

# Microwave Vacuum Drying of Turmeric, Tomato, and Cardamom and its Impact on Quality Characteristics

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**Abstract:** This study investigated the effectiveness of the microwave vacuum dehydrator (MVD) in drying selected commodities, namely turmeric slices, tomato slices, and cardamom, at 7 kW microwave power and 100 mbar partial pressure. The MVD successfully reduced the moisture content of the commodities to below 9%, guaranteeing safe storage conditions. The drying process was completed in 3 hours for turmeric slices, 6 hours for tomato slices, and 7.42 hours for cardamom. Additionally, MVD consumes significantly less energy, making it an economically viable choice for industrial applications. In terms of nutritional quality, microwave vacuum drying had no adverse effects on the macronutrient composition of the commodities, but there was a slight reduction in the micronutrient concentration of cardamom. The curcumin content in dried turmeric slices was 2.4%, meeting standard quality requirements, while the lycopene content in dried tomato slices was 40.27 mg/100g, indicating negligible degradation. Furthermore, the color and texture of the dried commodities were better preserved compared to other conventional and hybrid drying methods. Overall, microwave vacuum drying has proven to be an energy-efficient and time-saving technology that maintains the nutritional and bioactive properties of commodities.

**Keywords:** Microwave Vacuum Drying, Turmeric, Tomato, Cardamom, Curcumin, Lycopene.

## 1. Introduction

Drying and dehydration are fundamental unit operations in food preservation. This process lowers the moisture content of the food through heat exposure, thereby reducing its water activity. As a result, microorganisms, enzymes, and chemical substrates cannot utilize the available moisture, which hinders their growth and significantly extends the food's shelf life.

Consequently, drying and dehydration play a vital role in maintaining food quality, enhancing stability, and minimizing spoilage [1]. The purpose of drying in food processing is to extend the shelf life of foods such as fruits, vegetables, spices, herbs, and dairy products, with a reduction in the surface area and volume, and thus reducing the transportation, distribution, and storage costs in the food supply chain [2]. In general, conduction, convection, and radiation are the heat transfer mechanisms in food drying [3].

Novel drying techniques involve osmotic drying, vacuum drying, heat pump drying, freeze drying, super-heated steam drying, microwave drying, infrared drying, radiofrequency drying, explosion drying, refractance window drying, acoustic drying, etc. are evolving in food processing [2], [4]. Each technique operates on distinct principles, yet the fundamental mechanism of moisture removal remains the same, involving heat and mass transfer until the food reaches equilibrium moisture content. The above-mentioned techniques have the advantage of minimum energy consumption and sequel in higher physicochemical and sensorial properties of dried products in shorter drying time compared to conventional techniques like solar drying and hot air convective drying [5]. The emerging drying techniques are hybrid or combination drying techniques, which leverage the strengths of multiple drying methods to fabricate hybrid dryers [6]. The major benefit of hybrid drying is that it enhances drying kinetics and improves the quality of dried products by optimizing the strengths of each drying method. This dryer class comprises microwave-assisted convective dryers, microwave-assisted vacuum dryers, intermittent microwave convective driers, and heat pump-assisted hot air driers, and is successfully involved in drying agricultural commodities such as apples, sour cherries, tiger prawns, and squids [7].

Microwave-vacuum (MV) drying is a promising and environmentally friendly drying technology that combines the rapid internal heating of microwaves (MW) at low-temperature conditions and facilitates moisture removal [8]. Individually, in MW heating, electromagnetic waves at frequencies ranging from 300 MHz to 300 GHz, specifically 2,450 MHz, interact with polar molecules such as water, causing them to oscillate in the alternating electric field and generate heat within the product through dielectric heating. Unlike conventional drying methods, which transfer heat from the surface inward, MW heating delivers energy volumetrically, aligning heat flux with moisture and producing a strong driving force for water migration. This accelerates drying and shortens processing time [9]. However, under atmospheric conditions, the rapid temperature rise can cause localized overheating, as water boils at 100°C, potentially degrading heat-sensitive nutrients, pigments, and flavors. The vacuum environment overcomes this hurdle by reducing the ambient pressure below 0.61 to 101.33 kPa, which lowers the boiling point of water and allows evaporation at significantly lower temperatures, while also limiting oxidative damage due to reduced oxygen content [10]. The synergy of MW and vacuum enhances the mass transfer, prevents overheating, and preserves key quality attributes such as colour, flavour, bioactive compounds, and structural integrity, making MV drying particularly well-suited for heat-

sensitive agricultural commodities [11]. Thus, this study aims to evaluate the industrial-scale MVD for drying selected agricultural commodities.

## 2. Materials & Methods

### 2.1. Equipment Setup

The MVD fabricated by Frozen Comp Innovations Pvt Ltd, Theni, Tamil Nadu, was used to dry the commodities. The equipment featured a drying chamber with a capacity of 350 liters, with dimensions of 6.56 ft in length and 1.64 ft in diameter and was constructed from corrosion-resistant stainless steel. The MVD is powered by five magnetrons, each capable of delivering up to 1.3 kW, resulting in a maximum total output of 7 kW. It operated at a frequency of  $2450 \pm 50$  MHz, with a radiation penetration depth of 0.98 ft and a partial vacuum pressure range of 100 mbar. A programmable controller interface was used for monitoring real-time temperature and energy consumption. Safety features such as emergency stop functions and thermal protection to prevent machine overheating were expressed as provided. Figure 1 is the photograph of the industrial-scale microwave vacuum dehydrator used for drying the selected commodities.



**Figure 1.** Industrial-scale Microwave Vacuum Dehydrator

## 2.2 Selected Commodities and Experimental Plan

The turmeric (*Curcuma longa*) of the BSR 2 variety was procured from an organic supplier, Theni, Tamil Nadu, with an initial moisture content of  $83.76 \pm 0.59\%$ . Secondly, fresh ripe tomato (*Solanum lycopersicum*) was purchased from local markets of Thanjavur, Tamil Nadu, and the moisture content was  $94.93 \pm 1.93\%$ . Thirdly, Cardamom (*Elettaria cardamomum*) of Njallani variety was procured from Kattapana, Idukki, Kerala, with an initial moisture content of  $77.78 \pm 2.04\%$ .

Before drying, the commodities were pretreated by different methods depending on their characteristics. The turmeric rhizomes were thoroughly washed and then boiled until the fingers became soft by following the methodology of Saha *et al.*, [12]. The blanched rhizomes were sliced into long, thin dimensions ( $5 \times 1 \times 0.5$  cm). The fresh tomatoes were rinsed with water and sliced into thin and round shapes [13]. The fresh green cardamom pods were cured by soaking in a 2% sodium carbonate solution for 10 minutes, followed by a quick dip in water at  $40^\circ\text{C}$ , and the excess water was later drained out [14]. After weighing, the commodities were manually loaded onto 2 perforated trays ( $80 \times 40 \times 3$  cm) and subsequently placed into the drying chamber of the MVD. The initial weight of the samples loaded inside the dehydrator was  $2.0 \pm 0.16$  kg for turmeric slices,  $4.01 \pm 0.13$  kg for tomato slices, and  $4.16 \pm 0.99$  kg for Cardamom.

After loading the samples, the chamber was locked, and the product drying program was set through the control interface. Based on the trials, and preliminary experiments, the 'ON' and 'OFF' times were set as follows: for turmeric slices, the 'ON' and 'OFF' times were set to 1 minute and 30 seconds, respectively; for Cardamom, the 'ON' and 'OFF' times were set to 30 seconds and 60 seconds, respectively; and for tomato slices, the 'ON' and 'OFF' times were initially set to 2 minutes 'ON' and 40 seconds 'OFF' for the first two hours, followed by 1 minute 'ON' and 40 seconds 'OFF'. Once the program was set, the magnetrons and blower automatically started operating, and energy usage was monitored on the display. At hourly intervals, the moisture content was measured until the safe moisture level was reached, which varies for each commodity as follows: 8-10% for Cardamom, 6-9% for turmeric, and 8-12% for tomato [15-17]. The final weight of the dried commodities, the overall drying time, and the energy consumed by MVD were recorded during the experimental trials.

## 2.3 Physical Analysis of the Dried Commodities

### 2.3.1 Colour Measurement

The colour of both fresh and dried commodities was evaluated using a Hunter Lab colorimeter (Color Flex-EZ, Hunter Lab, United States of America). The color values were expressed in Hunter Lab units: L (ranging from 0 = dark to 100 = bright), a (+a = red, -a = green), and b (+b = yellow, -b = blue). The total color difference ( $\Delta E$ ) was calculated using Equation 1, representing the extent of color variation between fresh and dried commodities.

$$\Delta E = \sqrt{((L_1 - L_0)^2 + (a_1 - a_0)^2 + (b_1 - b_0)^2)} \quad (1)$$

In this equation, L1, a1, and b1 represent the Hunter colour parameters of the fresh commodities, while L0, a0, and b0 denote the dehydrated commodities.

### 2.3.2 Texture Profile Analysis

The texture profile of the dried commodities was analyzed using the Texture Analyzer (TA. HD. Plus Texture Analyzer, Stable Micro Systems). Table 1 presents the test parameters for each commodity, and texture analysis was performed through the compression test.

## 2.4 Proximate Analysis of the MV Dried Commodities

### 2.4.1 Moisture Content

Approximately 2 to 5 grams of both fresh and dried commodities were placed in the sample holder of the Infrared Moisture Analyzer (HE53, Mettler Toledo, Switzerland) to determine the moisture content on the wet basis (%).

### 2.4.2 Fat Content

The fat content of the dried commodities was determined as described in AACC (30-25.01) [18], with slight modifications. After measuring the weight of the empty flask (W1), about 2 to 5 g of sample was placed in the thimble, and then 90 mL of solvent (n-hexane) was added.

**Table 1.** Test parameters for texture analysis of the selected commodities

S.No	Commodity	Pre-Test Speed (mm/s)	Test Speed (mm/s)	Post-Test Speed (mm/s)	Strain (%)	Probe
1	Turmeric slices	1.00	1.00	1.00	75.0	P/35; 35 mm diameter cylinder aluminum probe
2	Tomato slices	1.00	1.00	1.00	75.0	P/35; 35 mm diameter cylinder aluminum probe
3	Cardamom	1.00	1.00	10.00	10.0	5 mm diameter cylinder stainless probe

The thimble was tightly plugged and placed in the Soxhlet apparatus (SOCS PLUS; Model: SCS 6 AS). After 45 minutes of extraction, the flask was cooled and weighed (W<sub>2</sub>).

$$\text{Fat (\%)} = ((W_2 - W_1) / (\text{Weight of the sample})) * 100 \quad (2)$$

### 2.4.3 Ash Content

The ash content of the dried commodities was determined by placing  $5 \pm 0.1$  g of sample in the pre-weighed crucible and incinerating at  $550^\circ\text{C}$  for 5 hours in the muffle furnace [19]. The hot crucible was cooled in a desiccator and weighed. The process was repeated until the difference in Mass between two consecutive weighs was less than one milligram, after which the ash content was determined by equation 3.

$$\text{Total Ash (\%)} = (\text{Weight of the ash obtained}) / (\text{Weight of the sample}) * 100 \quad (3)$$

### 2.4.4 Protein Content

The protein content of the dried commodities was quantified by the Kjeldahl method [20]. About 1 g of the sample was added to the digestion tube along with 5 g of anhydrous sodium sulfate, 1 g of anhydrous copper sulfate, and 10 ml of sulfuric acid, and digestion was carried out. After digestion, 30 ml of distilled water was added, and the solution was distilled. Finally, neutralization of the mixture was done with 40% sodium hydroxide and 4% boric acid. The nitrogen content in the dried commodities was determined by titration with 0.1 N hydrochloric acid, using methyl red as an indicator. The endpoint was indicated by the appearance of a pale pink color, with the titre value corresponding to the nitrogen content (N). The protein content was calculated using equation (4), and the conversion factor is 6.25.

$$\text{Total Protein content (\%)} = ((N * \text{Conversion Factor}) / (\text{Weight of the sample})) * 100 \quad (4)$$

### 2.4.5 Total Carbohydrate Content

The total carbohydrate content of the dried commodities was determined as the residual value obtained by subtracting the moisture, ash, fat, and protein contents from 100.

$$\text{Total Carbohydrate (\%)} = 100 - (\text{Moisture} + \text{Fat} + \text{Protein} + \text{Ash}) \quad (5)$$

## 2.5 Micronutrient Analysis

### 2.5.1 Vitamin C (Or Ascorbic Acid) Content

The vitamin C (or ascorbic acid) content of the dried commodities was estimated by volumetric test, as followed by Rakesh *et al.*, [21]. 5 ml of working standard (100  $\mu\text{g/ml}$ ) prepared from the stock standard (1 mg/ml) was pipetted out into a 100 ml conical flask containing 10 ml of 4% oxalic acid. This solution was then titrated against a freshly prepared 2,6-dichlorophenol

indophenol dye solution (V1) until a pale pink endpoint appeared. Besides, about 0.5 to 5 g of the dried commodity was extracted using 4% oxalic acid and made up to 100 ml using the same acid solution. The mixture was then centrifuged for 5 minutes. A 5 mL of the supernatant was pipetted out, followed by the addition of 10 mL of 4% oxalic acid. The mixture was then titrated against the dye solution until a pale pink endpoint was observed (V2). The vitamin C content in the dried commodities was then calculated using Equation 6.

$$\text{Vitamin C content (mg/100g)} = (0.5 \text{ mg})/V_1 \times V_2/(5 \text{ ml}) \times (\text{make up volume})/(\text{weight of sample taken}) \quad (6)$$

### 2.5.2 Calcium Content

The calcium content of the dried cardamom was estimated by following the method mentioned in clause 6.0 of IS 5949:1990 of IS [22]. Accordingly, the aliquot of the sample was taken in a 500 ml conical flask, and the following prepared solutions were added: triethanolamine (25 ml), hydroxylamine hydrochloride (10 ml), and potassium cyanide solution (2 ml). The mixture was then diluted to 150 ml with water, and the pH was adjusted to 12.5–13 using 20% sodium hydroxide. Approximately 0.1 g of Patton and Reeder's indicator was added, and the solution was titrated with 0.01 M ethylenediaminetetraacetic acid until the color changed from red to blue. The calcium content was then calculated using the following formula.

$$\text{Calcium (\%)} = ((V_1 - 0.04008))/M \quad (7)$$

Where V1 is the volume of EDTA solution consumed in titration and M is mass of the sample in the aliquot taken

### 2.5.3 Sodium and Potassium Contents

The sodium and potassium contents of the dried cardamom and tomato commodities were estimated by aspirating the sample solution into the flame along with standard sodium chloride and potassium chloride, respectively. The sample was prepared by microwave digesting it with hydrochloric acid, nitric acid, and water, followed by evaporating to syrup consistency. The residues were extracted using hydrochloric acid and filtered [23].

$$\text{Sodium or Potassium (\%)} = (e \cdot v) / [10]^{-6} \cdot 100/M \quad (8)$$

where e is the final concentration of sodium or potassium ( $\mu\text{g/ml}$ ), v is the final volume of the solution (ml), and M is the mass of the material in the final solution (g).

## 2.6 Bioactive Compounds Determination

### 2.6.1 Curcumin Content

Approximately 0.1 g of the dried turmeric slices was dissolved in 25 ml of ethanol and then made to 100 ml using ethanol. A 10 ml aliquot of this solution was transferred to another

volumetric flask and made up to 100 ml with ethanol. The absorbance of the prepared extract was measured at 425 nm using a spectrophotometer, with ethanol as the blank. The absorptivity and percentage of curcumin present in the dried turmeric were calculated using the following formulas.

$$\text{Absorptivity of the curcumin (A)} = 0.42 / (L * 0.025) \quad (9)$$

$$\% \text{ of curcumin} = (a * 100) / (L * A * w) \quad (10)$$

Where L is the path length (1 cm), a is the absorbance at 425 nm, and w is the weight of the sample taken (g)

## 2.6.2 Lycopene Content

The lycopene content in dried tomato was determined using the UV-spectrophotometric method [24]. The carotenoid pigment from the tomato was extracted using acetone twice until the color disappeared and then taken up in petroleum ether. For quantification, a 50 $\mu$ l aliquot of petroleum ether containing lycopene was diluted to 10 ml using petroleum ether, and absorbance was measured at 503 nm.

## 3. Results & Discussions

### 3.1 Evaluation of Microwave Vacuum Dehydrator

The drying process for turmeric slices, tomato slices, and cardamom varied in duration and energy consumption. Turmeric slices required 3 hours, with 2.10 hours of ON time and 1.11 hours OFF time, resulting in a final weight of  $0.31 \pm 0.01$  kg. Tomato slices underwent drying for 6 hours, including 3.89 hours ON and 2.30 hours OFF times, yielding  $0.20 \pm 0.03$  kg of dried product. Meanwhile, Cardamom took 7 hours and 25 minutes, consisting of 2 hours and 25 minutes ON and 5 hours OFF times to reach the desired moisture content, with a final weight of  $0.89 \pm 0.05$  g. Table 2 provides an evaluation of the MVD in drying selected commodities. The results indicate that the MVD consumes significantly less energy compared to conventional and hybrid drying methods. For example, the solar tunnel dryer required 1.16 kWh to reduce the mean moisture content of turmeric rhizomes from 78.25% to 8.90% (wb%), taking 9 days to complete the process [25]. In contrast, the MVD achieved the same drying result in just three hours, consuming only 10.97 kW for the entire operation (Table 2). Furthermore, the hot air dryer took 8.5 hours to reduce the moisture content of tomato slices to 10% at a temperature of 60°C and an air velocity of 1.0 m/s, consuming 3.83 kW per hour, while the butane gas dryer required 8 hours under the same conditions but consumed only 0.82 kW per hour [26]. However, the MVD dried the tomato slices to below 10% moisture in 6.24 hours, with a total energy consumption of 22.21 kW. Solar-biomass hybrid dryer consumed 33.34 kW per hour over 19 hours to dry cardamom to 9.1% (wb%), making it highly energy-intensive [27]. In

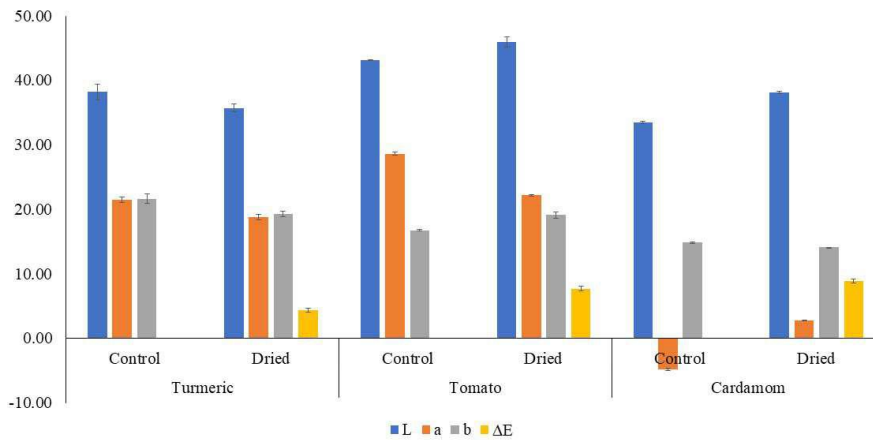
contrast, the MVD completed the drying process in 7 hours and 25 minutes, requiring only 19.94 kW. Thus, the MVD has a higher drying efficiency than other dryers, requiring less time and energy to dry agricultural commodities effectively.

### 3.2 Colour Value

Colour is an important sensorial attribute and is an indicator of flavour, safety, and nutritive value of the dried commodities [28]. As presented in Figure 2, the “L” and “b” values of the turmeric slices decrease, with the “a” value remaining unchanged. These changes indicate the occurrence of minimal browning reactions in turmeric slices during microwave vacuum drying [29]. Lower  $\Delta E$  values signify negligible oxidative and surface changes in dried turmeric. Ray *et al.*, [30] found that the  $\Delta E$  values of microwave-dried and hot air oven-dried turmeric slices were  $10.58 \pm 0.31$  and  $14.91 \pm 0.49$ , respectively. In contrast, the  $\Delta E$  value of microwave vacuum (MV) dried turmeric slices hovered only around  $4.42 \pm 0.31$ , suggesting that the MV drying process had little effect on the oxidation reactions and surface browning of the turmeric slices.

This could be attributed to a controlled temperature ( $39.00 \pm 5.65^\circ\text{C}$ ) and the vacuum conditions during drying. Though freeze-dried turmeric slices showed lower  $\Delta E$  values of  $4.44 \pm 0.14$ , the drying time was approximately 24 hours, while the MVD achieved a comparable colour difference in just three hours, displaying its drying efficacy. A lower  $\Delta E$  value also indicates minimal color change in tomatoes. The MV dried tomato slices had a much lower  $\Delta E$  value of  $7.478 \pm 0.30$ , compared to those dried in the sun, greenhouse, microwave, hybrid, air convective, and freeze drying, which had a mean value of  $23.06 \pm 7.66$  [31]. The “+a” value is used as the benchmark for tomato colour quality, and it showed a slight decline after MV drying. Temperature is the main factor in altering the “a” value, because tomatoes dried at 50 and 60°C in a thin-layer bed dryer showed roughly a 50% decrease in this value, and this decrease significantly affects the commercial value [32].

Added to this, higher L and b values are also preferred in tomatoes, as they imply negligible lycopene oxidation. Figure 2 indicates MVD is effective in retaining the L and b values, with an increase in these values, whereas L and b values decreased in foam mat dried tomatoes at 50°C, indicating oxidation [33]. The colour variations in cardamom become evident when the  $\Delta E$  value exceeds 5 units. In the present study, the recorded  $\Delta E$  value of  $8.89 \pm 0.30$  confirms the noticeable colour change in cardamom. However, cardamom exposed to solar biomass hybrid drying and biomass drying showed even higher  $\Delta E$  values, 13.07 and 10.63, respectively [27]. This highlights that MVD holds a superior hand in preserving the colour of the cardamom compared to other conventional and hybrid dryers. Thus, MVD outperforms other dryers in preserving the colour of the selected commodities, primarily due to its ambient drying conditions.



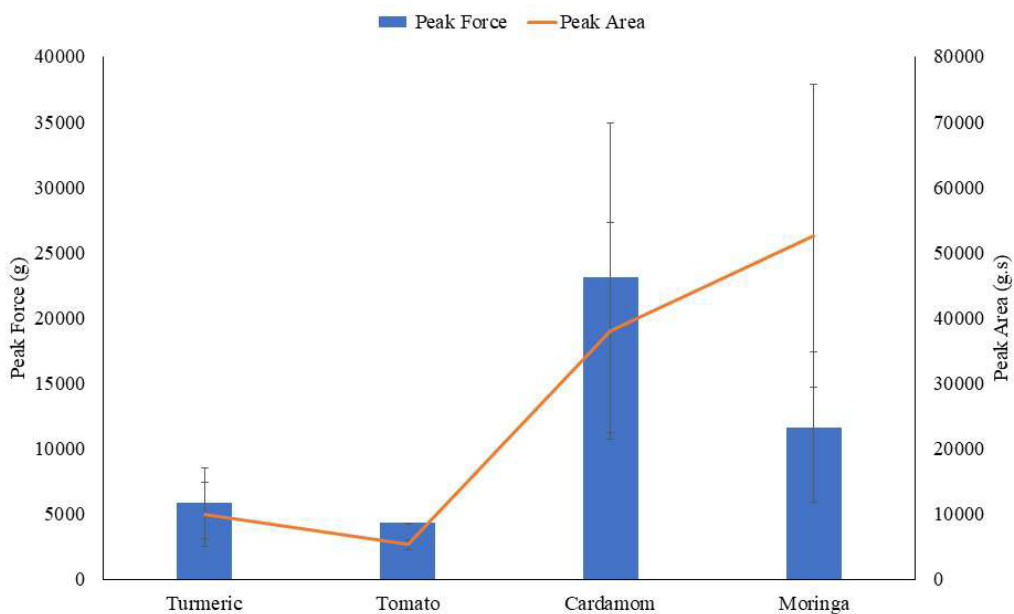
**Figure 2.** Colour value of fresh and MV-dried selected commodities

**Table 2.** Evaluation of MVD during drying of selected commodities

Parameters	MV - dried commodities		
	Turmeric slices	Tomato slices	Cardamom
Initial weight (kg)	2.00 ± 0.01	4.01 ± 0.01	4.16 ± 0.09
Final weight (kg)	0.31 ± 0.01	0.20 ± 0.03	0.89 ± 0.05
Initial moisture content (wb%)	83.76 ± 0.59	94.93 ± 1.93	77.78 ± 2.04
Final moisture content (wb%)	7.15 ± 0.50	9.17 ± 0.11	8.41 ± 0.16
ON time drying (hours)	2.10 ± 0.08	3.89 ± 0.12	2.44 ± 0.12
OFF time drying (hours)	1.11 ± 0.04	2.30 ± 0.12	5.22 ± 0.09
Total drying time (hours)	3.24 ± 0.16	6.24 ± 0.14	7.55 ± 0.12
Drying temperature (°C)	39.00 ± 5.65	41.00 ± 4.94	40.00 ± 5.65
Energy consumed (kW)	10.97 ± 0.57	22.214 ± 2.18	19.94 ± 0.24
Total electricity cost (Rs)	138.22 ± 7.26	279.89 ± 27.48	251.24 ± 3.10
(1 kWh = Rs.12)			

### 3.3 Texture Analysis

The force needed to crush or rupture dried commodities serves as an index of texture. Food texture is a key quality attribute influencing a product's market value [34]. Generally, harder foods necessitate greater force to break, and since drying removes moisture, the peak force required to break dried commodities would be higher compared to fresh ones. In the case of turmeric, it has been reported that the maximum force required to crush dried turmeric correlates with uniform drying. Uneven moisture removal was observed during sun drying and oven drying of turmeric slices, which required less peak force during texture analysis. In contrast, turmeric slices dried using an Integrated Drying System (IDS) required a higher peak force (8,789 g) because it was uniformly dried [35], [12]. MV dried turmeric slices are found to be uniformly dried, as the peak force requirement is 12,020.42 g, which is significantly higher than other drying methods (Figure 3). A minimum peak area signifies reduced energy requirements for size reduction. Compared to IDS-dried turmeric (10,745.26 gs), MVD-dried turmeric had a minimum peak area (9,977.71 gs), indicating minimal energy consumption in the post-processing of turmeric. Fresh tomatoes typically have a firm texture, which progressively decreases with different drying methods, and soft-textured tomatoes are preferable for pulping. The structural collapse caused by MW radiation during MW-assisted air drying resulted in softer tomato slices of lesser textural strength than those of vacuum-drying or hot air drying. It is important to note that the above result is obtained with pre-treatment of soaking in an osmotic solution [36].



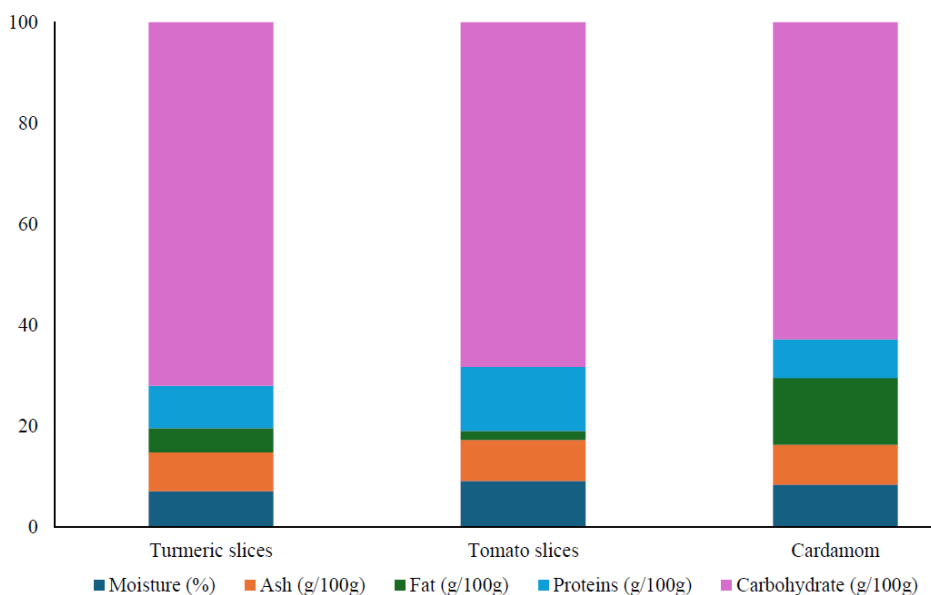
**Figure 3.** Texture profile analysis of the selected commodities: Peak force and Peak area

However, without any pretreatments, MV drying can dry the tomato slice to a textural strength of 4,752.50 g, which is significantly less than vacuum drying and hot air drying. This suggests that using a hybrid dryer, such as MVD, is effective in obtaining soft-textured tomatoes, particularly those that are to be processed into sauces and ketchups. Although the texture profile of cardamom is not extensively studied, the required peak force of 23,078.28 g indicates that cardamom skin has a higher structural strength. Furthermore, the larger peak area suggests that more energy is needed to crush cardamom (Figure 3). As a result, MVD ensures uniform drying of turmeric and cardamom while also maintaining the soft texture of tomatoes, making it a highly recommended drying method prior to size reduction operations.

### 3.4 Proximate Analysis of the Dried Commodities

#### 3.4.1 Moisture Content

Moisture is one of the underlying factors that contribute to spoilage. The primary objective of drying is to reduce the moisture of the agricultural commodities to a safe storage level [37]. In the present study, MVD effectively removes the moisture from the selected commodities, and the final moisture content of those commodities is shown in Figure 4. The moisture content of the turmeric slices reached 7.15% after 3 hours of drying in MVD, while the hot air dryer operating at 80°C with light exposure at wavelength 280 to 2750 nm took 3.67 hours to remove moisture, such in a final moisture content of 10.79%.



**Figure 4.** Impact of MV drying on the macro-nutritional composition of selected commodities

When the drying temperature was below 80°C, the drying time increased to 37 hours, and the final moisture content was 11.64%, which is above the safe storage level [38]. Though the moisture content of the turmeric slices dropped to 3.8% within 20 minutes of exposure to far infrared radiation, the colour of the turmeric slices faded away, and the  $\Delta E$  value was 17.18 [39]. On the contrary, Figure 2 displays a lower  $\Delta E$  value for turmeric slices, specifying that the MV drying retained the vibrant yellow colour of the turmeric, despite taking a relatively longer time to remove moisture. The domestic hybrid solar dryer took 10 hours to dry the tomato slices to a moisture content of 9.00% by internal heat generation mechanism. The drying rate steadily decreased with solid layer formation on the slices due to high water evaporation [40]. This affects the sensory quality of the tomato slices. However, in the present study, MVD took only 6 hours to dry the tomato slices by the oscillatory ion migration mechanism and there was no evidence of the solid layer formation on the slices. This process involves the interaction of an oscillating magnetic field with the fruit, causing water molecules to rapidly vibrate and evaporate. Additionally, the use of vacuum pressure lowers the drying temperature to the range of 32 to 42°C, minimizing thermal damage and preserving product quality. MVD reduced the moisture content of the cardamom to 8.41% in about 7 hours and 25 minutes, including ON and OFF times. MVD is known to take the least amount of time to dry cardamom, as the solar biomass hybrid drier took 19 hours to dry the cardamom, and its final moisture content reached 8.42%, whereas sun drying takes 3 to 7 days [10], [15]. The faster drying process in MVD is due to MW radiation's ability to convert electromagnetic energy into heat. Additionally, the absence of reliance on continuous weather monitoring as required in traditional drying methods further establishes MVD as a preferred drying method at an industrial scale.

### 3.4.2 Ash Content

Ash content is the measure of the total mineral concentration in foods and holds a significant position in the nutritional evaluation of foods [41]. The ash content in the dried commodities is presented in Figure 4, and values fall within the range of 7 to 9%. Notably, for turmeric, the maximum allowable ash content is 9%, and the ash content of MV-dried turmeric remains well within this limit [15]. The ash content of the MV dried tomatoes is 8.09%, which is relatively higher than that of microwave-dried tomatoes (1.35%) and kiln-dried tomatoes (1.30%) [42]. It indicates that MV drying significantly increases the ash content of the dried commodities. Polat *et al.*, [43] also found an increase in ash content of MV dried apples, operating with the MW power of 900 W, frequency of 2400 MHz, and a vacuum condition of 500 mm of Hg. As for cardamom, the ash content of MVD-dried samples was relatively lower than the standard requirement of 9%, mentioned by Govindarajan *et al.*, [15]. However, the impact of MV drying on mineral content remains largely unexplored. One possible reason could be the dipolar rotation and ionic polarization effects of microwaves, along with minimal oxidation due to vacuum conditions during drying, which may contribute to alterations in mineral concentration.

### 3.4.3 Fat Content

Fat is an essential macromolecule in human nutrition that provides metabolizable energy to drive body processes and has additional functions, like the adsorption of fat-soluble vitamins [44]. Figure 4 displays the fat content of the selected commodities following MV drying. MVD did not significantly alter the fat content of turmeric. This is because the fat content of turmeric slices dried in the tray dryer at 60.1°C with an air velocity of 2.0 m/s was in the same range, and both drying methods took only 3 hours to remove moisture to an acceptable level [45]. The MVD's versatility lies in its capacity, which accommodated up to 4 kg of turmeric slices at a time, whereas the tray dryer accommodated 50 g of turmeric slices. Furthermore, as shown in Table 2, MVD consumed significantly less energy (10.97 kW), highlighting its efficiency in drying turmeric slices. Regarding tomato, MVD retained the fat content better than sun drying, which reduced the fat content from 1.44% to 1.39%. Also, sun drying has challenges such as physical contamination, a high dependence on weather conditions, and longer drying time, which are not encountered in MV drying. Even solar-dried, oven-dried, tray-dried, and oven-dried tomatoes had lower fat content than MV-dried tomatoes [46]. Wang *et al.*, [47] reported lower essential oil yield from dried cardamom at 85°C, which was due to its reduced fat content, and drying cardamom at a comparatively lower temperature of 55°C was suggested for higher oil extraction yield. Since MVD operates relatively at a lower temperature of 50°C, it is expected to better retain fat content than other drying methods and support higher essential oil extraction. The fat content of the dried cardamom is not much discussed. Though MVD retains fat content in the commodities, there is no evidence that the operation causes oxidation, which accounts for the commodities' shorter shelf life. This is due to the intended use of vacuum conditions during the drying process.

### 3.4.4 Protein Content

Protein is another essential macronutrient required for the human body which plays a crucial role in tissue repair, muscle building, and the synthesis of hormones, enzymes, and antibodies. Maria *et al.*, [48] reported the protein content of dried turmeric to be 6.3%, while the protein content of the turmeric dried in MVD is 8.3%, specifying that MVD does not have a negative effect on the protein content of turmeric slices (Figure 4). Idah *et al.*, [49] reported that the protein content of tomatoes decreased from 14.38% to 13.97% at drying temperatures above 50°C. Similarly, the protein content of osmosized tomatoes decreased after different drying methods: from an initial 28.95% to 15.74% after sun drying, 15.28% after solar cabinet drying, 13.22% after oven drying, and 14.48% after hot air drying above 50°C [46]. Surprisingly, the MV-dried tomatoes had a protein content of only 12.70%, which was even lower than all of these methods. This might be due to protein denaturation caused by MW radiation during drying, with cleavage of the hydrophobic interaction and disulfide bonds between the protein molecules [50]. The protein content of the MV dried cardamom is 7.70%, which is comparable to cardamom dried in a fluidized bed dryer, solar thermal dryer, hot air convective dryer, and

refrigeration adsorption dehumidified dryer in 17 hours, 29 hours, 19 hours, and 23 hours, respectively [51]. It is important to note that MVD achieved the same protein retention within 8 hours, demonstrating its superior efficiency in drying while preserving nutritional properties better and in significantly less time.

### 3.4.5 Total Carbohydrate Content

Carbohydrates are a major source of energy for humans and are found in a variety of foods such as grains, fruits, vegetables, and others. It serves as both a structural and functional element in cells [52]. The carbohydrate content of turmeric was strongly influenced by pretreatment and drying temperature. Figure 4 shows the carbohydrate content of the dried commodities. Among the blanching times (15, 30, and 45 minutes) and drying temperatures (70°C, 80°C, and 90°C) given to turmeric slices, the highest carbohydrate content was found in turmeric slices exposed to the shortest blanching time and lower drying temperature, and the lowest carbohydrate was found in turmeric slices blanched for the longest time and dried at higher temperatures [25]. Also, a study by Parmar *et al.*, [53] disclosed that drying turmeric at higher temperatures (80°C) resulted in a reduction in total carbohydrate contents up to 44.65% from 46.54%. However, drying turmeric slices in MVD will not encounter this reduction, as it operates at ambient conditions, and the carbohydrate content was about 71.98%. Yusufe *et al.*, [54], found that when drying tomatoes at 70 and 80°C for 7 and 8 hours. Higher temperature and longer drying time resulted in greater carbohydrate retention of 60.1% at 90°C for 8 hours, implying that other proximate compositions degraded with longer drying time and higher temperature. However, after MV drying for 6 hours at ambient temperature, the dried tomatoes had a higher carbohydrate content of 68.1%. The increase in carbohydrates is primarily attributed to the reduction in protein content, due to denaturation (refer to section 4.4.3). The carbohydrate content of dried commodities represents the residual mass from other macronutrients, so its increase correlates with a decrease in other nutrients during drying. Likely, the lower ash content of cardamom, which is below the standard requirement, can be linked to its higher carbohydrate content of 62.78%. Overall, MV drying does not have a negative impact on the carbohydrate content of the three dried commodities.

## 3.5 Micronutrient Analysis

### 3.5.1 Vitamin C Analysis

Vitamin C belongs to the water-soluble class of vitamins and has a key role as an antioxidant that protects the body's cells from damage. It is also known as "Ascorbic acid," which is found in certain fruits and vegetables [55]. The impact of MV drying on the vitamin C content of the selected commodities is represented in Table 3. The vitamin C content in the turmeric after MV drying was found to be 4.30 mg/100g. This is relatively higher than the turmeric dried in the oven at 65°C, which was 1.947 mg/100g [56]. Among various drying methods, MV drying

demonstrated superior retention of vitamin C in tomatoes, with the proportion of 48.40 mg/100g whereas the tomatoes exposed to vacuum drying at 75°C, hot air drying at 75°C with an air velocity of 1 to 2 m/s, and freeze drying retained only 3.605 mg/100 g, 10.16 mg/100 g, and 41.155 mg/100 g of vitamin C, respectively [57]. This comparison reveals that vitamin C is highly sensitive to heat, and its degradation can be correlated to the loss of colour and quality of agricultural produce. This is because L, a, and b values of the turmeric and tomatoes were significantly higher than the respective commodities dried in other methods (Refer to section 4.2). As heat generation is completely limited during MV drying of the selected commodities, loss of vitamin C is minimized.

### 3.5.2 Mineral Content

Minerals are inorganic substances found in food that the human body requires for proper development and functioning. They are essential micronutrients because deficiencies in specific minerals can lead to anemia, cardiovascular disease, osteoporosis, and other health problems [58]. Table 3 reveals the mineral concentration of the MV dried commodities. Drying operation increases the mineral concentration in agricultural commodities by increasing the dry matter content [59]. Nevertheless, MV drying excels over other drying methods in preserving the minerals in the selected commodities. This is because the sodium content of the turmeric slices after MV drying is significantly higher at 513 mg/kg, compared to only 7.060 mg/kg after oven drying at 65°C [56]. Also, the MV drying of tomatoes resulted in a remarkable potassium content, with a concentration of 23411 mg/kg. In comparison, the potassium concentrations in tomatoes dried by freeze-drying, vacuum drying, and hot air drying at 75°C were lower, at 19863.60 mg/kg, 17963.3 mg/kg, and 17821.30 mg/kg, respectively [58]. One possible reason could be the vacuum environment in MV drying, which likely minimizes mineral oxidation, but the exact mechanism needs to be investigated. Alternatively, MV drying appears to be less effective in preserving calcium content in cardamom.

**Table 3.** Impact of MV drying on the micro-nutritional composition of selected commodities

Nutritional Composition	Turmeric slices	Tomato slices	Cardamom
Vitamin C (mg/100g)	4.30	48.40	7.40
Minerals (mg/kg)	Sodium: 513.00	Potassium: 23411.00	Sodium: 1069.00 Calcium: 264.00
Curcumin (%)	2.40	n.d	n.d
Lycopene (mg/100g)	n.d	40.27	n.d

n.d: Not detected

For instance, the calcium content of air-dried cardamom with a moisture content of 8.51% was 1098.70 mg/kg [60]. This is significantly greater than the calcium content of MV dried cardamom (264.00 mg/kg). Furthermore, cardamom with a moisture content of 7.52% was found to contain 6197.1 mg/kg of calcium [61]. Thus, MV drying is effective in retaining sodium and potassium, while less effective in retaining calcium in the selected commodities.

### 3.6 Bioactive Compounds Determination

#### 3.6.1 Curcumin Content in Turmeric Slices

Curcuminoid is the major phenolic compound found in turmeric, commonly known as "curcumin." It is a non-polar compound with antioxidant activity and serves as a natural coloring agent in the food industry [62]. The curcumin content in turmeric rhizomes varies by region and variety, ranging from 0.06% to 6.02% (dry weight), while the commercial variety in India has a curcumin content between 0.06% and 5.09% [63]. Thermal degradation of curcumin occurs in two stages at temperatures above 60°C, as it is sensitive to heat [64]. For example, the curcumin content of infra-red assisted hot air (IRHA) dried turmeric increased from 0.70% to 4.39% at 60°C, but decreased to 3.84% at 70°C [29]. Meanwhile, the curcumin content of the MV dried turmeric is only 2.4% (Table 3), which is within the acceptance limit set by IS 3576:2010 (not less than 2.0%) [65]. However, MVD takes only 3 hours to complete the drying operation, while IRHA takes about 8 hours. Different variety of turmeric collected from Indian cultivators, namely Salem, Krishna, and Thekurpetha, was dried in the cabinet dryer operated at  $60 \pm 2^\circ\text{C}$ , and the curcumin content was 5.04, 2.75, and 2.80%, respectively [66]. This implies that, though the curcumin content of turmeric slices varies by variety, it must be within an acceptable range.

#### 3.6.2 Lycopene Content in Tomato Slices

Lycopene is a heat-sensitive bioactive pigment found abundantly in tomatoes, giving their characteristic red-to-yellow colour to the foods [67]. Its retention and stability largely depend on the processing temperature [68]. After hot air drying at 40°C and 60°C, lycopene degradation reached 54%, leaving only 1.2 mg/100g in dried tomatoes compared to 2.59 mg/100g in fresh tomatoes. On the other hand, MW drying at the power of 50%, 75%, and 100% resulted in significantly higher lycopene concentration in tomatoes, ranging between 4.4 mg/100g and 5.32 mg/100g [69]. Even more impressive, MW combined with vacuum drying led to a remarkable lycopene retention of 40.27 mg/100g, as observed in this study (Table 3). This striking difference can be attributed to the volumetric heating effect of electromagnetic waves in MW drying. By reducing drying time and minimizing heat exposure, MV drying helps preserve heat-sensitive compounds [70]. Moreover, the low-oxygen environment created during vacuum drying plays a crucial role in preventing oxidation and keeping the pigment intact.

## 4. Conclusion

The evaluation of the MVD in drying turmeric slices, tomato slices, and cardamom demonstrated greater drying efficiency. The process resulted in shorter drying times, reduced energy consumption, and better retention of nutritional quality, including key micronutrients like vitamin C, Curcumin, Potassium, and Calcium. The dried products maintained high-quality characteristics, such as color and texture, making them more desirable for consumption and storage. However, the initial cost of equipment remains a barrier to scaling up the process. Despite this, MVD offers a more sustainable, efficient, and high-quality alternative to traditional drying methods in food processing and other industries.

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K. Andrya Antony: Methodology; Formal analysis; Investigation; Data Curation; Writing - Original Draft; Visualization. Monica Velusamy: Visualization; writing- Original Draft. L. Muthumanikandan: Formal analysis; Validation; Data Curation. Venkatachalapathy Natarajan: Supervision; Project administration. Mahendran Radhakrishnan: Conceptualization, Validation, Writing - Review & Editing, Supervision, Project administration, funding acquisition.

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