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Effect of radio frequency assisted drying on qualities of high valued medicinal and aromatic plants

M. Anand[♦], M. Balakrishnan, S. Parveen, K. Gurusamy, G. Amuthaselvi, T. Pandiarajan and P. Sudha

Department of Food Process Engineering, Tamil Nadu Agricultural University, Coimbatore-641 003, Tamil Nadu, India

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Abstract

This study evaluated the efficiency and quality outcomes of radio frequency (RF) drying compared to conventional tray drying for four medicinal and aromatic plants: *Moringa oleifera* (Moringa leaves), *Solanum nigrum*, (Black nightshade), *Rosmarinus officinalis* (Rosemary) and *Cymbopogon citratus* (Lemongrass). RF drying, a dielectric heating method, offers rapid and uniform moisture removal, potentially preserving thermolabile bioactive compounds better than conventional methods. Drying experiments were carried out using bed thicknesses ranging from 180 to 210 mm and a constant electrode gap of 190 mm. The most effective moisture removal was achieved at a bed thickness of 210 mm, where final moisture content dropped below 11% within 45 to 59 min for all plant species. In contrast, conventional tray drying at temperatures of 40°C, 50°C, and 60°C required up to 16 h to reach similar moisture levels, with the shortest drying time at 60°C, albeit with a higher likelihood of bioactive compound degradation. Quality analysis showed that RF drying at a 200 mm bed thickness retained greater amounts of phenolic and tannin compounds in *M. oleifera* and *S. nigrum* leaves compared to samples dried using traditional tray methods. For aromatic herbs, essential oil content was better retained under RF drying, with *R. officinalis* and *C. citratus* retaining 0.46% and 0.40%, respectively, compared to lower values in tray-dried samples, particularly at higher temperatures. These results suggest that RF drying not only accelerates the drying process but also enhances the preservation of nutritional and functional compounds, making it a superior alternative for processing medicinal and aromatic plants. Further optimization could focus on balancing energy efficiency, throughput, and product quality for commercial scalability.

1. Introduction

Radio frequency (RF) assisted drying has emerged as an innovative food processing technology offering advantages over conventional methods. This non-contact dielectric heating generates heat within products through electromagnetic wave interaction with polar molecules, resulting in uniform temperature distribution and faster moisture removal (Wang *et al.*, 2020). Conventional drying often degrades bioactive compounds and sensory attributes, while RF drying shows promise in preserving quality and functionality of agricultural products (Jiao *et al.*, 2016).

Moringa leaves (*M. oleifera*), sometimes known as the “miracle tree,” are well known for their therapeutic and nutritional benefits. It is abundant in proteins, vital vitamins, minerals, and a variety of bioactive substances like glucosinolates, flavonoids, and phenolic acids. The main source of Moringa’s anti-inflammatory, antioxidant, antibacterial, and antidiabetic properties are these compounds (Gopalakrishnan *et al.*, 2016). However, traditional drying methods can lead to considerable degradation of heat-sensitive compounds, thereby diminishing the plant’s functional and therapeutic qualities.

Radio frequency (RF) drying, through its rapid and uniform volumetric heating mechanism, presents a valuable alternative for conserving critical bioactives such as quercetin glycosides and chlorogenic acid derivatives, which play a key role in Moringa’s pharmacological properties (Vongsak *et al.*, 2013). Black nightshade (*S. nigrum*) is traditionally used for hepatoprotective, anti-inflammatory, antipyretic, and antioxidant properties. Its therapeutic potential comes from alkaloids (solanine and solasonine), glycoproteins, polyphenols, and steroidal glycosides (Jain *et al.*, 2011). Conventional drying causes significant degradation of these compounds. RF drying’s rapid moisture removal and shorter temperature exposure presents an opportunity to minimize degradation of heat-sensitive compounds, as demonstrated in previous studies on similar plant materials (Chen *et al.*, 2008; Banu *et al.*, 2024).

Rosemary (*R. officinalis*) contains essential oils (α -pinene, 1,8-cineole, and camphor) and phenolic compounds (rosmarinic acid, carnosic acid, and carnosol), contributing to its antioxidant, antimicrobial, and anti-inflammatory activities (Borrás-Linares *et al.*, 2014). These volatile compounds are particularly challenging to preserve during conventional drying, which often leads to significant losses of essential oils and degradation of phenolic compounds. RF drying’s rapid heating mechanism and shorter processing time can potentially minimize these losses by reducing high-temperature exposure (Calin-Sánchez *et al.*, 2014). Lemongrass (*C. citratus*) is valued for its essential oil content, particularly citral (neral and geranial) responsible for its characteristic lemon aroma and therapeutic properties. It possesses antimicrobial, antioxidant, anti-inflammatory, and

Corresponding author: Dr. M. Anand

Associate Professor, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641003, Tamil Nadu, India

E-mail: anandhort@gmail.com

Tel.: +91-8870222090

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insecticidal properties (Shah *et al.*, 2011). Conventional drying can result in up to 50% loss of essential oil content due to evaporation and thermal degradation. RF drying offers a promising alternative for preserving volatile compounds through rapid moisture removal and more uniform heating (Martinov *et al.*, 2015). In light of the existing background, this study aims to investigate how radio frequency-assisted drying influences the quality characteristics of high-value medicinal and aromatic plants.

2. Materials and Methods

2.1 Collection and authentication of the plant material

Fresh medicinal herbs such as moringa leaves (*M. oleifera*), black nightshade (*S. nigrum*), along with aromatic plants like lemongrass (*C. citratus*) and rosemary (*R. officinalis*), were procured from farmers' fields located in the Coimbatore District and Ooty region. The plant samples were authenticated with reference to herbarium specimens available at Botanical Survey of India, Coimbatore. The herbarium numbers for the collected specimens are as follows: *M. oleifera* (MH00199740), *S. nigrum* (MH00148726), *C. citratus* (BSI0000065018), and *R. officinalis* (K000194356). These herbarium specimens have been deposited in the department for future reference and research purposes. Subsequent experimental analyses were carried out at the Department of Food Process Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore.

2.2 Radio frequency drying

The experiment was conducted in RF Sterilizer 10/4, manufactured by Lakshmi card clothing manufacturing company Pvt. Ltd, Coimbatore, Tamil Nadu, India, and is designed to deliver a 10 kW radio frequency (RF) power output to the target product. The RF energy is supplied at a frequency of 40.68 MHz with a tolerance of ± 0.05 MHz. Equipment is manufactured to adhere to global health and safety regulations concerning radio frequency emissions. The RF sterilizer comprises several essential components, including a conveyor assembly, oven assembly, generator assembly, control console, control panel, and a main isolator. This system, consisting of fans and ducts, serves to lower internal temperatures, aids in removing moisture from processed items, and prevents excessive condensation buildup during startup. Cool ambient air is drawn through a filter into the HT transformer compartment by the oscillator cooling fan, reducing the transformer's temperature. This air is then directed to the base of the triode valve in the oscillator cavity, where it moves upward, cooling the valve. Afterward, the heated air exits the cavity and disperses beneath the bottom electrode in the central oven applicator area. Inside the oven, an exhaust fan removes the warm, humid air, which is then expelled through the top exhaust vent of the RF Sterilizer and Technical specification for the RF sterilizer is power installed 20 KVA, RF operating frequency in MHz 40.68, RF power output 10 KW, overall height 2400 mm, overall length 2500 mm, overall width 2000 mm, conveyor belt width 400 mm, electrode system flat plate, valve cooling by air, control system by PLC, supply voltage range 415 V $\pm 1\%$; 3-50 Hz, input power is 20 KVA, radio frequency 40.68 MHz $\pm 0.5\%$, conveyor speed 2.5-50m/h, electrode height 190 mm. Radio frequency (RF) drying treatment details for medicinal and aromatic plants as follows:

Parameter	Details
Bed thickness (mm)	180, 190, 200, 210 mm
Electrode gap (mm)	190 (fixed)
Belt speed (m/h)	2.5 (fixed)
Drying method	Radio frequency (RF) drying
Sample type	Moringa leaves (<i>M. oleifera</i>), black nightshade (<i>S. nigrum</i>), lemongrass (<i>C. citratus</i>), rosemary (<i>R. officinalis</i>)

Each 1kg of moringa leaves, black night shade leaves, lemon grass and rosemary leaves were stripped off, cleaned free of pest and diseases and 50% of the moisture content was removed by shade drying and the shade dried leaves were subjected to radio frequency drying. Initial (67.4%) and final (9.8%) moisture contents were determined and the samples were dried to a safer moisture content of 10% and the secondary metabolites were estimated.

2.3 Tray drier

A tray or cabinet dryer is a drying unit where materials are laid out on perforated trays and dried by the circulation of heated air. The drying mechanism involves convective heat transfer from the air to the product, and moisture is removed as the hot air sweeps across the trays. Heat may also be transferred *via* conduction from heated trays or shelves, and in some cases, radiation from warm surfaces contributes to the drying process. Most tray dryers rely on forced air heating, which simultaneously warms the product and carries away moisture-laden air. The tray dryer used in this study was composed of several key components: heating coils, a blower, a drying chamber, air inlets, and a thermostatic control system. The heating system featured 18 vertical coils, each rated at 500 watts, installed on both sides of the drying chamber with eight coils were positioned on the suction side and ten coils on the delivery side. These coils provided the thermal energy necessary to heat the incoming air for effective moisture removal. Airflow within the system was generated by a blower powered by a 0.5 hp electric motor, which drew in fresh air and expelled the humid air after passing through the chamber. The drying chamber, constructed from 3 mm thick mild steel sheets, measured 100 \times 100 \times 100 cm, and was capable of holding 24 aluminum trays (each tray sized 90 \times 40 \times 2.5 cm). The trays featured 2 mm perforations to facilitate uniform airflow and efficient drying of the product. Temperature regulation inside the dryer was achieved using a thermostat, allowing precise control of the drying conditions to match product requirements and minimize thermal degradation of sensitive compounds. Tray drying treatment details for medicinal and aromatic plants as follows:

Parameter	Details
Drying method	tray drying
Temperature ($^{\circ}$ C)	40, 50, 60
Sample Type	Moringa leaves (<i>M. oleifera</i>), black nightshade (<i>S. nigrum</i>), lemongrass (<i>C. citratus</i>), rosemary (<i>R. officinalis</i>)

2.4 Phenol content

The Folin-ciocalteu assay, a widely accepted colorimetric technique, was applied to estimate the total phenolic content in the plant

samples. To begin the procedure, 1.0 g of dried and finely ground plant material was extracted with 10 ml of 80% methanol, followed by constant shaking for 2 h at room temperature. The resulting extract was filtered to obtain a clear solution suitable for analysis. For the determination of phenolic compounds, 0.5 ml of the filtrate was mixed with 2.5 ml of Folin-ciocalteu reagent, which had been diluted in a 1:10 ratio with distilled water. After allowing the mixture to react for 5 min, 2.0 ml of a 7.5% sodium carbonate solution was added. The reaction mixture was then incubated in the dark at room temperature for 30 min to allow the development of the characteristic blue color. Absorbance was measured at 765 nm using a spectrophotometer. A standard calibration curve was prepared using gallic acid solutions ranging from 20 to 100 µg/l. The total phenolic content in the samples was calculated and expressed as milligrams of gallic acid equivalents per gram of dry weight (mg GAE/g DW) (Singleton *et al.*, 1999).

2.5 Tannin content

For this assay, 400 µl of the plant extract was assorted with 3 ml of a 4% vanillin solution prepared in methanol, followed by the addition of 1.5 ml of concentrated hydrochloric acid. The mixture was then left to stand at room temperature for 15 min to facilitate color development. The absorbance of the resulting solution was measured at 500 nm using a UV-Visible spectrophotometer. Catechin added the calibration standard, and the results were reported as grams of catechin equivalents per 100 g of dry matter (mg tannic acid/g) (Braodhurst *et al.*, 1978).

2.6 Oil extraction

Oil isolation was conducted *via* Soxhlet extraction with ethanol acting as the solvent. The procedure was conducted at 50°C, 60°C, and 70°C for 2, 3, and 4 h, respectively. These temperature-time combinations were optimized based on preliminary trials. For each condition, three replications were showed to ensure the accuracy and reproducibility. A fixed amount of plant material (10 g) was used in each extraction, maintaining a ratio of 20:1 (v/w). After extraction, the solvent was removed by placing the collected extract in a water bath at approximately 50°C for 2-3 h, followed by gentle refluxing at 70°C to eliminate any residual solvent. The resulting oil was then collected and stored for further analysis (Gafar *et al.*, 2012).

2.7 Statistical analysis

The collected data were initially organized and processed using Microsoft Excel, followed by detailed statistical analysis conducted in R Studio. Advanced analytical procedures were performed utilizing the *agricolae* and *ggplot2* packages for statistical computations and data visualization, respectively (R Core Team, 2022).

3. Results

3.1 Drying performance using radio frequency heating

Preliminary investigations revealed that the initial moisture content of *M. oleifera* leaves ranged from 67.25% to 69.42%. Drying experiments were conducted using radio frequency (RF) heating with a fixed electrode gap of 190 mm and varying bed thicknesses of 180 mm, 190 mm, 200 mm, and 210 mm were presented in Table 1.

Among the treatments, a bed thickness of 210 mm yielded the most efficient drying performance, reducing the moisture content to 10.00% within 45 min. This was followed by 200 mm bed thickness,

which achieved a final moisture content of 10.12% in 57 min. The 190 mm bed thickness resulted in a moisture content of 10.78% after 62 min of drying. In contrast, the 180 mm bed thickness required the longest time, reaching a moisture content of 10.25% only after 75 min.

The initial moisture content of *S. nigrum* leaves ranged from 82.50% to 83.50%. Drying experiments using radio frequency heating demonstrated that a bed thickness of 210 mm provided the most efficient drying, reducing the moisture content to 9.62% in just 59 min. Similarly, at a bed thickness of 200 mm, the initial moisture content of 84.53% was reduced to 9.62% after 60 min. In contrast, the 180 mm bed thickness showed the slowest drying rate, requiring 93 min to reach a final moisture content of 9.85%.

The initial moisture content of *R. officinalis* leaves ranged from 77.50% to 80.00%, while for *C. citratus*, it ranged from 81.65% to 83.50%. Both herbs were subjected to drying under similar conditions, and a consistent reduction in moisture content was observed over time. For *R. officinalis*, the most efficient drying occurred at 56 min, where the moisture content was reduced from 80.00% to 9.95% with bed thickness of 210 mm. As drying time increased to 75 min, the final moisture content reached 10.95%, starting from an initial value of 79.22% with bed thickness of 180 mm. This indicates a slightly diminishing rate of moisture removal as drying progressed beyond 60 min.

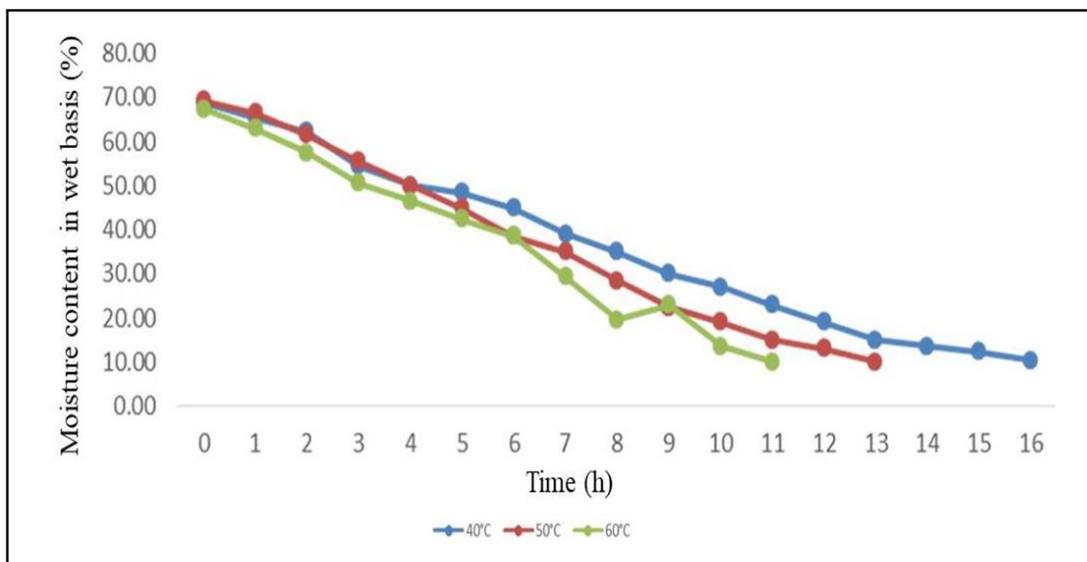
Similarly, *C. citratus* showed a rapid decrease in moisture content, with the most efficient reduction observed at 51 min, where moisture content dropped from 82.50% to 10.65% with bed thickness of 210 mm. At 71 min in bed thickness of 180 mm, the final moisture content was 10.95%, starting from an initial value of 83.50%. Overall, both *R. officinalis* and *C. citratus* achieved final moisture contents below 11% within a drying time range of 51 to 75 min. *C. citratus* consistently showed slightly faster drying compared to *R. officinalis*, reaching lower final moisture levels in less time at equivalent moisture reduction rates. This could be attributed to differences in leaf structure, surface area, or initial moisture distribution.

3.2 Drying performance using tray drying

This study evaluated the drying kinetics of *M. oleifera* leaves at three controlled temperature 40°C, 50°C, and 60°C (Figure 1). Moisture content (%) was recorded over a drying period of up to 16 h to assess the rate of water removal under each temperature condition. The findings showed that drying time and temperature had a definite inverse connection. As expected, higher temperatures significantly accelerated the drying process due to enhanced evaporation rates driven by greater thermal energy and increased vapor pressure differentials. Initial moisture content across all treatments ranged between 67.5% and 69.35%, which is typical for fresh leafy greens. At 60°C, the leaves reached a final moisture content of 9.95% by the 11th h, representing the most efficient drying performance among the tested conditions. At 50°C, a similar moisture content (~10.01%) was attained after 13 h, indicating a moderate drying rate. At 40°C, the drying process was considerably slower. It required up to 16 h to reach a final moisture content of 10.35%, and was the least effective in terms of reaching the target moisture level suitable for safe storage (<10%) within a practical timeframe.

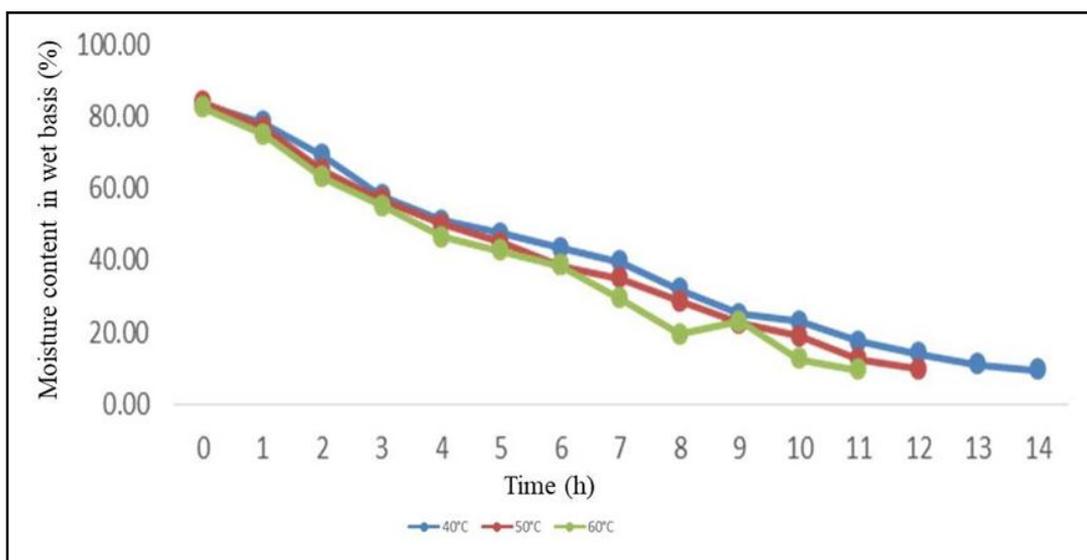
Table 1: Effect of radio frequency drying on moisture content of medicinal and aromatic plants

Bed thickness (mm)	<i>M. oleifera</i> leaves			<i>S. nigrum</i> leaves			<i>R. officinalis</i> leaves			<i>C. Citratus</i> leaves		
	Moisture content (%)									Initial (%)	Final (%)	Time (min)
	Initial (%)	Final (%)	Time (min)	Initial (%)	Final (%)	Time (min)	Initial (%)	Final (%)	Time (min)			
180	68.78	10.25	75	83.50	9.85	93	79.22	10.95	75	83.50	10.95	71
190	69.42	10.78	62	83.45	9.75	65	78.50	10.50	67	81.65	10.75	65
200	69.25	10.12	57	84.53	9.62	60	77.50	10.20	60	82.00	10.69	59
210	67.25	10.00	45	82.50	9.53	59	80.00	9.95	56	82.50	10.65	51

**Figure 1: Tray drying of *M. Oleifera* leaves.**

The effect of temperature on the tray drying of *S. nigrum* leaves was investigated at three different drying temperatures of 40°C, 50°C, and 60°C. The results demonstrated that the rate of moisture loss increased with higher temperatures (Figure 2). At 60°C, drying was

the most rapid, with moisture content decreasing from 82.5% to 9.5% within 11 h. At 50°C, a similar reduction was achieved in approximately 12 h, while drying at 40°C was slower, with the moisture content remaining at 11% even after 13 h.

**Figure 2: Tray drying of *S. nigrum* leaves.**

The tray drying characteristics of *R. officinalis* leaves at 60°C, the leaves exhibited the fastest moisture loss, with the content dropping from 83% to 8.5% within 11 h (Figure 3). At 50°C, a similar reduction was observed more gradually, reaching 10.85% after 12 h. In contrast,

drying at 40°C was slower, with moisture content decreasing from 80% to 10% over 13 h. In *C. citratus* at the start (time 0), the values are highest across all temperatures, with 83.5 at 40°C, 80.0 at 50°C, and 81.5 at 60°C (Figure 4).

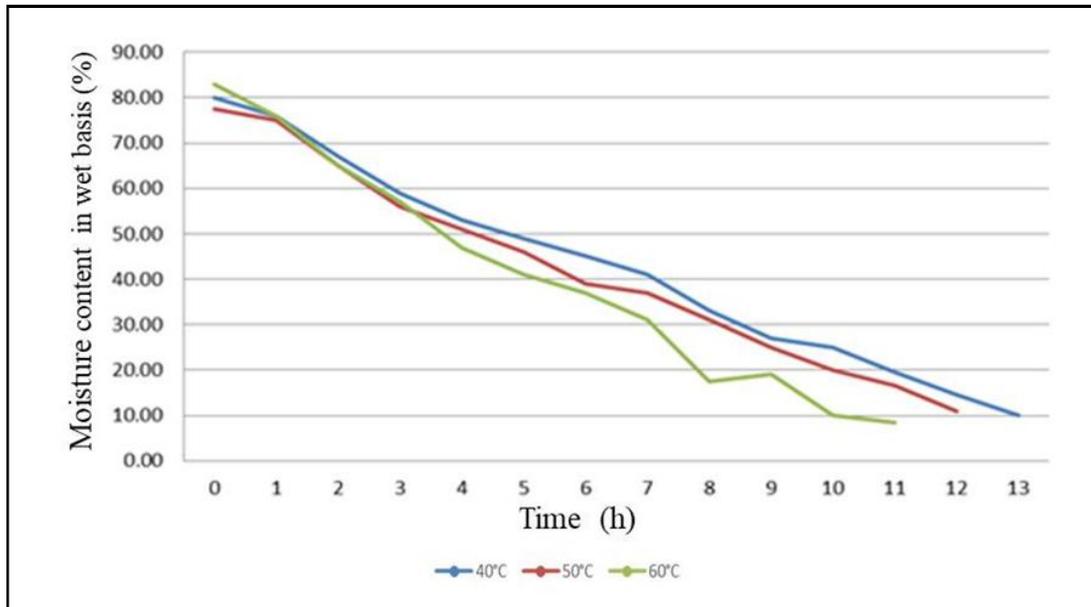


Figure 3: Tray drying of *R. officinalis* leaves

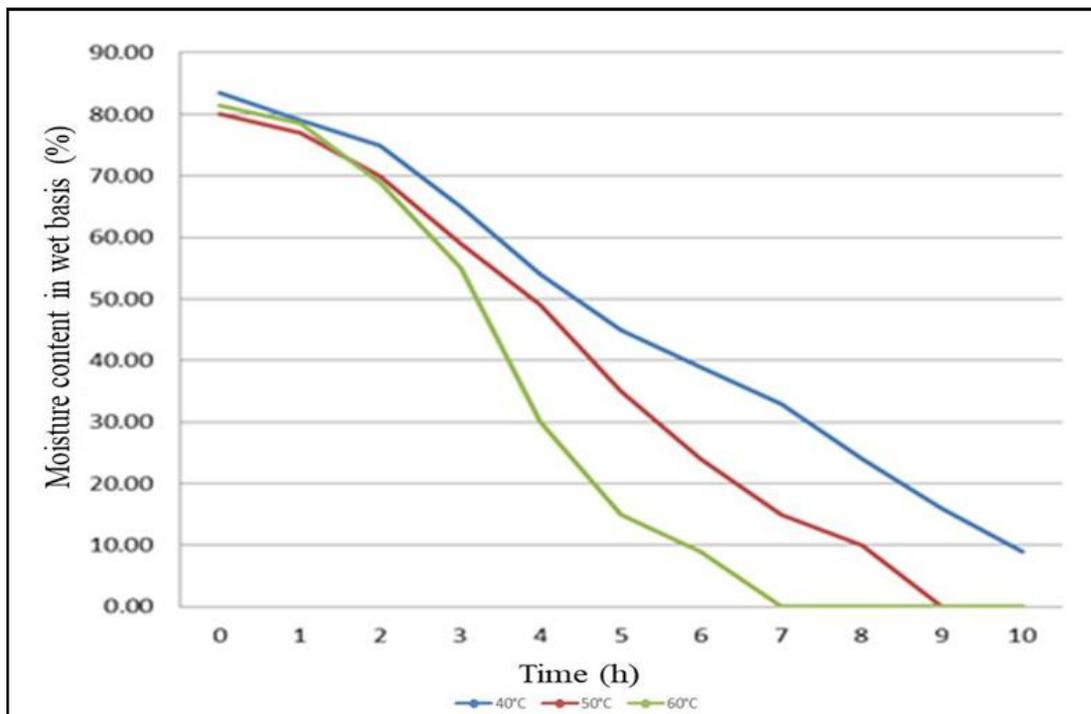


Figure 4: Tray drying of *C. citratus* leaves.

3.3 Quality parameters of phenol and tannin content

Radio frequency dried *M. oleifera* leaves with bed thickness of 200 mm, distance between the electrodes 190 recorded higher phenol (13.30 GAE/g), followed by bed thickness of 190 mm which recorded

the phenol content of 12.90 GAE/g and the lowest phenol content was recorded in bed thickness of 210 mm of 12.65 GAE/g (Figure 5). Similarly, trend was also observed for tannin contents (1.49 mg tannic acid/g) compared to the other treatments (Figure 6).

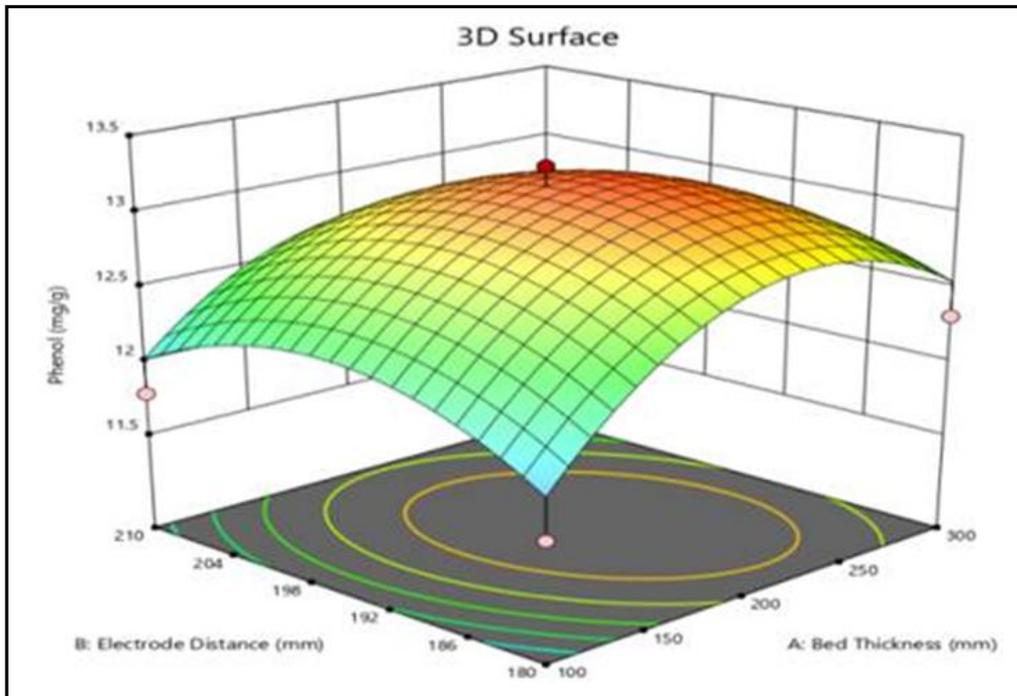


Figure 5: Effect of radio frequency drying on the phenolic content of *M. oleifer* leaves.

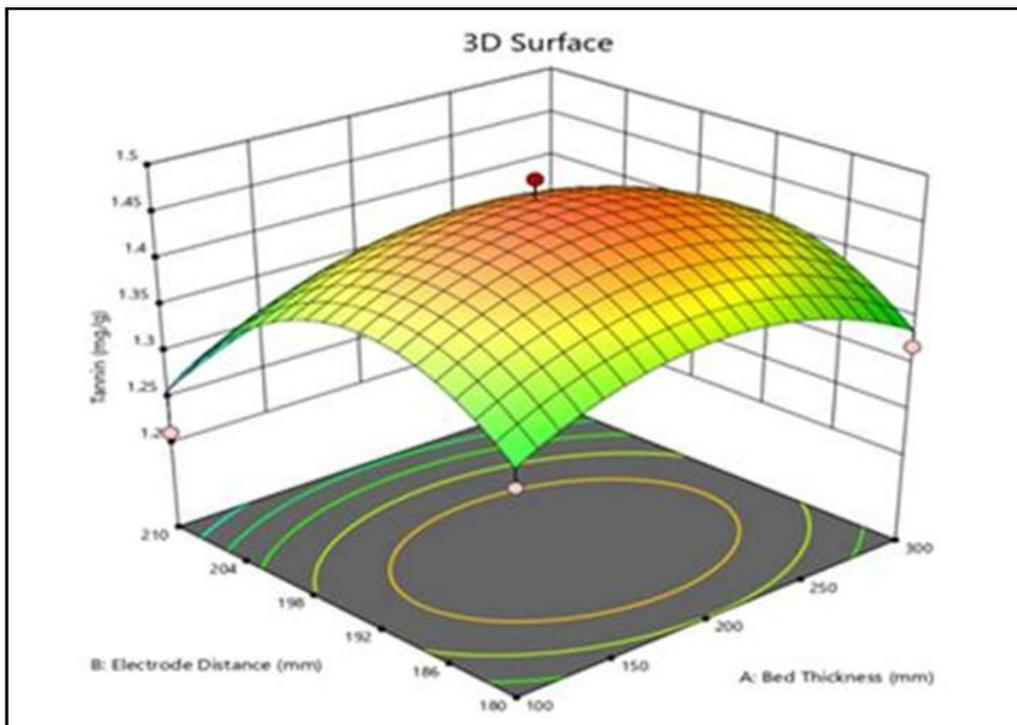


Figure 6: Effect of radio frequency drying on the tannin content of *M. oleifer* leaves.

S. nigrum leaves were dried at different bed thickness and at the different electrode position and the observations on total phenol and tannin contents were recorded and presented in the Figures 7 and 8. The *S. nigrum* leaves dried at a medium bed thickness of 200 mm with the electrode distance of 190 mm recorded a higher phenol

(16.67 GAE/g) and tannin content (1.28 mg tannic acid/g) compared to the other treatments.

The retention of phenolic and tannin compounds in *R. officinalis* and *C. citratus* was significantly influenced by bed thickness during radio frequency drying (Table 2). As bed thickness increased from 180

mm to 200 mm, both herbs showed a consistent improvement in phenol and tannin content, indicating enhanced preservation of thermolabile bioactive compounds. *R. officinalis* achieved peak levels at 200 mm, with phenol content reaching 10.00 ± 0.29 GAE/g and tannin content at 1.37 ± 0.02 mg tannic acid/g, *C. citratus* exhibited

its highest phenol (7.33 ± 0.20 GAE/g) and tannin (1.15 ± 0.02 mg tannic acid/g) content at this thickness. These improvements can be attributed to more uniform energy distribution and efficient moisture removal, which reduce thermal stress and protect sensitive compounds.

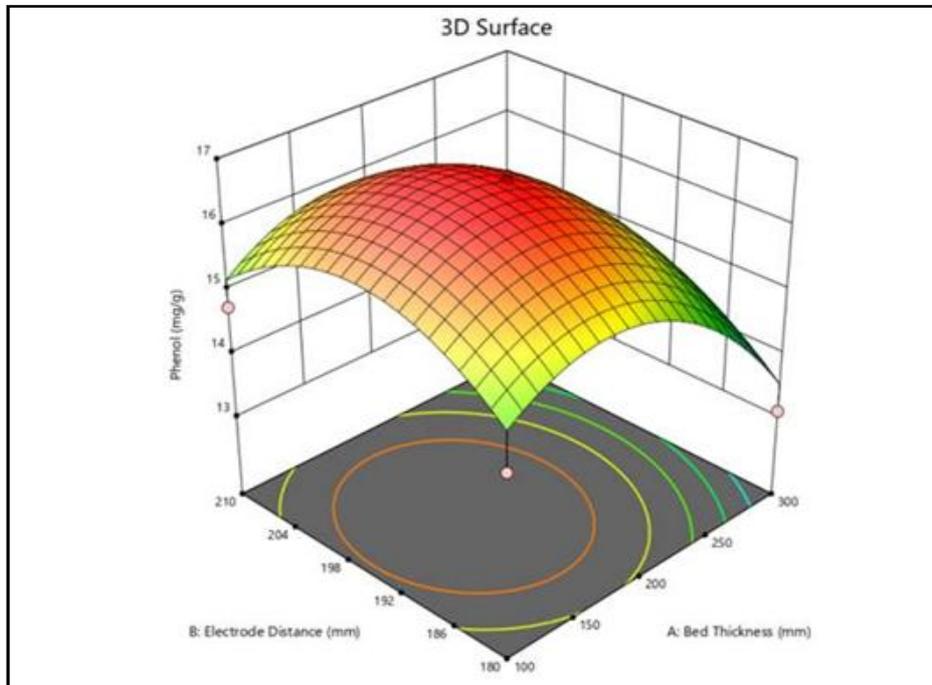


Figure 7: Effect of radio frequency drying on the phenolic content of *S. nigrum* leaves.

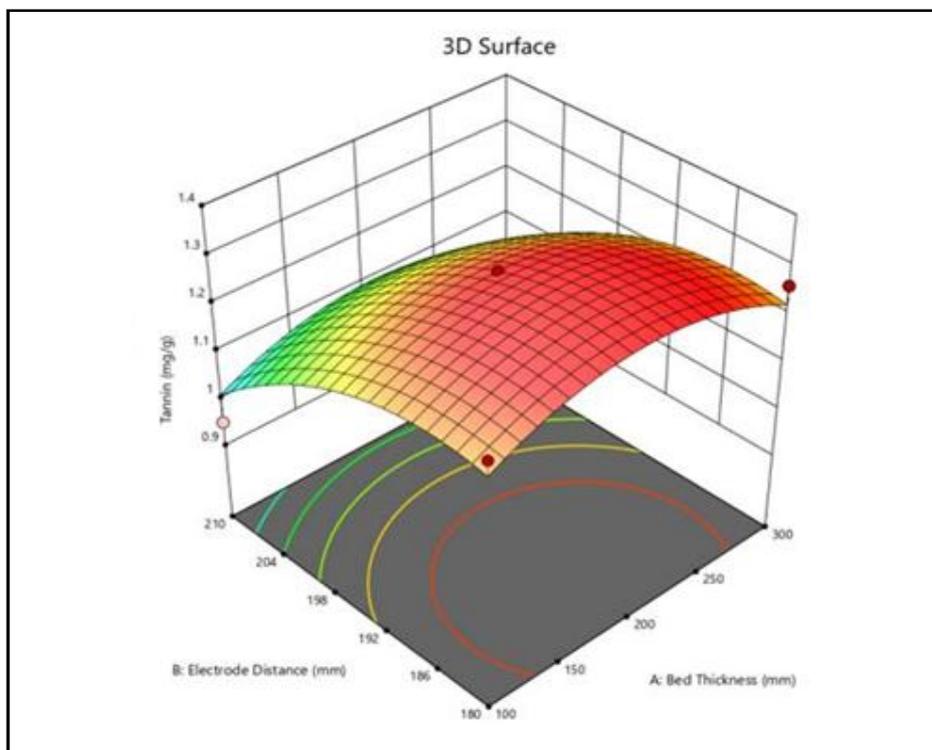


Figure 8: Effect of radio frequency drying on the tannin content of *S. nigrum* leaves.

Table 2: Phenol and tannin content on herbs under radio frequency drying

Bed thickness (mm)	<i>R. officinalis</i>		<i>C. citratus</i>	
	Phenol (GAE/g)	Tannin (mg tannic acid/g)	Phenol (GAE/g)	Tannin (mg tannic acid/g)
180	8.93 ± 0.21	1.10 ± 0.04	6.24 ± 0.17	0.93 ± 0.04
190	9.47 ± 0.30	1.24 ± 0.03	6.79 ± 0.19	1.01 ± 0.03
200	10.00 ± 0.29	1.37 ± 0.02	7.33 ± 0.20	1.15 ± 0.02
210	9.73 ± 0.21	1.31 ± 0.01	7.09 ± 0.18	1.09 ± 0.05

3.4 Quality parameters of phenol and tannin content by tray drying

M. oleifera and *S. nigrum* leaves were tray dried at 40, 50 and 60°C and the observations on total phenol and tannin contents were recorded and presented in the Table 3. The *M. oleifera* leaves dried at

50°C recorded a higher phenol (13.35 GAE/g) and tannin content (1.43 mg tannic acid/g) compared with the other treatments. The *S. nigrum* leaves dried at 50°C recorded a higher phenol (16.45 GAE/g) and tannin content (1.80 mg tannic acid/g) compared to the rest of the treatments.

Table 3: Effect of tray drying on the total phenol and tannin content of medicinal plants

Crops	Temperature (°C)	Phenol (GAE/g)		Tannin (mg tannic acid/g)	
		Initial	Final	Initial	Final
<i>M. oleifera</i>	40	8.38 ± 0.20	11.50 ± 2.79	1.06 ± 0.02	1.01 ± 0.020
	50		13.35 ± 2.89		1.43 ± 0.050
	60		12.45 ± 2.50		1.10 ± 0.045
<i>S. nigrum</i>	40	11.76 ± 0.35	14.28 ± 2.50	1.75 ± 0.110	1.25 ± 0.047
	50		16.45 ± 3.45		1.80 ± 0.112
	60		14.45 ± 3.01		1.01 ± 0.020

Tray drying significantly influenced the retention of phenolic and tannin compounds in *R. officinalis* and *C. citratus* leaves (Table 4). A gradual decline in both phytochemicals was observed as drying temperature increased from 40°C to 60°C. In *R. officinalis*, phenol content decreased from 10.8 ± 0.25 GAE/g at 40°C to 8.7 ± 0.20 GAE/g at 60°C, while

tannins declined from 1.35 ± 0.04 mg tannic acid/g to 1.10 ± 0.04 mg tannic acid/g across the same temperature range. Similarly, *C. citratus* showed a reduction in phenols from 7.9 ± 0.18 GAE/g at 40°C to 6.9 ± 0.15 GAE/g at 60°C, and tannin content decreased from 1.05 ± 0.03 mg tannic acid/g to 0.90 ± 0.03 mg tannic acid/g.

Table 4: Effect of tray drying on the total phenol and tannin content of herbs

Crops	Temperature (°C)	Phenol (GAE/g)		Tannin (mg tannic acid/g)	
		Initial	Final	Initial	Final
<i>R. officinalis</i>	40	11.50 ± 0.30	10.80 ± 0.25	1.50 ± 0.05	1.35 ± 0.04
	50		9.90 ± 0.22		1.22 ± 0.03
	60		8.70 ± 0.20		1.10 ± 0.04
<i>C. citratus</i>	40	8.20 ± 0.20	7.90 ± 0.18	1.12 ± 0.04	1.05 ± 0.03
	50		7.30 ± 0.15		0.97 ± 0.02
	60		6.90 ± 0.15		0.90 ± 0.03

3.5 Essential oil content

Aromatic herbs were dried at different bed thickness and electrode position and the observations on essential oil contents were recorded and presented in the Figures 9 and 10. *R. officinalis* leaves dried at bed thickness of 200 mm with electrode distance of 190 mm recorded a higher essential oil content (0.46%). Similarly in tray drying essential oil content highest was recorded at 40°C (0.30%) for *R. officinalis* leaves and lowest essential oil content (0.25%) was recorded at 60°C (Table 5). In radio frequency drying, the *C. citratus* recorded the higher essential oil content of 0.40% compared to the other treatments, whereas 40°C recorded the highest essential oil content of 0.35%.

Table 5: Effect of tray drying on essential oil content of aromatic herbs

Crops	Temperature (°C)	Essential oil (%)
<i>R. officinalis</i>	40	0.40 ± 0.010
	50	0.30 ± 0.009
	60	0.25 ± 0.008
<i>C. citratus</i>	40	0.35 ± 0.009
	50	0.25 ± 0.007
	60	0.19 ± 0.006

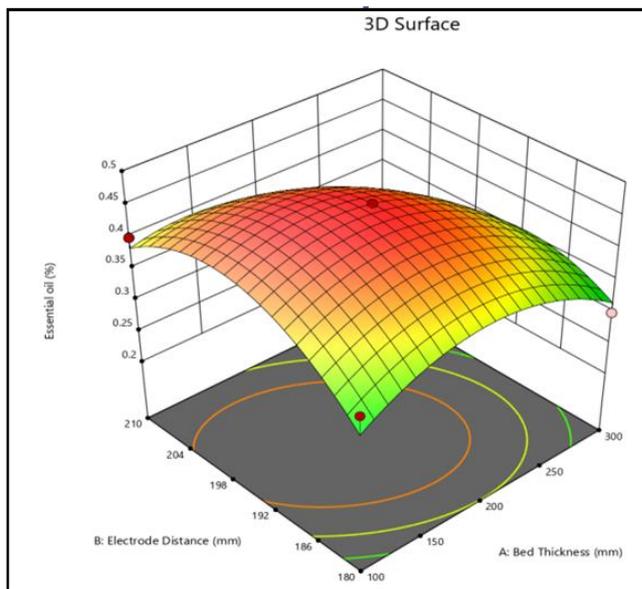


Figure 9: Effect of Rf drying of essential oil content in *R. officinalis* leaves.

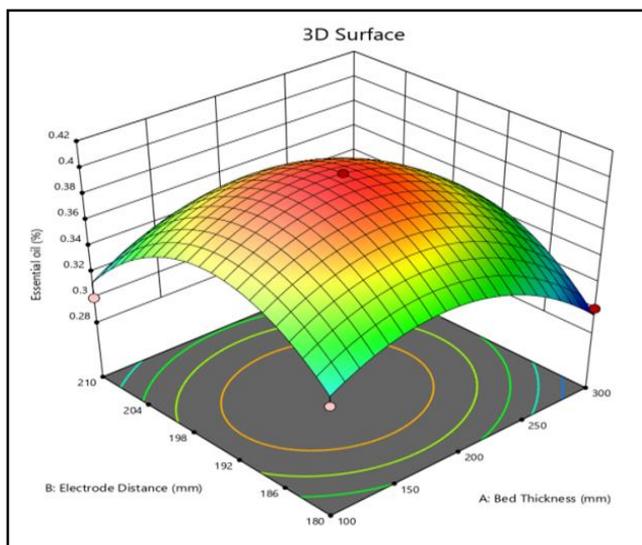


Figure 10: Effect of Rf drying of essential oil content in *C. citratus* leaves.

4. Discussion

The drying behavior of *M. oleifera*, *S. nigrum*, *R. officinalis* and *C. citratus* leaves under radio frequency heating demonstrated a clear influence of bed thickness on drying efficiency. Across all plant types, a 210 mm bed thickness consistently enabled faster drying and achieved lower final moisture contents compared to thinner beds. This enhancement is attributed to the volumetric heating characteristics of RF energy, which allows deep penetration and uniform internal heat generation, promoting effective moisture migration from the interior to the surface. The results support previous findings (Sahu, 2020; Deepa, 2019; Ahmed *et al.*, 2022), emphasizing that optimal control of RF parameters, particularly bed thickness improves drying uniformity, reduces processing time, and supports retention of critical bioactive compounds. In high-

moisture leaves such as *S. nigrum*, the benefits of increased bed thickness were especially evident, as thicker beds maintained consistent vapor pressure gradients, accelerating internal moisture transport and avoiding surface hardening (Zhong *et al.*, 2018; Wang and Zhang, 2021; Li *et al.*, 2020).

For *R. officinalis* and *C. citratus*, similar drying patterns were observed, further highlighting the role of bed configuration in radio frequency-assisted dehydration. The improved drying rate at higher bed thicknesses was due to better energy distribution and minimized surface to core temperature differentials. Between the two herbs, *C. citratus* dried slightly faster than *R. officinalis*, likely due to its thinner leaves, larger surface area relative to volume, and less complex microstructure. These morphological and anatomical differences facilitate more efficient moisture evaporation and contribute to the herb's responsiveness to RF energy. Moreover, disparities in initial water content distribution and cellular moisture retention capacity may have influenced drying kinetics. These observations are in line with the conclusions of Martínez-Las *et al.* (2023); Chen and Liu (2019); and Guo *et al.* (2022), who reported that plant structural properties significantly affect drying behavior under radio frequency treatment. The consistent performance of thicker beds across different species underlines the importance of optimizing bed thickness to enhance radio frequency drying outcomes, maintain product integrity, and support scalable, energy-efficient drying technologies in herbal processing (Darvishi *et al.*, 2020; Babu *et al.*, 2018; Chandrasekaran *et al.*, 2022).

Tray drying of *M. oleifera*, *S. nigrum*, *R. officinalis* and *C. citratus* revealed a consistent influence of temperature on drying efficiency, moisture migration dynamics, and quality retention. Across all crops, increasing the drying temperature significantly reduced drying time due to enhanced thermal energy transfer, elevated vapour pressure gradients, and improved moisture diffusion rates. These findings align with classical drying theories and prior work by Doymaz (2004) and Mujumdar (2014), who demonstrated that elevated temperatures accelerate the constant rate drying phase by promoting surface evaporation and shorten the subsequent falling rate period by facilitating internal moisture migration.

Each crop, however, exhibited distinct responses due to differences in leaf structure, initial moisture content, and phytochemical composition. *M. oleifera*, with moderate initial moisture levels (67.25% - 69.42%), dried efficiently at higher temperatures, but prolonged exposure risked degradation of chlorophyll, ascorbic acid, and phenolic compounds known for their antioxidant and medicinal properties (Krokida and Marinos-Kouris, 2003; Ratti, 2001). *S. nigrum* leaves, which began with a higher moisture content (82.50% - 84.53%), followed a typical two stage drying curve, a rapid constant rate period followed by a slower falling rate phase and indicating that internal diffusion became the limiting step. However, thermal sensitivity of bioactives like flavonoids and phenolics (Kumar *et al.*, 2016) necessitates cautious temperature optimization to avoid losses in nutritional quality.

R. officinalis and *C. citratus*, both rich in essential oils and aromatic compounds, also responded positively to increased drying temperatures in terms of reduced drying time. However, compounds such as rosmarinic acid, citral and geraniol critical for the herbs' sensory and therapeutic value are highly volatile and prone to degradation under excessive heat (Aziz *et al.*, 2021). Rosemary, with

thicker and more resinous leaves, exhibited a slightly slower drying rate than lemongrass, which has a finer structure and higher surface-area-to-volume ratio. This structural difference allowed lemongrass to lose moisture more quickly, though both crops demonstrated the same characteristic drying pattern, initial surface water removal followed by moisture diffusion from internal tissues (Ratti, 2001).

Despite the efficiency gains at elevated temperatures, all four crops faced similar challenges related to quality deterioration when drying conditions were not properly optimized. High temperatures led to pigment loss, reduced antioxidant capacity, and potential texture changes across all samples. Therefore, optimal tray drying of leafy and aromatic herbs requires a strategic balance between process speed and preservation of sensory and nutritional quality. These findings are consistent with established literature emphasizing the trade off between drying kinetics and product quality (Krokida and Marinou-Kouris, 2003; Ratti, 2001; Doymaz, 2004; Mujumdar, 2014), and further reinforce the need for crop-specific optimization in postharvest processing systems.

These results highlight the critical role of optimizing radio frequency drying parameters particularly bed thickness for maximizing the retention of phenolic and tannin compounds. Excessive bed thickness (e.g., 210 mm) can compromise the uniformity of electromagnetic field distribution and hinder heat penetration, potentially leading to localized overheating or under-drying. Such conditions can accelerate the degradation of heat sensitive bioactives (Tiwari *et al.*, 2011). Conversely, very thin beds may promote rapid or uneven drying, which can also adversely affect the stability of these compounds. An intermediate bed thickness appears to strike an optimal balance by enhancing energy penetration, promoting uniform heat distribution, and supporting effective moisture migration, thereby preserving bioactive constituents.

The efficiency of radio frequency drying is attributed to its volumetric heating mechanism, which enables internal moisture evaporation while minimizing surface overheating. This characteristic is particularly beneficial for drying *M. oleifera* leaves, known for their high content of polyphenols and antioxidants that are vulnerable to thermal degradation (Tang *et al.*, 2018). Similarly, in *S. nigrum*, *R. officinalis* and *C. citratus* leaves improved retention of phenolic and tannin compounds may be due to drying conditions that ensure uniform volumetric heating and reduced thermal stress. As these compounds are valued for their antioxidant and therapeutic properties, maintaining their stability during drying is essential to preserve the functional quality of the final product (Alhakmani *et al.*, 2013; Skendi *et al.*, 2023).

In tray drying retention of phenolic and tannin compounds at 50°C in both *M. oleifera* and *S. nigrum* can be attributed to the moderate thermal conditions that enable efficient moisture removal while minimizing damage to heat sensitive bioactives. At this temperature, the drying process proceeds at an optimal rate that avoids both enzymatic oxidation, common at lower temperatures due to incomplete enzyme inactivation and thermal degradation, which becomes more pronounced at higher temperatures. Phenolic compounds, being thermolabile, are particularly susceptible to breakdown when exposed to excessive heat, resulting in a reduction of antioxidant activity (Que *et al.*, 2008; Alhakmani *et al.*, 2013).

These results are in agreement with previous studies suggesting that the optimal drying temperature for preserving phytochemical quality in leafy vegetables lies within the range of 45-55°C (Doymaz, 2004; Ratti, 2001). Within this range, moisture removal is effective without compromising the structural integrity of bioactive compounds. For both *M. oleifera* and *S. nigrum*, maintaining phenolics and tannins is essential due to their antioxidant and therapeutic properties, which define the functional value of the dried product.

Further supporting this, recent findings by Skendi *et al.* (2023) indicate that drying herbs at elevated temperatures leads to significant reductions in antioxidant capacity and phenolic stability compared to more controlled thermal conditions. Additionally, degradation mechanisms such as disruption of hydrogen bonding, enzymatic browning, and oxidative breakdown have been implicated in the loss of polyphenolic content above 50°C (Sagar and Kumar, 2010). Therefore, drying at 50°C offers a practical balance allowing for sufficient dehydration within a reasonable time while preserving the integrity of thermolabile bioactives. This temperature emerges as the most favorable condition for optimizing the nutritional and medicinal quality of dried leafy vegetables, particularly when targeted for use in nutraceuticals, herbal formulations, and functional food products.

This inverse relationship between drying temperature and essential oil content is consistent with the thermal sensitivity of volatile aromatic compounds such as 1, 8-cineole, camphor, and α -pinene, which degrade or evaporate more rapidly at elevated temperatures (Ratti, 2001; Aziz *et al.*, 2021). Lower drying temperatures, though slower, help preserve aroma and medicinal value by reducing the risk of thermal decomposition.

5. Conclusion

This study evaluated the impact of different drying methods using radio frequency drying and tray drying at 40°C, 50°C, and 60°C on the quality of medicinal and aromatic herbs, including *M. oleifera*, *S. nigrum*, *R. officinalis* and *C. citratus*. Among the methods tested, radio frequency drying consistently outperformed tray drying by significantly reducing processing time and achieving uniform, volumetric heating. Most importantly, radio frequency drying resulted in the highest retention of secondary metabolites, which are crucial for the therapeutic efficacy of these herbs. In contrast, tray drying, especially at 60°C, led to notable degradation of these bioactive compounds, thereby potentially compromising both shelf life and medicinal value. Therefore, radio frequency drying is recommended as the most effective and efficient method for drying medicinal herbs, offering superior preservation of quality, color, and functional properties while enhancing energy and time efficiency.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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