of sample}) \times 100 \quad (1)$$

Water activity of both the fresh and dried leaves was measured using the Aqua Lab CX-2 Water Activity meter (Aqua Lab, Washington, USA). Surface colour of leaves was measured using a CR-410 Chroma Meter (Konica Minolta Sensing Americas, Inc., NJ, USA). Hunter colour values (L*, a*, b*) were recorded for four samples. Hue angle (°) and chroma of fresh and dried leaves were calculated according to the method described by Mujaffar and Lee Loy (2016). Subjective visual colour was also assessed using a four (4) point scale: 4-dark green, 3-light green, 2-green-brown, 1-brown (Mujaffar and John, 2018).

Phenolic compounds were extracted following Loh and Lim (2018) using 50% ethanol at a ratio of 1:50 sample to solvent. Ground leaf samples (2g) were mixed with the solvent and shaken for 1h at 150 rpm. The mixtures were filtered by vacuum filtration, and the filtrates were stored in the dark prior to analysis. The extracts obtained were used for all subsequent analyses, in triplicate. Total phenolic content was determined using the Folin–Ciocalteu method as described by Yamassaki et al. (2017), with gallic acid used for the calibration curve. Absorbance was measured at 760 nm using a spectrophotometer. Results were expressed as mg gallic acid equivalents (GAE)/g DM. Total antioxidant capacity was determined according to Islam et al. (2013) using the phosphor-molybdenum method. Samples were incubated at 95°C for 1h, and absorbance was measured at 695 nm. Results were expressed as gallic acid equivalents (mg GAE/g DM). Total flavonoid content was determined following Moreno et al. (2000) using quercetin as the standard. Absorbance was measured at 415 nm after incubation at room temperature. Results were expressed as mg quercetin equivalents (mg QE/g DM). Condensed tannins were determined using the vanillin–HCl method as described by Rabeta and Lai (2013). Absorbance was measured at 500 nm, and colour intensity was used as an indicator of tannin concentration. All analyses were conducted in triplicate unless otherwise stated.

Drying data was analysed using the standard approach to drying studies as previously reported in detail (Mujaffar and Lee Loy, 2016; Mujaffar and Bynoe, 2019), that is, the generation of drying curves, drying rate curves and moisture ratio (MR) data, and curve fitting. Effective moisture diffusivity (Deff) was calculated using a leaf thickness of 0.0024m. A range of empirical and semi-empirical thin-layer drying models (Table 1) were

applied to the moisture ratio data to describe the drying behaviour (Erbay and Icier, 2010; Ertekin and Firat, 2017). Curve fitting was carried out using Curve Expert Professional software (Version 2.3, Hyams, 2016) and fit assessed through the use of the coefficient of determination (R^2), root mean square error (RMSE) and the chi-square statistic (χ^2). ANOVA and post hoc analysis carried out using “Rapid publication-ready MS-Word tables for one-way ANOVA” (Assaad et al., 2014).

Table 1. Thin Layer Drying Models

Model	Mathematical expression
Newton	$MR = \exp(-Kt)$
Page	$MR = \exp(-Kt^n)$
Modified Page	$MR = \exp(-Kt)^n$
Henderson and Pabis	$MR = a \exp(-Kt)$
Modified Henderson and Pabis	$MR = a \exp(-Kt) + b \exp(-gt) + c \exp(-ht)$
Logarithmic	$MR = a \exp(-Kt) + c$
Two-Term	$MR = a \exp(-K_0 t) + b \exp(-K_1 t)$
Two-Term Exponential	$MR = a \exp(-Kt) + (1-a) \exp(-Kat)$
Wang and Singh	$MR = 1 + at + bt^2$
Verma	$MR = a \exp(-Kt) + (1-a) \exp(-gt)$
Hii	$MR = a \exp(-Kt^n) + c \exp(-gt^n)$
Midilli	$MR = a \exp(-Kt^n) + b t$
Weibull distribution	$MR = a - b \exp(-Kt^n)$
Diffusion approach	$MR = a \exp(-Kt) + (1-a) \exp(-Kbt)$
Aghbashlo <i>et al.</i>	$MR = -K_1 t / (1 + K_2 t)$
Logistic	$MR = a_0 / ((1 + a \exp(Kt)))$
Jena and Das	$MR = a \exp(-t + b t^{1/2}) + c$
Demir <i>et al.</i>	$MR = a \exp(-Kt^n) + c$
Alibas	$MR = a \exp(-Kt^n + b t) + g$

Estimated energy consumption during hot air drying was calculated using Equation 2, adapted from Nguyen et al. (2018):

$$E_t = (D_t / M_t) \times M_o \times t \quad (2)$$

where E_t is the estimated energy consumption ($W \cdot h$), D_t is the drying temperature used ($^{\circ}C$), M_t is the maximum operating temperature of the oven ($107^{\circ}C$), M_o is the maximum power output of the oven (800W), and t is the drying time (h).

Energy consumption during microwave drying was calculated using Equation 3 (Hebbbar et al., 2004) where E_t is energy ($W \cdot h$), P is the power level (W) and t is the time (h).

$$E_t = P \times t \quad (3)$$

3. Results

3.1 Appearance and General Observation

During the drying process, avocado leaves underwent several physical observable changes such as colour, texture and size (Figure 2). Subjective colour assessment of leaves is given in Figure 3. Fresh leaves were dark green (colour rating of 4) in colour and had a pliable texture. Leaves dried at an oven temperature of 50 and $60^{\circ}C$ were similar in colour and texture that is, greenish brown (colour rating of 2) and brittle; however, leaves dried at $70^{\circ}C$ were completely brown (colour rating of 1) and were very brittle. All leaves were curled at the end of the drying period; however, the time at which curling of the strips occurred varied with oven temperature. For microwave drying, leaves that were dried at 500W and 700W appeared dark green (colour rating of 4), similar to the fresh leaves, however, leaves that were dried at 200W appeared greenish brown (colour rating of 2). The time at which curling of the strips occurred also varied with power level. It is possible that due to the slow drying at this power the leaves were cooked (Mujaffar and Bynoe, 2019).

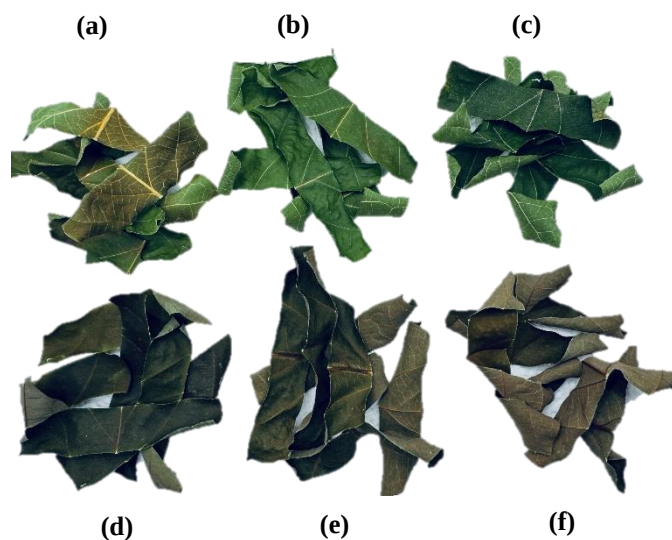


Figure 2. Appearance of avocado leaves dried at microwave power levels: (a) 200W, (b) 500W and (c) 700W; and oven temperatures: (d) 50°C, (e) 60°C and (f) 70°C

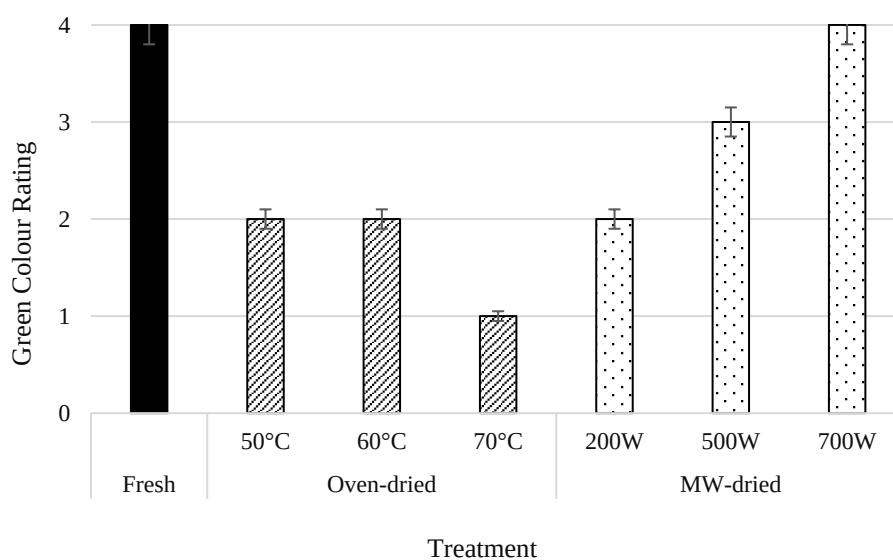


Figure 3. Subjective colour assessment of fresh and dried avocado leaves 4-dark green, 3-light green, 2-green-brown, 1-brown

Comparing both drying methods, leaf samples that were dried in the oven were more brittle when compared to leaves dried in the microwave and also underwent more curling and greater degree of colour change. At high oven temperatures, dried strips experienced a loss of quality, which can be because of browning reactions and loss of chlorophyll (Mujaffar and John, 2018).

The colour attributes of fresh and dried avocado leaves showed significant differences ($p \leq 0.05$) across treatments (Table 2).

Table 2. Colour attributes of fresh and dried avocado leaves

Colour Attribute	Treatment						
	Fresh	Oven-dried			Microwave-dried		
		50°C	60°C	70°C	200W	500W	700W
L*	34.63 ± 0.009 ^f	51.79 ± 0.006 ^a	50.84 ± 0.003 ^d	49.91 ± 0.009 ^e	50.83 ± 0.009 ^d	51.46 ± 0.003 ^c	51.63 ± 0.003 ^b
a*	-6.67 ± 0.009 ^g	-1.92 ± 0.003 ^d	-0.80 ± 0.003 ^a	-1.01 ± 0.009 ^b	-1.76 ± 0.009 ^c	-5.62 ± 0.003 ^e	-6.19 ± 0.003 ^f
b*	6.40 ± 0.009 ^g	7.05 ± 0.000 ^d	7.31 ± 0.006 ^c	6.76 ± 0.007 ^e	6.64 ± 0.003 ^f	8.67 ± 0.003 ^b	9.71 ± 0.003 ^a
Hue (°)	136.20 ± 0.025 ^a	105.20 ± 0.025 ^d	96.22 ± 0.026 ^g	98.52 ± 0.090 ^f	104.90 ± 0.070 ^e	123.00 ± 0.026 ^b	122.50 ± 0.013 ^c
Chroma	9.24 ± 0.012 ^c	7.31 ± 0.001 ^e	7.35 ± 0.006 ^d	6.84 ± 0.005 ^f	6.87 ± 0.005 ^f	10.33 ± 0.001 ^b	11.52 ± 0.004 ^a

Values are means ± SEM, n = 3 per treatment group

Means in a row without a common superscript letter differ ($p \leq 0.05$) as analysed by one-way ANOVA and the TUKEY test.

Fresh leaves exhibited lower lightness (L*) values, indicating a darker appearance, while drying resulted in a marked increase in L* values for both oven- and microwave-dried samples, reflecting a lighter colour. The a* values remained negative for all treatments, confirming retention of greenness; however, drying generally resulted in less negative values for oven drying, indicating a reduction in greenness. Notably, microwave drying at higher power levels (500 and 700W) produced a* values closer to that of fresh leaves, suggesting better preservation of green colour compared to oven drying. The b* values were positive for all samples, indicating the presence of yellow tones, with higher values observed at 500 and 700W, although no consistent trend was evident across all treatments. Hue angle decreased upon oven drying, indicating a shift away from the characteristic green colour, while microwave-dried samples retained higher hue values. Chroma values decreased for oven-dried samples, indicating reduced colour intensity, whereas microwave drying at higher power levels resulted in increased chroma. Overall, microwave drying, particularly at higher power levels, better preserved the green colour of the leaves, whereas oven drying resulted in a shift towards greenish-brown tones.

3.2 Bioactive Compounds and Antioxidant Activity

The quality attributes of avocado leaves were significantly affected ($p \leq 0.05$) by both drying temperature and microwave power level (Table 3).

Table 3. Bioactive compounds and antioxidant activity of fresh, oven-dried and microwave-dried avocado leaves

	Treatment						
	Fresh	Oven-dried			Microwave-dried		
		50°C	60°C	70°C	200W	500W	700W
Total phenolic content (mg GAE/g DM)	7.71 ± 0.112 ^b	5.56 ± 0.009 ^e	5.44 ± 0.008 ^e	4.47 ± 0.007 ^f	5.95 ± 0.004 ^d	7.48 ± 0.018 ^c	10.03 ± 0.041 ^a
Total antioxidant capacity (mg GAE/g DM)	0.61 ± 0.007 ^b	0.51 ± 0.003 ^d	0.38 ± 0.002 ^f	0.41 ± 0.001 ^e	0.49 ± 0.003 ^d	0.55 ± 0.004 ^c	0.80 ± 0.001 ^a
Total flavonoid content (mg QE/g DM)	2.75 ± 0.010 ^a	0.76 ± 0.007 ^d	0.95 ± 0.009 ^{cd}	0.72 ± 0.008 ^d	1.08 ± 0.005 ^c	1.16 ± 0.013 ^c	1.51 ± 0.141 ^b

Values are means ± SEM, n = 3 per treatment group.

Means in a row without a common superscript letter differ ($p \leq 0.05$) as analysed by one-way ANOVA and the TUKEY test.

In general, oven drying reduced phenolic compounds relative to fresh leaves, with greater losses at higher temperatures, while microwave drying, particularly at higher power levels, resulted in greater retention and, in some cases, increased concentrations. This demonstrates a clear distinction between the two methods, with microwave drying at 500-700W showing superior preservation of quality attributes. Total phenolic content decreased significantly with oven drying, confirming progressive degradation with increasing temperature. In contrast, microwave drying showed an increasing trend with power level, reaching 10.03 mg GAE/g DM at

700W, exceeding that of fresh leaves, while values at 200-500W ranged from 5.95 to 7.48 mg GAE/g DM, indicating partial retention. Total antioxidant capacity followed a similar trend, decreasing under oven drying and increasing under microwave drying to a maximum of 0.80 mg GAE/g DM at 700W. Intermediate microwave levels (200–500W) showed values of 0.49 and 0.55 mg GAE/g DM, indicating improved retention relative to oven drying. Flavonoid content decreased under both drying methods, with greater losses observed during oven drying. Microwave drying resulted in higher retention, although values remained below those of fresh leaves. Condensed tannins, assessed qualitatively, showed increasing intensity with drying severity, progressing from lighter coloration in fresh and low-temperature oven-dried samples to darker red coloration in microwave-dried samples at higher power levels. This suggests increased extractability or transformation of tannin compounds, with microwave drying producing the most pronounced effects.

The phenolic content values obtained in this study fall within the range reported for avocado leaves and comparable leafy materials, confirming both qualitative and quantitative agreement with existing literature. Loh and Lim (2018) reported reductions in total phenolic content of approximately 20–50% following oven drying, consistent with the decrease from 7.71 to 4.47–5.56 mg GAE/g DM observed here. They also reported minimal losses under microwave drying, which aligns with the higher values observed at 500–700W. Similarly, Yamasaki et al. (2017) reported lower phenolic content and antioxidant activity at temperatures greater than 70°C, consistent with the lowest values observed at 70°C in this study. The higher phenolic values observed in microwave-dried samples cannot be attributed to moisture differences, as results were expressed on a dry matter basis. Instead, they are likely due to enhanced extractability following cell disruption, combined with reduced enzymatic and oxidative degradation during shorter drying times. A similar pattern was observed for flavonoid content, which showed greater losses under oven drying compared to microwave drying. Flavonoids are known to be sensitive to prolonged thermal exposure and oxidative conditions; therefore, the shorter drying times associated with microwave treatment likely contributed to their improved retention. Despite this, flavonoid levels in dried samples remained lower than in fresh leaves, indicating that some degradation still occurred regardless of drying method. Condensed tannins exhibited an apparent increase in intensity with drying severity, particularly under microwave drying at higher power levels. As results were assessed qualitatively, this trend is interpreted as an increase in extractability or possible structural transformation rather than a true increase in concentration. The enhanced release of bound tannins due to cellular disruption during drying, especially under rapid microwave heating, may account for the more pronounced colour development observed.

3.3 Moisture Reduction and Drying Rate

Weight reduction of avocado leaves was influenced by both drying temperature and microwave power level. For oven drying, the highest reduction was observed at 70°C (56.5%), followed by 60 and 50°C, with increasing temperature reducing the time to equilibrium. In microwave drying, the highest reduction occurred at 700W (53.8% within 10 min), followed by 500W, while 200W required substantially longer drying times (approximately 268 min). Overall, microwave drying achieved comparable weight reduction to oven drying but in significantly shorter times, particularly at higher power levels, confirming that increasing temperature or power accelerates moisture removal.

Initial moisture content and water activity averaged 1.39 g H₂O/g DM (58.3% wb) and 0.958, respectively. Drying curves are shown in Figure 4 (a and b), and equilibrium moisture content and water activity values are presented in Table 4.

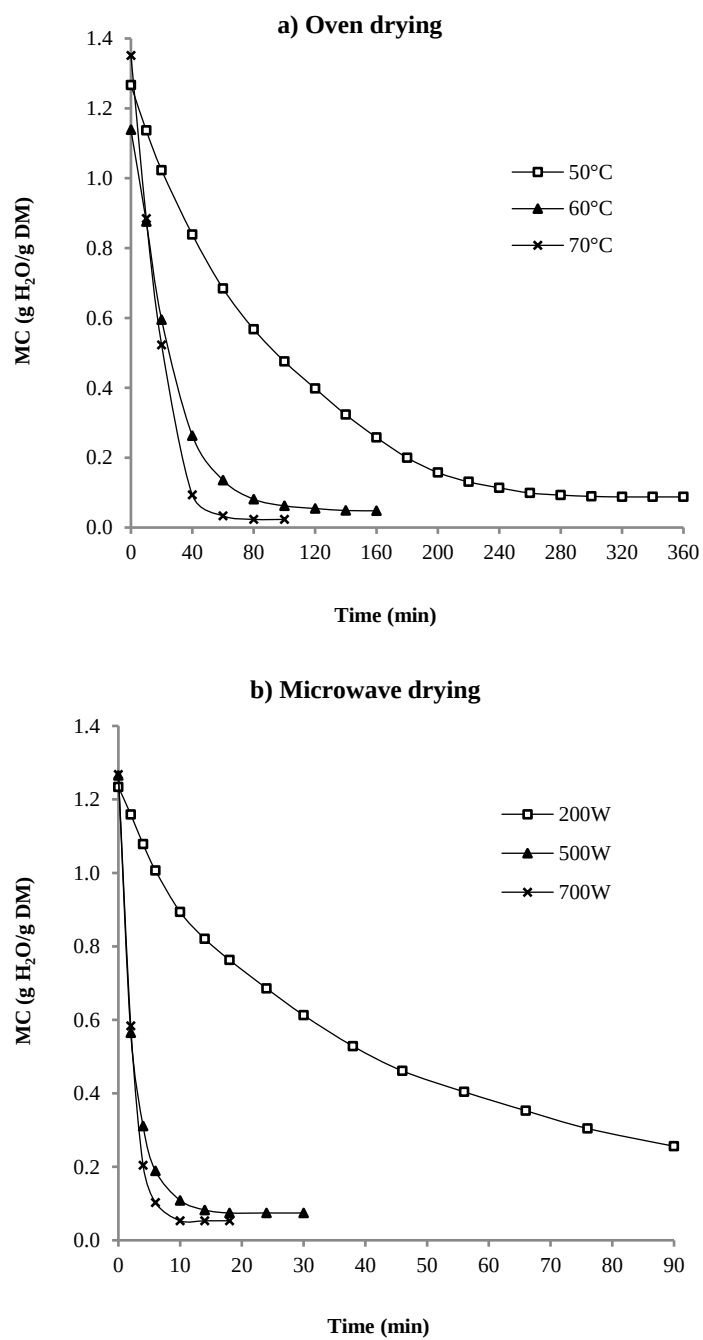


Figure 4. Drying curves for (a) oven-dried and (b) microwave-dried avocado leaves

Table 4. Equilibrium moisture content (dry basis), water activity (a_w) and time to equilibrium for oven and microwave drying treatments

	Treatment					
	Oven-dried			Microwave-dried		
	50°C	60°C	70°C	200W	500W	700W
Time to eqm (min)	313.3 ± 6.600 ^a	136.7 ± 6.700 ^c	66.7 ± 8.800 ^d	208.0 ± 0.000 ^b	16.33 ± 0.300 ^e	10.0 ± 0.000 ^e
Eqm MC (g H ₂ O/g DM)	0.090 ± 0.006 ^a	0.050 ± 0.000 ^{bc}	0.023 ± 0.003 ^d	0.088 ± 0.012 ^a	0.074 ± 0.002 ^{ab}	0.045 ± 0.003 ^{cd}
Eqm a_w	0.390 ± 0.010 ^c	0.380 ± 0.004 ^c	0.323 ± 0.009 ^d	0.481 ± 0.010 ^a	0.4337 ± 0.004 ^b	0.3967 ± 0.006 ^c

Values are means ± SEM, n = 3 per treatment group.

Means in a row without a common superscript letter differ ($p \leq 0.05$) as analysed by one-way ANOVA and the TUKEY test.

The drying curves for avocado leaves showed a continuous decrease in moisture content with drying time for all treatments, with no constant rate period observed, indicating that drying occurred predominantly in the falling rate period. Increasing oven temperature from 50 to 70°C resulted in a faster decline in moisture content and a shorter time to reach equilibrium, with drying time decreasing from approximately 313 min at 50°C to 67 min at 70°C. A similar trend was observed for microwave drying, where increasing power level from 200 to 700W significantly accelerated moisture removal, with equilibrium achieved at approximately 208, 16 and 10 min, respectively. However, at the lowest microwave power level (200W), moisture removal was markedly slower, and equilibrium moisture content was not effectively attained within the same timeframe as the higher power treatments. The decline in moisture for these leaves was comparable to that of oven dried leaves at 50°C. However, despite this similarity, low-power microwave drying (200W) was not effective in producing a desirable dried product in a reasonable time. In contrast, microwave drying achieved comparable reductions in moisture content to oven drying but in substantially shorter times.

Similar trends have been reported for leafy materials, where increasing temperature reduces drying time. For example, Mujaffar and John (2018) reported a decrease in drying time for lemongrass leaves from approximately 1280 min at 40°C to 240 min at 70°C, while Doymaz (2014) reported a reduction from 170 to 60 min for *Laurus nobilis* leaves as temperature increased from 50 to 70°C. Similar behaviour has also been observed in microwave drying of leafy materials such as amaranth and bay leaves, where increasing power reduces drying time and increases drying rate constants and diffusivity (Mujaffar and Lee Loy, 2016; Mujaffar and Bynoe, 2019). For example, Mujaffar and Bynoe (2019) reported a reduction in drying time for bay leaves from 48.8 min at 200W to 5.2 min at higher power levels. These findings are consistent with the present study.

As shown in Table 5, the estimated oven energy consumption ranged from 580 to 1950 W·h, decreasing with increasing temperature due to shorter drying times. In comparison, microwave drying required substantially less energy, ranging from 102.67 to 162.67 W·h. The lowest energy consumption was observed at 700W microwave drying, which also achieved equilibrium in the shortest time. Although oven energy consumption was estimated from equipment specifications rather than measured directly, the comparison indicates that microwave drying offered a clear energy advantage under the conditions used in this study.

Table 5. Estimated energy consumption for oven and microwave drying of avocado leaves

	Treatment					
	Oven-dried			Microwave-dried		
	50°C	60°C	70°C	200W	500W	700W
Energy consumption (W·h)*	1950.00	1020.00	580.00	162.67	130.00	102.67

*Oven energy consumption was estimated from equipment specifications, while microwave energy consumption was calculated from power level and drying time.

Similar trends in energy consumption have been reported for other leafy materials. Alibas Ozkan et al. (2007) reported that drying of spinach using microwave power resulted in reduced energy consumption at higher power levels, with a minimum energy requirement of approximately 120 W·h at 750 W, reflecting the effect of shorter drying times. Comparable behaviour was also observed for West Indian bay leaves, where energy consumption decreased with increasing microwave power, with values of approximately 100 W·h reported at higher power levels (Mujaffar and Bynoe, 2019). The values obtained in the present study (approximately 103 W·h) are therefore in close agreement with those reported for similar leafy materials. However, the higher energy consumption observed at lower power levels (200W) in avocado leaves may be attributed to their greater thickness and waxy surface characteristics, which increase resistance to moisture transfer and prolong drying time.

Although the present study was conducted under thin-layer conditions, industrial batch drying of leaves would involve deeper packed beds, which may influence moisture removal and energy efficiency. In oven drying, increased bed thickness would be expected to reduce air contact with individual leaf surfaces, increase resistance to moisture movement and prolong drying time, particularly for leaves located in the centre of the bed. In microwave drying, a thicker bed may improve the quantity of material processed per batch, but it may also introduce non-uniform heating due to limited microwave penetration, uneven exposure of leaves within the bed and variation in moisture distribution within the bed. Therefore, while microwave drying at 700W was the most effective treatment under the thin-layer conditions used in this study, scale-up to deeper beds would require optimisation of bed depth, loading density, mixing or turning frequency and microwave power distribution to ensure uniform drying. The present findings therefore support microwave drying as a promising method for avocado leaves, but additional pilot-scale studies would be required before direct application to industrial batch processing.

Continuous drying may provide a more practical option for larger-scale processing of avocado leaves, particularly where uniform product quality and higher throughput are required. Conveyor or belt drying systems could allow leaves to be spread in controlled layers, improving air contact and reducing the variability associated with deep static beds. For microwave drying, continuous or hybrid microwave-assisted systems may reduce processing time; however, scale-up would require careful control of belt speed, layer thickness, microwave power distribution and product mixing to minimise localised overheating and ensure uniform drying. Therefore, while microwave drying showed superior performance under the conditions of this study, industrial application would require further evaluation using pilot-scale batch or continuous systems.

Moisture removal occurred in the falling rate period for both oven and microwave drying, with drying rate increasing with temperature and microwave power level (Figure 5). This behaviour is typical for leafy materials such as spinach, parsley, mint and bay leaves (Ozbek and Dadali, 2007; Demirhan and Ozbek, 2011; Mujaffar and Lee Loy, 2016; Mujaffar and Bynoe, 2019). The initial drying rate at 50°C was low (0.013 g H₂O/g DM/min) and decreased steadily, indicating diffusion-controlled drying, while microwave drying at 700W showed a substantially higher initial rate (0.720 g H₂O/g DM/min) and two falling rate periods, suggesting a transition from surface evaporation to internal diffusion control.

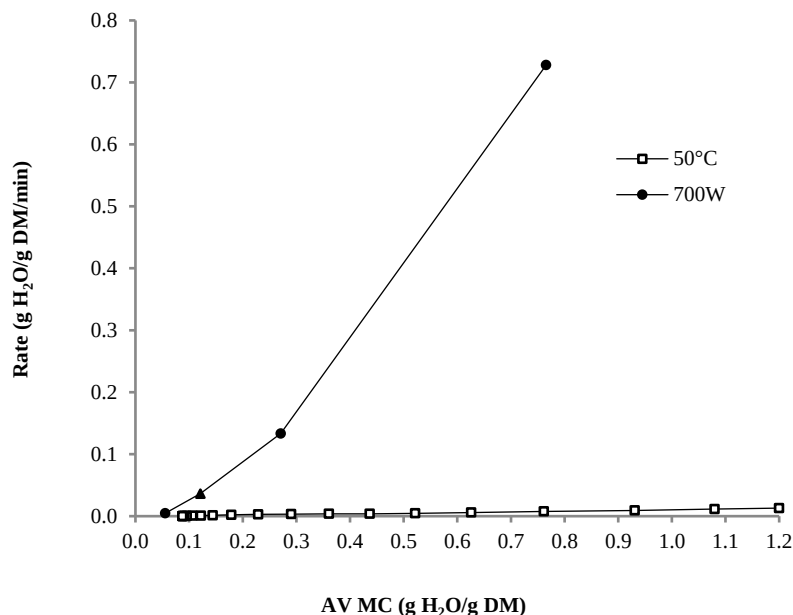


Figure 5. Plots of drying rate vs average moisture content for avocado leaves dried at 50°C and 700W

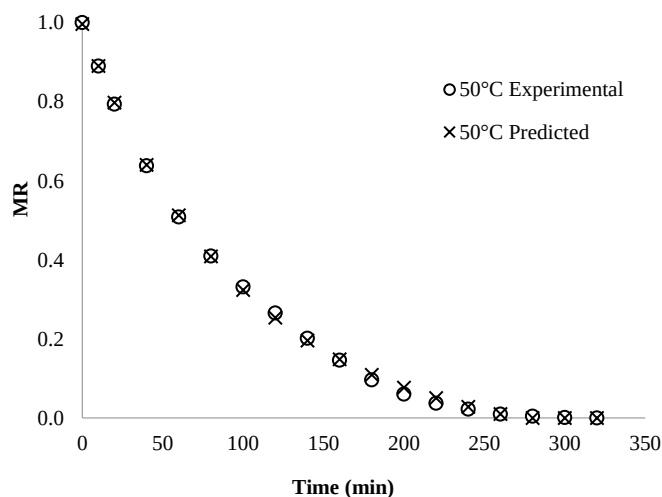
3.4 Moisture Ratio (MR) - Curve Fits and Thin-layer Models

Of the thin layer models that were applied to the MR data for oven-drying, the Alibas, Logistic and Aghbashlo et al. models best described oven drying at 50, 60 and 70°C, respectively. Of the thin layer models that were applied to the drying data for microwave-drying, the Modified Henderson and Pabis, Logarithmic and Aghbashlo et al. models best described microwave drying behaviour at 200-700W, respectively. Table 6 gives the thin layer models and constants in order of best fit for oven- and microwave dried avocado leaves at 50°C and 700W, respectively. The comparison of Predicted versus Experimental MR values for leaves dried at 500 and 700W shows good agreement of values (Figure 6).

Table 6. Thin layer models and constants in order of best fit for oven- and microwave dried avocado leaves at 50°C and 700W

Treatment	Model	Model Constants								RMSE	χ^2
		a	k	n	b	g	k ₁	k ₂	R ²		
Oven 50°C	Alibas	1.0749	0.9217	0.9997	0.9107	0.0786	-	-	0.9996	0.007424	0.000076
MW 700W	Aghbashlo et al.	-	-	-	-	-	0.9085	0.0712	0.9953	0.029463	0.001042

(a) 50°C



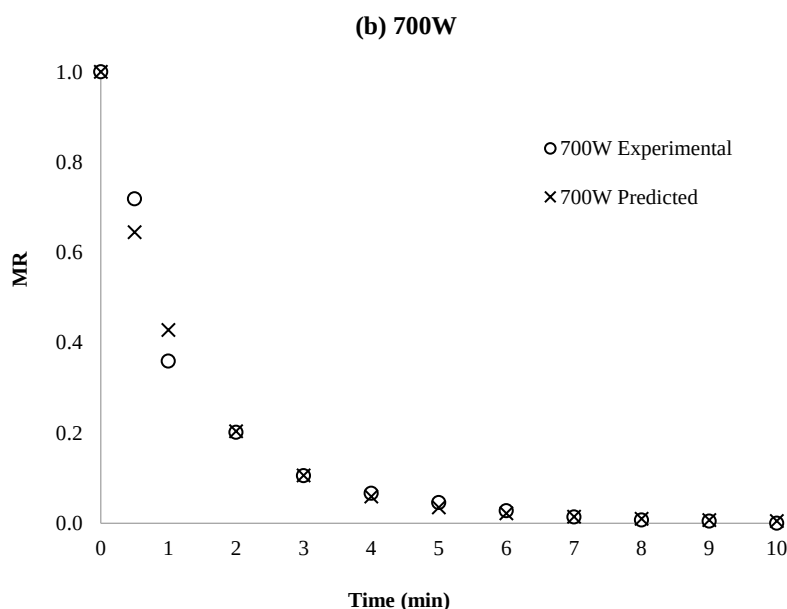


Figure 6. Experimental and predicted values of MR vs time for (a) oven-dried and (b) microwave-dried avocado leaves

With respect to oven drying, the models identified in this study are consistent with those reported for other leafy materials, although the specific best-fit model varies depending on the material and drying conditions. Previous studies on spinach and bay leaves have commonly reported Page, Logarithmic and Henderson and Pabis-type models as providing good fits to moisture ratio data during hot air drying (Dadali et al., 2007; Doymaz, 2014). In the drying of West Indian bay leaves, the Logistic model was found to best describe oven drying behaviour, which is in agreement with the present study at intermediate temperatures. The identification of the Alibas model at 50°C and the Aghbashlo et al. model at higher temperatures in this study reflects the flexibility of these models in capturing the non-linear moisture removal behaviour typical of leafy materials.

For microwave drying, similar variability in model suitability has been reported in the literature, with models such as Page, Logarithmic, Midilli and Aghbashlo frequently providing good fits depending on power level and material characteristics. In the present study, the Modified Henderson and Pabis model best described drying behaviour at low microwave power (200W), while the Logarithmic and Aghbashlo et al. models provided better fits at intermediate and high power levels (500-700W), respectively. This trend reflects the increasing dominance of rapid internal heating and non-linear moisture transport at higher microwave power levels.

Overall, these findings confirm that while no single thin-layer model universally describes drying behaviour across all conditions, model selection is largely governed by the shape of the moisture ratio curve and the underlying drying mechanism. Empirical and semi-empirical models based on exponential decay functions consistently provide good representations of moisture movement during both oven and microwave drying of leafy materials, but the most appropriate model depends on how well it captures the curvature of the drying profile under specific conditions. Differences in model suitability are therefore linked to variations in leaf structure, thickness and drying intensity, which influence internal moisture diffusion and surface evaporation mechanisms. Under the selected optimal conditions, the Alibas model at 50°C and the Aghbashlo et al. model at 700W were identified as the most appropriate for representing the drying behaviour of avocado leaves.

3.5 Drying rate constants (k) and Diffusion Coefficients (D_{eff})

The drying rate constants (k) and effective diffusivity values (D_{eff}) for the initial minutes of drying of avocado leaves are given in Table 7.

Table 7. Drying rate constants (k) and diffusion coefficients (Deff) for oven- and microwave-dried avocado leaves

Drying kinetic parameter	Treatment					
	Oven-dried			Microwave-dried		
	50°C	60°C	70°C	200W	500W	700W
k (1/min)	0.0116 ± 0.001 ^c	0.0358 ± 0.104 ^c	0.0507 ± 0.010 ^c	0.0359 ± 0.002 ^c	0.3574 ± 0.012 ^b	0.5784 ± 0.019 ^a
D _{eff} (m ² /s)	1.13 × 10 ⁻¹⁰	3.48 × 10 ⁻¹⁰	4.93 × 10 ⁻¹⁰	3.50 × 10 ⁻¹⁰	3.48 × 10 ⁻⁹	5.63 × 10 ⁻⁹

Values are means ± SEM, n = 3 per treatment group.

Means in a row without a common superscript letter differ ($p \leq 0.05$) as analysed by one-way ANOVA and the TUKEY test.

Drying rate constants were significantly affected by microwave power level ($p \leq 0.05$). For oven drying, the drying rate constant increased from 0.0116 1/min at 50°C to 0.0507 1/min at 70°C, indicating enhanced moisture removal with increasing temperature. A similar trend was observed for effective diffusivity, which increased from 1.13×10^{-10} to 4.93×10^{-10} m²/s over the same temperature range. For microwave drying, substantially higher values were obtained compared to oven drying. The drying rate constant increased markedly from 0.0359 min⁻¹ at 200W to 0.5784 min⁻¹ at 700W, while diffusivity values increased from 3.50×10^{-10} to 5.63×10^{-9} m²/s. The pronounced increase in both parameters with microwave power level reflects the enhanced internal heating and vapour pressure gradients generated during microwave drying, which accelerate moisture migration within the leaf structure. Overall, microwave drying resulted in significantly higher drying rate constants and diffusivity values than oven drying, confirming the greater efficiency of this method. The highest values observed at 700W further support the selection of this power level as the optimal microwave drying condition, while 50°C was identified as the most appropriate oven drying condition based on a balance between drying rate and quality retention.

The activation energy (E_a) for moisture diffusion was determined using an Arrhenius-type relationship between effective moisture diffusivity (D_{eff}) and temperature, expressed as:

$$\ln(D_{eff}) = \ln(D_0) - E_a / RT \quad (4)$$

where D_0 is the pre-exponential factor, E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). Based on this approach, the activation energy for oven drying of avocado leaves was calculated as 67.7 kJ/mol ($R^2 = 0.919$). This value is comparable to those reported for other leafy materials, including lemongrass and amaranth leaves (Mujaffar and Lee Loy, 2016; Mujaffar and John, 2018). The magnitude of the activation energy reflects the sensitivity of moisture diffusivity to temperature and is consistent with diffusion-controlled drying behaviour in leafy materials. While several studies have examined the phytochemical properties of avocado leaves, there is limited information on their drying kinetics, including drying rate constants, effective moisture diffusivity and activation energy.

The increase in drying rate constant with microwave power level for avocado leaves was found to follow a linear relationship, which could be described by:

$$k = 0.00108P - 0.18194 \quad (5)$$

where k is the drying rate constant (min⁻¹) and P is the microwave power level (W). The high coefficient of determination indicates a strong linear dependence of drying rate on microwave power level within the experimental range studied. This behaviour contrasts with that observed for West Indian bay leaves, where the relationship between drying rate constant and microwave power level was better described by a power function, suggesting differences in moisture transport behaviour between the two materials. The linear relationship observed in this study indicates a more direct proportionality between energy input and moisture removal rate, which may be attributed to differences in leaf structure, thickness and moisture distribution.

4. Conclusions

The drying behaviour and quality attributes of avocado (*Persea americana*) leaves were significantly influenced by both drying method and processing conditions. Drying occurred predominantly in the falling rate period for both methods, indicating that internal diffusion governed moisture removal. Microwave drying exhibited higher drying rate constants and effective diffusivity values compared to oven drying, reflecting enhanced internal heating and moisture migration. Within oven drying treatments, 50°C was identified as the most suitable condition, providing a better balance between drying efficiency and retention of bioactive compounds compared to higher temperatures, where greater degradation was observed. In contrast, microwave drying, particularly at 700W, was more efficient than all other treatments, achieving comparable moisture reduction in substantially

shorter times while also preserving or enhancing key bioactive compounds, including phenolics and antioxidant capacity. Thin-layer modelling demonstrated that no single model universally described the drying behaviour across all conditions; however, selected models provided good fits for oven and microwave drying under specific conditions. The strong dependence of drying rate on temperature and microwave power level further highlights the importance of process optimisation. Overall, microwave drying at 700W is recommended as the optimal drying condition, outperforming oven drying and lower microwave power levels in both efficiency and product quality. These findings contribute to the limited body of knowledge on the drying kinetics of avocado leaves and support their potential use in functional food and nutraceutical applications.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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