

Article

Dynamic Temperature-Responsive MW Pulsing for Uniform and Energy-Efficient Plant-Based Food Drying

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Abstract

This study conducts a simulation-based approach to improve microwave (MW) convective drying using a temperature-responsive pulse ratio (TRPR) method. Traditional fixed-time pulse ratio (TimePR) techniques often result in uneven heating and reduced product quality due to uncontrolled temperature spikes. To address this, a physics-based model was developed using COMSOL Multiphysics 6.3, executed on a high-performance computing (HPC) platform. The TRPR algorithm dynamically adjusts MW ON/OFF cycles based on internal temperature feedback, maintaining the maximum point temperature below a critical threshold of 75 °C. The model geometry, food materials (apple) properties, and boundary conditions were defined to reflect realistic drying scenarios. Simulation results show that TRPR significantly improves temperature and moisture uniformity across the sample. The TRPR method showed superior thermal stability over time-based regulation, maintaining a lower maximum COV of 0.026 compared to 0.045. These values are also well below the COV range of 0.05–0.26 reported in recent studies. Moreover, the TRPR system maintained a constant microwave energy efficiency of 40.7% across all power levels, outperforming the time-based system, which showed lower and slightly declining efficiency from 36.18% to 36.29%, along with higher energy consumption without proportional thermal or moisture removal benefits. These findings highlight the potential of the temperature-responsive pulse ratio (TRPR) method to enhance drying performance, reduce energy consumption, and improve product quality in microwave-assisted food processing. This approach presents a scalable and adaptable solution for future integration into intelligent drying systems.



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Keywords: microwave-assisted drying; apple slices; heating nonuniformity; intermittent drying; temperature-responsive pulse ratio (TRPR); energy consumption

1. Introduction

Drying plays a critical role in extending the shelf life of perishable foods, including fruits and vegetables, while retaining their quality. However, traditional food drying methods—particularly convection drying—often present challenges such as high energy consumption, prolonged drying times, and difficulty in maintaining product quality. In response to these issues, researchers have been exploring innovative drying techniques to enhance efficiency and preserve food quality. Microwave (MW) technology has emerged as a promising alternative due to its energy efficiency and rapid drying capabilities, enabled

by its ability to generate heat volumetrically [1]. MW energy can penetrate materials until it reaches moisture, where it interacts with water molecules. This interaction causes the dipolar water molecules to oscillate rapidly, generating heat throughout the material in a volumetric manner. This mechanism is particularly effective for heating water, as its polar nature makes it highly responsive to MW energy, resulting in efficient and uniform heating [2].

Despite its advantages, significant challenges still hinder the large-scale industrial application of MW heating. One of the primary obstacles is uneven heating, which can lead to several issues. These issues include non-uniform moisture distribution, the formation of hot and cold spots, and localized heating concentrations. Such inconsistencies can compromise product quality, reduce process efficiency, and pose safety risks, making it challenging to implement microwave (MW) heating reliably at an industrial scale [3,4]. These include non-uniform moisture distribution, the formation of hot and cold spots, and localized heating concentrations. These inconsistencies can compromise product quality, process efficiency, and safety, making it difficult to implement MW heating reliably at an industrial scale [1,5–7].

To mitigate this issue, one proposed solution involves intermittent MW application in conjunction with convective heating [2]. Many studies have discovered intermittent heating methods, often achieved by altering the conditions of heated air. The convenient use of MW [1], radiofrequency [8], and ultrasound [9] has allowed researchers to use secondary energy sources intermittently.

Microwave-assisted convective drying (MW-CD) has emerged as a highly efficient technique for moisture removal, combining the rapid volumetric heating of microwaves with the surface-level drying effects of hot air. This hybrid approach offers significant advantages in terms of drying speed, energy efficiency, and product quality retention [10]. A critical aspect of advancing MW-CD technology lies in understanding and modeling the drying kinetics that govern the rate and mechanism of moisture migration within the material.

Drying models used in this context range from empirical formulations, based on experimental curve fitting, to more advanced multiscale approaches that capture the complex interactions of heat and mass transfer across different spatial and temporal scales [11]. Empirical models are often favored for their simplicity and ease of implementation, but they may lack predictive power under varying conditions. In contrast, multiscale models incorporate physical principles and computational simulations to describe moisture diffusion, internal temperature gradients, and structural changes during drying, offering deeper insights into process optimization.

Recent research has emphasized the importance of integrating heat and mass transfer modeling to improve drying uniformity and energy utilization. These models are increasingly being used to simulate drying behavior under different microwave power levels and airflow conditions, enabling better control over thermal profiles and moisture removal rates. As MW-CD systems become more sophisticated, the role of accurate and scalable modeling becomes essential for designing efficient drying protocols and ensuring consistent product quality in industrial applications [12].

A continuous MW energy supply to food materials results in an uneven EMF distribution and causes the development of hot and cold spots. This uneven temperature distribution results in inefficient heating and poor food quality. Two approaches are typically used to address these challenges. One involves the incorporation of a rotating turntable and the optimization of the shapes and sizes of food materials. The second approach focuses on the optimization of MW power, frequency, number of waveguides, application of reflective materials, and the combination of different drying techniques [13,14].

To minimize this non-uniformity, intermittent application of MW can be an effective option. Successive heating distribution and redistribution allow the material to reach thermal uniformity, which eventually maintains the expected range of temperature within the food materials [15]. This intermittent MW convective drying (IMCD) allows periodic use of MW energy by turning ON and OFF the magnetron with predetermined or dynamically controlled ON/OFF ratio. However, these improvements often come at the cost of excessively high temperatures during the MW ON periods, sometimes exceeding 100 °C, which can negatively impact product quality, especially for heat-sensitive materials.

During the ON period, MWs are generated and applied to the drying material, causing the moisture inside the material to heat and evaporate. During the OFF period, the MW source is deactivated, allowing the material to undergo a tempering phase. During this phase, the moisture inside the material redistributes toward the surface due to concentration gradients. This redistribution reduces the temperature difference within the drying material, resulting in improved product quality. Controlled switching between the heating and tempering periods allows heat redistribution, reduces overheating, and promotes more uniform heating. This method prevents extreme temperature variations by ensuring better energy management during the drying process. Most of the literature on intermittent MW drying reports the use of a constant time-based ON/OFF approach, where MW energy is applied in fixed-duration pulses followed by rest periods [16–18]. The ratio of total cycle (ON + OFF) and MW ON time is termed as pulse ratio PR.

While constant time-based pulse ratio (timePR) strategies in MW convective drying are effective in reducing overall drying time, they often lead to excessive temperature buildup, which can significantly deteriorate product quality. For instance, at a PR of 3 (e.g., 30 s ON and 60 s OFF), the average drying temperature has been observed to exceed 90 °C, with peak temperatures occasionally surpassing 100 °C [19]. Such elevated temperatures can cause thermal degradation, including discoloration, nutrient loss, and texture damage in heat-sensitive food products. Despite this, the literature rarely reports the maximum temperature reached during IMCD cycles, focusing instead on average sample temperatures. This oversight neglects the importance of monitoring and controlling peak temperatures to ensure uniform and safe drying conditions across the entire sample [18].

Additionally, pulse ratios (PRs) used in prior studies have generally been selected through a trial-and-error approach [18,20]. This method is highly empirical and specific to the sample shape, size, MW power level, and even the air velocity used. Consequently, a new set of PRs must often be determined for each unique drying setup, limiting the generalizability and scalability of the approach [21]. Moreover, due to the volumetric nature of MW heating, the highest temperatures do not always occur at the surface, but often develop internally, making surface-based temperature control insufficient. This highlights the need for more advanced control strategies, such as mathematical modelling, to predict internal temperature profiles and determine realistic, adaptive pulse ratios that balance drying efficiency with product quality preservation.

Despite the widespread use of constant timePR strategies in microwave convective drying, current IMCDs are limited by uncontrolled internal temperature spikes, empirical PR selection, and inadequate monitoring of volumetric heating effects. These gaps hinder drying uniformity and compromise product quality, especially in heat-sensitive materials. This study addresses these limitations by introducing a temperature-responsive pulse ratio (TRPR) approach, which utilizes real-time thermal feedback to dynamically regulate microwave application.

This study presents a comparison between timePR and the TRPR MW application, focusing on their effects on drying temperature profiles and drying uniformity. Unlike conventional approaches that rely on fixed ON/OFF cycles, this study incorporates volumetric

temperature monitoring to identify internal hot spots often overlooked in surface-based control methods. By integrating this internal temperature data, the study aims to determine the optimum MW application strategy that balances drying efficiency with product quality preservation. This approach offers a more realistic and adaptive framework for MW-convective drying, particularly for heat-sensitive food materials. The findings of this study can enable better temperature uniformity, minimize quality degradation, and reduce the need for extensive preliminary testing when processing new materials. This can streamline process development, lower energy costs, and facilitate the broader adoption of IMCD in sectors such as food processing, pharmaceuticals, and biomaterials.

2. Problem Formulation and Simulation Approach

The MW-assisted drying model for apple slice involves solving the electromagnetic field (EMF) distribution within both the MW oven cavity and the waveguide. The resulting EMF is coupled with heat and mass transfer equations within the food domain to predict drying kinetics and temperature distribution. The MW-induced heat generation is computed based on the electric field distribution, which is derived from Maxwell's equations.

In developing the mathematical model for intermittent MW-convective drying, the following assumptions were made:

- Initial temperature and moisture content within the apple slices are uniform;
- The water vapor pressure is equal to the equilibrium vapor pressure according to the sorption data of the product;
- The thermo-physical and dielectric properties varied with the moisture content of the sample;
- Uniform electric field distribution exists around the sample, and the electric field is normal to the surface;
- The water flux is caused only by diffusion, considered by an effective diffusion constant.

2.1. Model Development

The schematic of the computational domain showing the drying chamber, position of magnetrons, position of the samples, and intermittent MW convective drying (IMCD) approaches are presented in Figure 1.

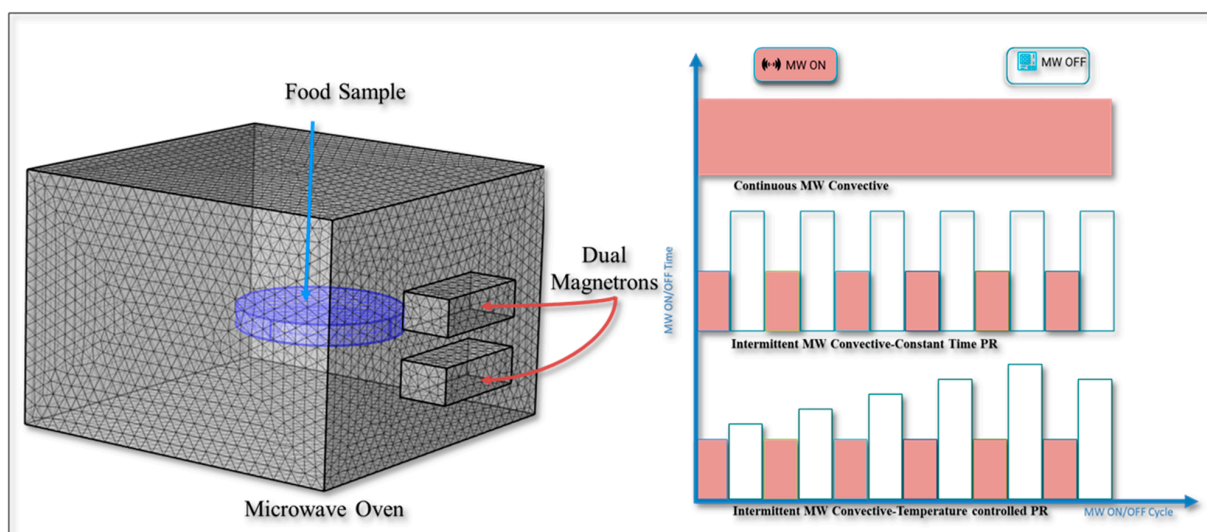


Figure 1. Simulation domain and different strategies of MW application along with convective drying.

In the simulation model, a food sample was placed centrally within the MW cavity to receive consistent exposure to both MW radiation and convective airflow. Four drying modes were employed: (i) convective drying, (ii) continuous MW convective drying (CMCD), (iii) intermittent MW convective drying with timePR, and (iv) intermittent MW convective drying with TRPR. In CMCD, MW energy was applied continuously throughout the drying process. In timePR IMCD, MW energy was alternated between ON and OFF states at fixed time intervals, maintaining constant PR. In TRPR-IMCD, the ON/OFF cycles were dynamically controlled based on the set volume maximum temperature of the sample, with MW energy turned off once a set temperature threshold was reached.

To simulate IMCD, we incorporated convective drying at 60 °C and intermittently deployed two 100–500 W magnetrons for MW heat generation. MWs enter the drying chamber via rectangular waveguides situated on different sides. In this study, we developed and simulated a mathematical model incorporating electromagnetic principles using Maxwell's equations, alongside simultaneous heat and mass transfer phenomena.

2.2. Governing Equations

To model IMCD, a set of coupled equations is used to represent how microwaves, heat, and moisture interact during the drying process. Maxwell's equations of EMF distribution describe how electromagnetic fields are distributed within the microwave cavity and waveguides. These fields are then linked to heat transfer equations that account for both microwave-induced internal heating and external convective heating. Additionally, mass transfer equations are used to model how moisture moves from inside the food to its surface. Together, these equations allow for the accurate prediction of drying rates and temperature profiles during IMCD.

The heat transfer equation is based on the Fourier law of heat transfer:

$$\rho_p C_p \frac{\partial T}{\partial t} = \nabla \cdot (k_{eff} \nabla T) + \dot{Q}_{mic} \quad (1)$$

where $\dot{Q}_{mic}$ is electromagnetic heat generation ($\frac{W}{m^3}$). Maxwell's equations provide the electromagnetic field at any point in the computational domain which can be written as [22]:

$$\nabla \times \frac{1}{\mu_r} (\nabla \vec{E}) - \left(\frac{2\pi f}{c} \right)^2 (\epsilon' - i\epsilon'') \vec{E} = 0 \quad (2)$$

where $\vec{E}$ is the electric field strength (V/m), f is the MW frequency (Hz), c is the speed of light (m/s), ϵ' , ϵ'' , μ_r are the dielectric constant, dielectric loss factor, and electromagnetic permeability of the food sample, respectively. The heat generation equation can be expressed as follows:

$$Q_{mic} = \pi f \epsilon_0 \epsilon'' |\vec{E}|^2 \quad (3)$$

To enable IMCD, a specialized intermittency function is employed. This function is then multiplied by the heat generation term within the energy equation, effectively capturing the intermittent nature of the MW heat source.

Microwave heating was modeled using Maxwell's equations of EMF distribution, and the resulting heat (Q_{MW}) was transferred to the heat transfer phenomena.

To implement the TRPR algorithm, two temperature thresholds were defined: a maximum temperature (T_{max}) and a minimum temperature (T_{min}). Microwave power was turned ON when the internal temperature was below T_{max} , and OFF when it exceeded this limit. A conditional variable (MW_{switch}) was used to control the heat source:

$$Q_{mic} = MW_{switch} \times Q_{MW}$$

This allowed real-time adjustment of microwave ON/OFF cycles based on internal temperature feedback, improving drying uniformity and preventing overheating. It is worth mentioning that the literature presents inconsistent definitions of intermittent MW application. Some define it as the ratio of total time to MW ON time, while others use the ratio of MW ON time to OFF time [23]. A major drawback of these definitions is the lack of clarity regarding the actual MW ON duration, which is critical for process reproducibility and comparison. For instance, a setting of 15 s MW ON with PR 11 (1:10) corresponds to 15 s ON and 150 s OFF. However, the same PR 11 could also result from 30 s ON and 300 s OFF, highlighting the importance of clearly reporting MW ON time alongside PR. To address this, our study defines intermittent MW application by specifying both the pulse ratio (PR) and the MW ON time.

To maintain an average controlled temperature of 60 °C, a volumetric temperature controller has been configured with an ON setpoint of 70 °C and an OFF setpoint of 75 °C. Although the target average temperature for drying is 60 °C, the system uses a volumetric temperature controller that operates within a specific range to maintain this average.

The set temperature in this study refers to the maximum point temperature within the sample domain during microwave drying, not the average temperature. The ON and OFF setpoints of 70 °C and 75 °C, respectively, are intentionally higher than the target average temperature of 60 °C to account for the natural temperature gradients that develop during volumetric microwave heating. Since these thresholds are based on localized point measurements, they help prevent the formation of internal hotspots without significantly affecting the overall average temperature. This approach ensures better control over thermal distribution while maintaining product quality.

The mass transfer equation is developed using Fick's law of diffusion, as defined [24]:

$$\frac{\partial c}{\partial t} = \nabla \cdot (-D_{eff} \nabla c) \quad (4)$$

where c is the instantaneous sample moisture concentration ($\text{mol} \cdot \text{m}^{-3}$) and D_{eff} is the effective moisture diffusivity ($\text{m}^2 \cdot \text{s}^{-1}$):

2.3. Input Parameters and Boundary Conditions

The initial and boundary condition for heat transfer is given by Equations (5) and (6), respectively:

$$T = T_i \quad (5)$$

$$-(k_{eff} \nabla T) = h_T (T - T_{amb}) + h_m \frac{(p_{v,eq} - p_{v,air})}{RT} \lambda M_w \quad (6)$$

The initial and boundary condition for the mass transfer equation is given by Equations (7) and (8), respectively:

$$c = c_0 \quad (7)$$

$$(-D_{eff} \nabla c) = h_m \frac{(p_{v,eq} - p_{v,air})}{RT} \quad (8)$$

The input parameters for the model are represented in Table 1. Apart from the study-specific parameters, the transport parameters can be found in the literature [1]:

Table 1. Input parameters of the IMCD model.

Parameter	Value	Reference
Sample diameter, Dia_s	40 mm	This work
Sample thickness, Th_s	10 mm	This work
Initial temperature, T_0	30 °C	Room temperature

Table 1. Cont.

Parameter	Value	Reference
Moisture content, wet basis	0.87	Calculated
Drying air temperature, T	333 K	This work
Universal gas constant, R	8.314 J mol ⁻¹ K ⁻¹	
Molecular weight of water, M_w	18.016 g mol ⁻¹	[25]
Latent heat of evaporation, h_{fg}	2.26×10^6 J kg ⁻¹	[25]
Binary diffusivity, D_{va}	2.6×10^{-6} m ² /s	[26]
Ambient vapor pressure, $p_{v,air}$	2992 Pa	Calculated
Heat transfer coefficient, h_T	16.746 W/(m ² K)	Calculated
Mass transfer coefficient, h_m	0.017904 m/s	Calculated
MW power, P	100–1000 W	This study

The equilibrium vapor pressure, $p_{v,eq}$, is obtained via the sorption isotherm of apple given by [27] as:

$$p_{v,eq} = P_{v,sat}(T) \exp\left(-0.182M_{db}^{-0.696} + 0.232e^{-43.949M_{db}}M_{db}^{0.0411}\ln[P_{sat}(T)]\right) \quad (9)$$

and the saturated vapor pressure of water, $P_{v,sat}$ (Pa), is a function of temperature and is given by Vega-Mercado et al. [28] as:

$$P_{v,sat} = \exp\left[\frac{-5800.2206/T + 1.3915 - 0.0486T + 0.4176 \times 10^{-4}T^2}{-0.01445 \times 10^{-7}T^3 + 6.656\ln(T)}\right]. \quad (10)$$

Thermo-Physical and Dielectric Properties of the Sample

Thermal conductivity and specific heat of apple can be expressed as a function of moisture content as shown in Equations (11) and (12), respectively:

$$k = 0.148 + 0.00493 \times MC_{wb} \quad (11)$$

$$c_p = 1000(1.4 + 3.22 \times MC_{wb}) \quad (12)$$

Moreover, the density of the apple during drying changes with moisture content. The following relationship (Equation (13)) of density with moisture content was used:

$$\rho_{apple} = 569.01 \times MC_{wb} + 415.94 \quad (13)$$

The dielectric constant, ϵ' and dielectric loss, ϵ'' , are the most important parameters that control the MW power absorption of the materials. Here we use the data of Martín-Esparza et al. [29] in a quadratic regression analysis in which the intercept of the ϵ' and ϵ'' versus M_{wb} graph was set to 0.1 to avoid numerical singularity in ϵ' and ϵ'' when M_{wb} is zero. The resulting quadratic expressions are found to be:

$$\epsilon' = 36.638M_{wb}^2 + 30.289M_{wb} + 0.1 \quad (14)$$

$$\epsilon'' = -13.543M_{wb}^2 + 26.815M_{wb} + 0.1 \quad (15)$$

2.4. Energy Consumption and Heating Uniformity Calculations

2.4.1. MW Energy Consumption

MW energy consumption during drying is calculated by first determining the volumetric power absorbed by the material over time using Equation (16). This absorbed power is then integrated across the entire sample volume to obtain the total instantaneous power

at each time step. Finally, the instantaneous power values are accumulated over the full drying period to compute the total MW energy consumed:

$$MW_{abs(t_{drying})} = \int_0^t \int Q \, dV \, dt \quad (16)$$

2.4.2. Coefficient of Variance (COV)

The COV was evaluated for sample temperature and moisture content to evaluate the uniformity at different configurations of magnetron. The COV of temperature distribution can be calculated by the following equation:

$$COV = \frac{1}{T_{avg}} \sqrt{\frac{1}{n} \sum (T_i - T_{avg})^2} \quad (17)$$

where T_{avg} , and T_i are the average temperature of samples and the temperature of selected samples at any time, respectively, n is the number of samples.

2.5. Sample Description

This study compares rectangular cuboid and cylindrical apple samples with nearly identical volumes to investigate the impact of sample geometry on MW heating. The rectangular samples have a base of 144 mm × 144 mm, while the cylindrical samples have a fixed diameter of 162.5 mm. The height of each sample is set to 5 mm, ensuring consistent volume across both geometries for a fair comparison. For the cylindrical samples, the height is adjusted accordingly to match the volume of the corresponding cuboid samples.

2.6. Simulation Strategy

Two physics-controlled meshes were employed for the domains to solve the electromagnetics, heat, and mass transfer phenomena. An extremely fine physics-controlled mesh has been deployed for heat and mass transfer physics-related domains, while a normal-sized physics-controlled mesh has been deployed for electromagnetic physics. A time stepping of 10 s was used to solve the equations. All simulations in this study were conducted using COMSOL Multiphysics 6.3 on a Dell Precision Tower high-performance computing (HPC) workstation. The HPC system is equipped with an Intel Core i7 CPU running at 3.4 GHz and 64 GB of RAM, and an NVIDIA RTX A6000 GPU, enabling efficient handling of large-scale multiphysics simulations with high spatial and temporal resolution.

3. Results and Discussions

This section presents the results of the TRPR and timePR IMCD approach in terms of temperature evolution, drying kinetics, and energy consumption. Heating and drying uniformity has been described using the coefficient of variation (COV) of temperature and moisture content over time during IMCD of different MW power levels.

3.1. Drying Kinetics Drying

3.1.1. Temperature Controlled Intermittency (MW ON and OFF) Pattern

Figure 2 presents the MW ON and OFF time patterns observed during TRPR-IMCD of rectangular and circular apple slice samples at 500 W. The analysis highlights how sample geometry influences the dynamic adjustment of OFF durations, aimed at maintaining thermal uniformity and preventing localized overheating as drying progresses.

As drying progresses, the MW OFF time increases for both sample shapes, introducing longer pauses in the later stages to prevent hot spot formation. As moisture content decreases, the risk of uneven heating rises; these OFF intervals help redistribute heat more uniformly, minimizing localized overheating. The MW ON time (brown bars) remains

relatively constant, indicating a nearly fixed energy input per cycle. In contrast, the OFF time is dynamically adjusted based on the sample's thermal response, particularly as it approaches the upper temperature limit of 75 °C.

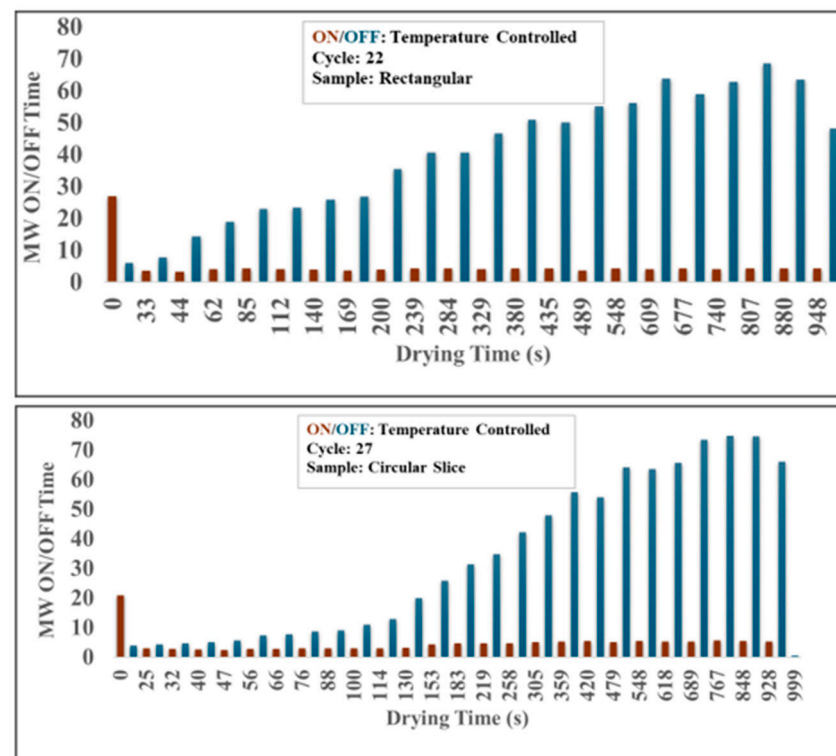


Figure 2. MW ON and OFF time patterns for rectangular and circular apple slice samples during TRPR IMCD at 500 W.

The circular slice sample, with 27 cycles, undergoes more frequent ON/OFF transitions than the rectangular sample (22 cycles), likely due to geometric differences affecting heat distribution. The implementation of temperature-responsive ON/OFF cycling in microwave-assisted drying (MWAD) represents a notable advancement in the simulation capabilities of IMCD. A recent study investigating temperature-controlled microwave-assisted freeze drying (MWFD) reveals that higher maximum drying temperatures ($T_{\max}$) significantly reduce total energy consumption but also intensify temperature non-uniformity, especially when equilibration times are shortened. Despite the intuitive expectation, variations in microwave power input did not yield statistically significant effects on either energy demand or thermal uniformity, likely due to the constrained range of tested values and the overriding influence of temperature control mechanisms [30].

Another study employed a stage-based intermittent-time control strategy, applying a fixed microwave power of 500 W with progressively increasing OFF times: 20 s for the initial 4 min, 40 s for the subsequent 24 min, and 60 s for the remainder of the drying period. This arbitrary increase in OFF time was reported to enhance drying uniformity, likely by mitigating localized overheating and promoting more even moisture distribution [18].

In contrast, our study introduces a dynamic control strategy based on real-time temperature feedback. Rather than relying on predefined OFF time intervals, the microwave OFF duration is adaptively adjusted in response to the material's surface temperature. This approach allows the drying system to respond to the thermal state of the product, thereby reducing the risk of thermal degradation and improving energy efficiency. Our simulated results also demonstrated improved drying uniformity by extending OFF periods gradually with the progression of the drying process, while maintaining consistent ON durations.

Such simulation precision underscores the growing sophistication of IMCD models in optimizing energy efficiency and product quality. In the following section, we compare the effect of dynamic Power Ratio (PR) variation, further exploring its effect on thermal regulation and drying uniformity across different sample geometries.

3.1.2. Moisture Distribution

Figure 3 illustrates a comparison of the moisture content evolution and distribution of four different methods: IMCD with constant time-based pulsed ratio, IMCD with temperature-responsive pulsed ratio, continuous MW convective drying, and conventional convective drying.

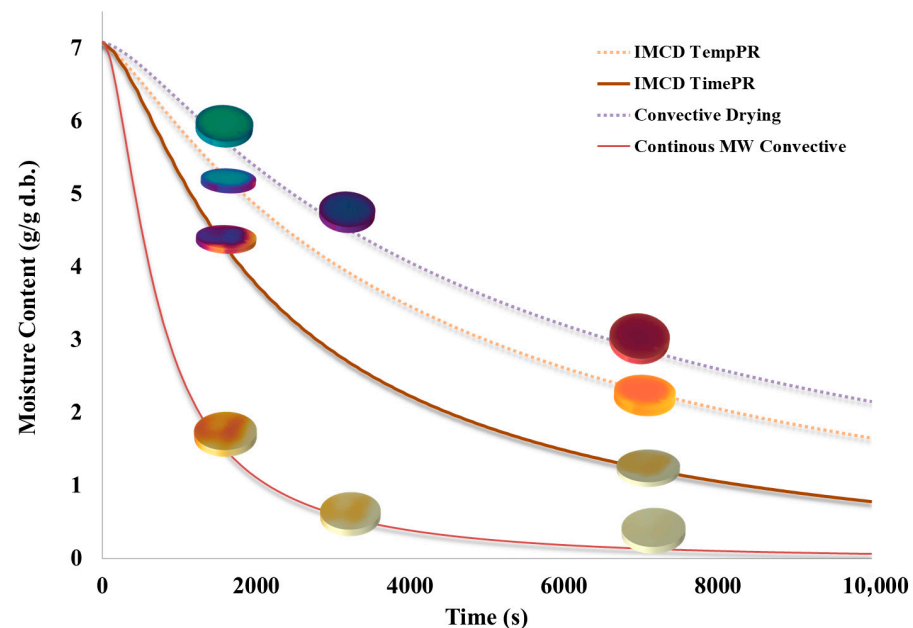


Figure 3. Moisture evolution and distribution during convective, CMW and IMCD drying.

The moisture content (dry basis) was plotted against drying time (seconds) to evaluate the drying performance of each method. As shown in Figure 3, the highest drying rate was observed in the CMCD mode, followed by IMCD-CTPR, while the slowest drying occurred under conventional convective drying. This trend highlights the enhanced drying performance of microwave-assisted methods compared to traditional convective techniques. The comparative drying kinetics observed in the time-based IMCD align closely with trends reported by the authors' IMCD experimental observation for apple [31]. IMCD-TRPR, which regulates microwave application based on temperature thresholds, exhibited moderate drying kinetics, slower than the timePR IMCD but faster than conventional convective drying. Convective drying was the slowest method, retaining the highest residual moisture content over the same drying period. This outcome is expected due to its reliance on surface heat transfer and the absence of volumetric heating, which limits drying [32].

3.1.3. Temperature Distribution and Evolution

The thermal profiles of food samples under IMCD-CTPR and IMCD-TRPR have been presented in Figure 4.

Temperature distribution has been presented for circular and rectangular samples during drying IMCD-TRPR and IMCD-timePR, at four time points, 10 min, 30 min, 1 h, and 2 h. TRPR kept the sample temperature within the safe limit ($\leq 75^\circ\text{C}$), while CTPR caused uneven heating and hot spots, especially later in drying. TRPR also produced

smoother and more uniform temperature profiles. Rectangular samples showed more uneven heating under timePR due to edge effects, while circular samples, though naturally more balanced, still improved with TRPR. Overall, TRPR helped prevent overheating and improved temperature uniformity, which is important for product quality.

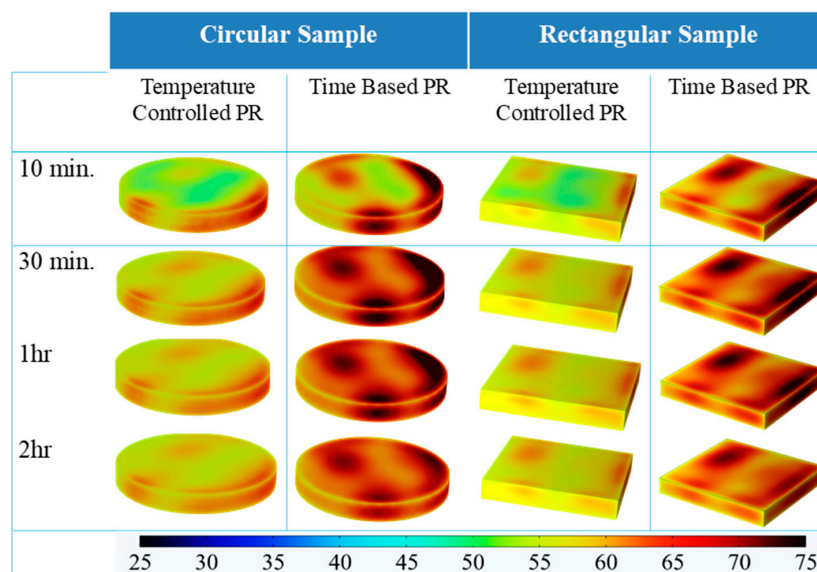


Figure 4. Temperature evolution of the sample at different MW power at constant time PR approach (In time-based pulse ratio (PR) samples, regions with temperatures exceeding 75 °C are highlighted in dark red. This color representation is used consistently across all drying strategies to maintain a uniform legend and facilitate comparison.

Figure 5 presents the maximum temperature, average temperature evolution and COV of temperature at MW power 500 W for both circular and rectangular slices under IMCD-TRPR and IMCD-timePR.

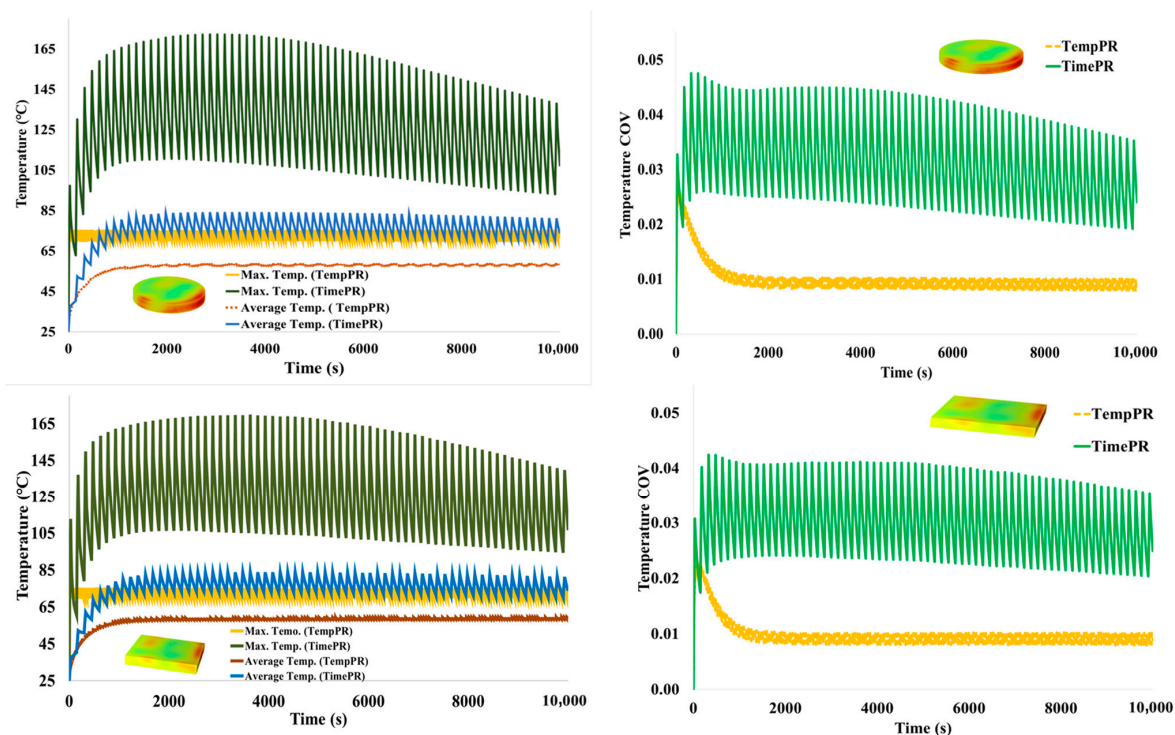


Figure 5. Maximum temperature, average temperature evolution and COV of temperature at MW power 500 W.

For both sample shapes, the IMCD-TRPR method successfully kept the maximum temperature below the critical limit of 75 °C throughout drying. In contrast, IMCD-timePR showed higher temperature peaks, increasing the risk of overheating. The average temperature under TRPR was lower and more stable, indicating better thermal control and reduced chances of heat-related quality loss.

IMCD-TRPR consistently produced lower COV values, indicating better temperature uniformity. This was especially evident in the rectangular sample, where IMCD-timePR caused significant thermal gradients, likely due to edge effects and uneven microwave field distribution. Although the circular sample naturally offers more symmetric heating, it still showed improved uniformity under TRPR, with smoother temperature profiles and reduced variability.

These findings highlight the limitations of constant timePR strategies, which fail to adapt to the sample's changing thermal state, often resulting in localized overheating and uneven drying. In contrast, TRPR dynamically adjusts microwave input based on real-time thermal feedback, ensuring both safety and uniformity. To further investigate non-uniformity, Figure 6 presents the evolution and distribution of surface and internal maximum temperatures.

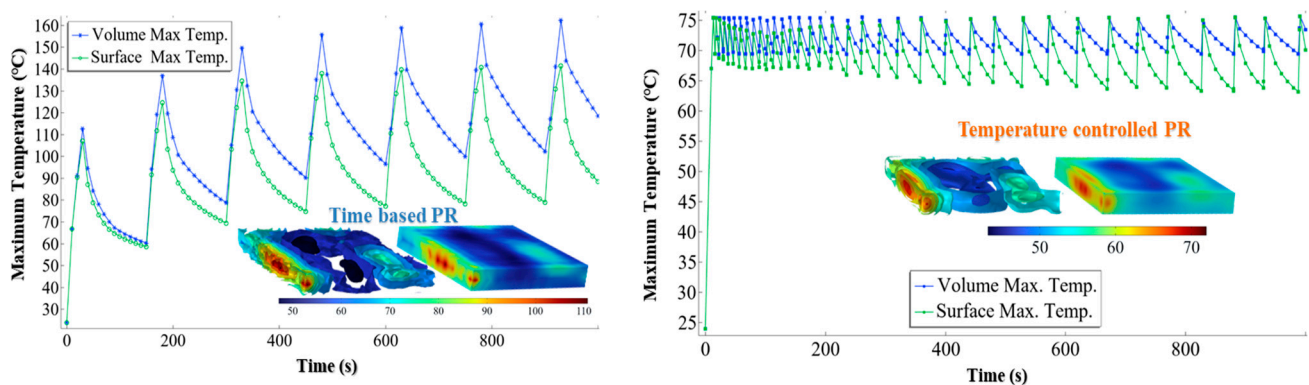


Figure 6. Volume and surface maximum temperature distribution and evolution during IMCD drying.

Under TimePR, both surface and internal maximum temperatures exhibit a cyclical pattern, marked by sharp increases followed by gradual declines. Notably, the internal maximum temperature consistently exceeds the surface temperature throughout the cycles. This persistent difference indicates the formation of internal hot spots, where the core of the material reaches significantly higher temperatures than the surface. Such thermal gradients can lead to non-uniform material properties, potential thermal damage, and reduced process predictability.

In contrast, the temperature-controlled PR method adjusts the OFF time based on real-time temperature feedback, resulting in a more stable thermal profile. Both surface and internal maximum temperatures fluctuate within a narrower range, and importantly, the surface temperature closely follows the internal temperature. This alignment indicates effective thermal regulation, minimizing internal hot spots and promoting more uniform heat distribution. A recent study investigated the optimized responsive intermittent operation (R-IO) strategy for IMCD for carrot drying where the ON/OFF cycles of microwave energy are dynamically adjusted based on arbitrary variable OFF time unlike the conventional fixed-time pulse ratio (PR) methods, they found the R-IO mode consistently maintained more stable sample temperatures compared to the fixed PR mode [18]. These findings align with our study, which demonstrates that a temperature-responsive PR strategy, such as the R-IO mode, offers superior thermal regulation compared to fixed-time PR methods.

3.2. Effect of MW Power Variation

This section presents the results of varying microwave (MW) power levels during the drying process. The analysis demonstrates how different power settings affect temperature evolution, thermal uniformity, drying kinetics, and energy efficiency. These findings highlight the importance of power modulation in optimizing drying performance and maintaining product quality under the TRPR approach.

3.2.1. Temperature Evolution and Thermal Uniformity

The influence of MW power variation was investigated under two distinct operational strategies: Time-based Power Regulation (PR) and Temperature-controlled PR. The results, presented in Figure 7, reveal significant differences in thermal behavior and uniformity across these approaches.

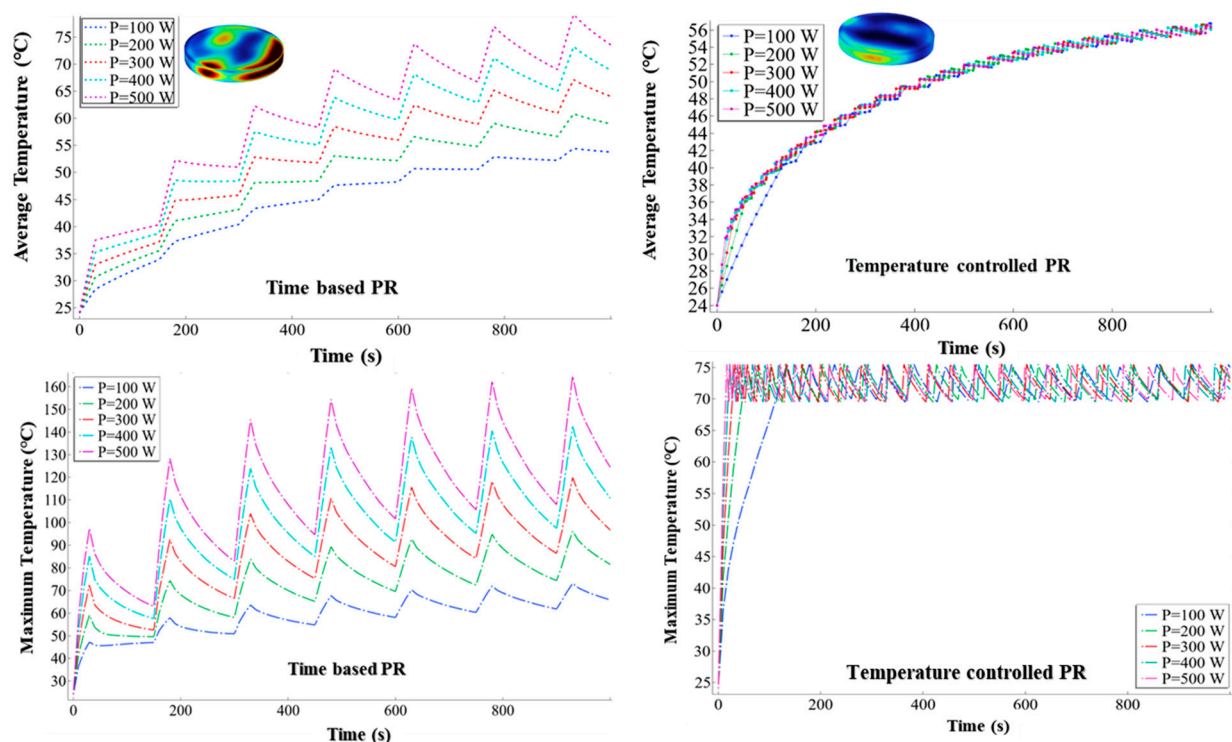


Figure 7. Maximum and average temperature evolution at different MW power during IMCD drying.

The comparative temperature profiles between timePR and TRPR microwave drying reveal distinct thermal behaviors. In the timePR mode, the drying process exhibited uncontrolled temperature escalation, with average temperatures ranging from approximately 55 °C to 75 °C, and maximum temperatures peaking above 160 °C at higher microwave power levels (e.g., 400–500 W). These fluctuations were especially pronounced during pulse cycles, leading to uneven heating and potential thermal damage. A similar trend of uncontrolled higher temperature up to 150 °C has been reported for plant-based materials during time-based PR microwave drying [33].

In contrast, the TRPR mode maintained average temperatures between 50 °C and 60 °C, and maximum temperatures consistently close to the set 75 °C, regardless of power level. This controlled intermittency allowed for effective heat redistribution during OFF periods, significantly improving thermal uniformity and reducing the risk of overheating. These findings underscore the importance of temperature-based PR modulation in achieving energy-efficient and gentle microwave drying.

Figure 8 shows the COV of temperature at different MW powers during IMCD drying. The comparative analysis of the COV between time-based and temperature-responsive PR methods reveals a clear advantage in thermal stability for the TRPR approach. Across all tested power levels (100 W to 500 W), the TRPR consistently maintained lower COV values, peaking at approximately 0.026, whereas time-based PR exhibited significantly higher variability, with COV values reaching up to 0.045 at higher power levels. This reduction in COV indicates superior thermal regulation and reduced fluctuation in temperature-controlled PR, affirming its suitability for high-power applications where precision and thermal consistency are critical. Notably, these results are substantially lower than the COV range of 0.05 to 0.26 reported in recent multi-aspect studies on microwave heating uniformity across a broader power range (100 W to 4000 W) [34–37].

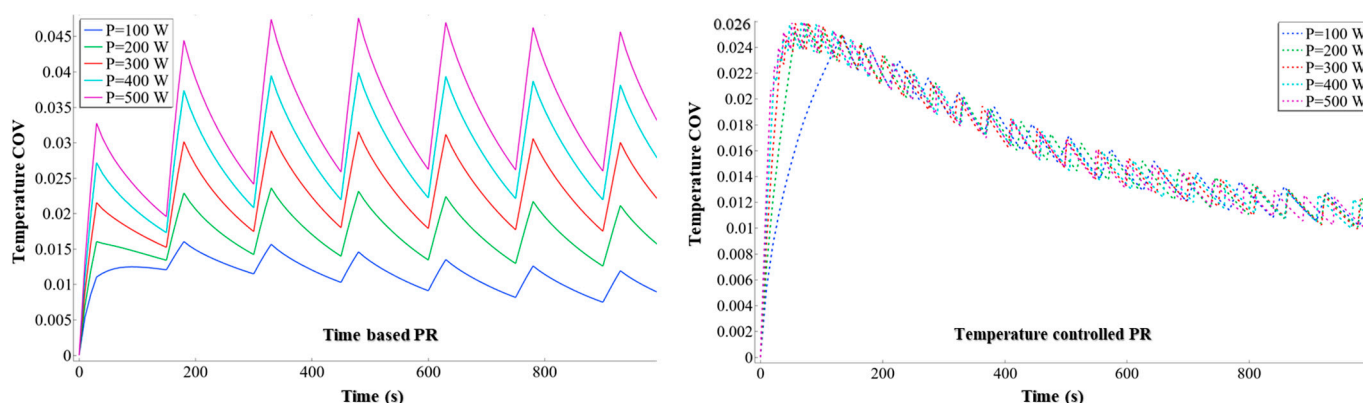


Figure 8. COV of temperature at different MW powers during IMCD drying.

The temperature-responsive PR approach employed a feedback mechanism to dynamically adjust MW power in response to real-time temperature measurements. This strategy resulted in a more gradual and stable temperature evolution, with both average and maximum temperatures converging smoothly across all power levels. Most notably, the COV values were significantly lower compared to the time-based approach, indicating enhanced thermal uniformity.

3.2.2. Drying Kinetics

The drying kinetics of the material were evaluated under two distinct power regulation strategies: time-based power regulation (PR) and temperature-controlled PR, across five power levels, and are presented in Figure 9.

The drying kinetics varied significantly with microwave power under time-based PR control. As shown in Figure 9, higher power levels (e.g., 400 W and 500 W) led to a faster reduction in moisture content, indicating faster drying. In contrast, lower power levels showed slower moisture removal. However, under temperature-responsive PR, the drying curves across all power levels were much closer, suggesting that temperature regulation helped maintain consistent drying rates regardless of power input. This highlights the effectiveness of temperature-responsive control in stabilizing drying kinetics and preventing excessive moisture loss at high power levels. A similar trend of variation of moisture content evolution during different MW power has been reported for plant-based materials during time-based PR microwave drying [33].

Figure 10 presents the COV of moisture content, which serves as a quantitative indicator of drying uniformity. The drying curves reveal that the time-based PR approach exhibits a clear trend of accelerated moisture removal with increasing microwave power levels, consistent with typical microwave drying behavior. However, this acceleration often comes at the expense of uniformity, as reflected in higher COV values at elevated power settings.

Similar trends have been reported in the drying of red pepper, where microwave powers of 597 W and 697 W under different PR conditions led to rapid moisture loss but also increased variability in drying performance [15]. However, the temperature-controlled PR approach consistently showed smoother and almost similar amounts of moisture removal for all MW power drying. This is due to efficient temperature control during IMCD-TRPR.

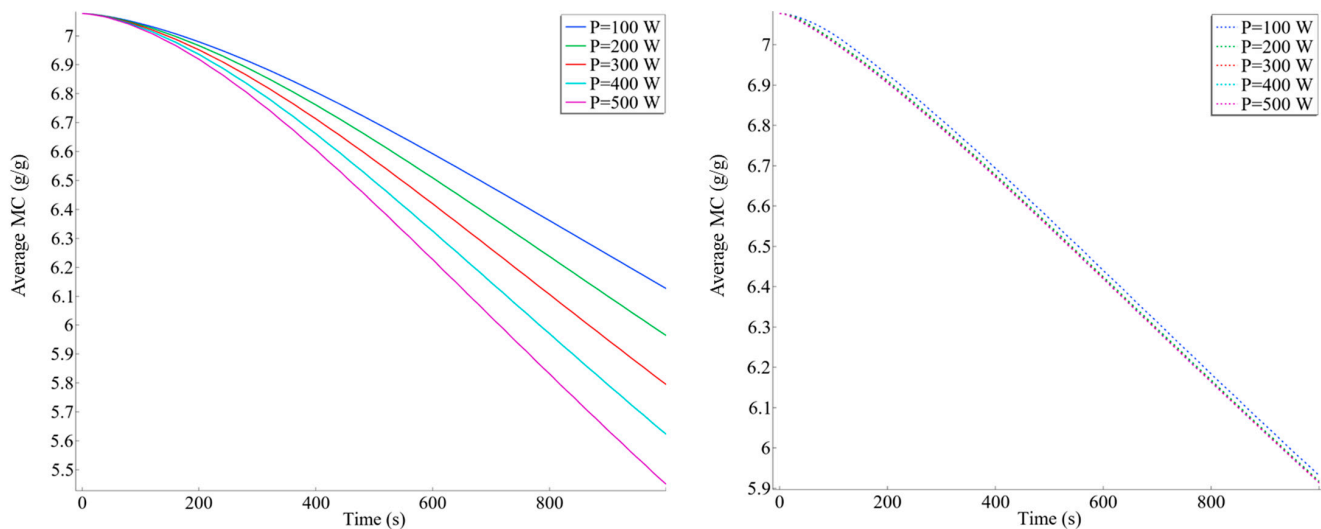


Figure 9. Moisture evolution at different MW powers of IMCD.

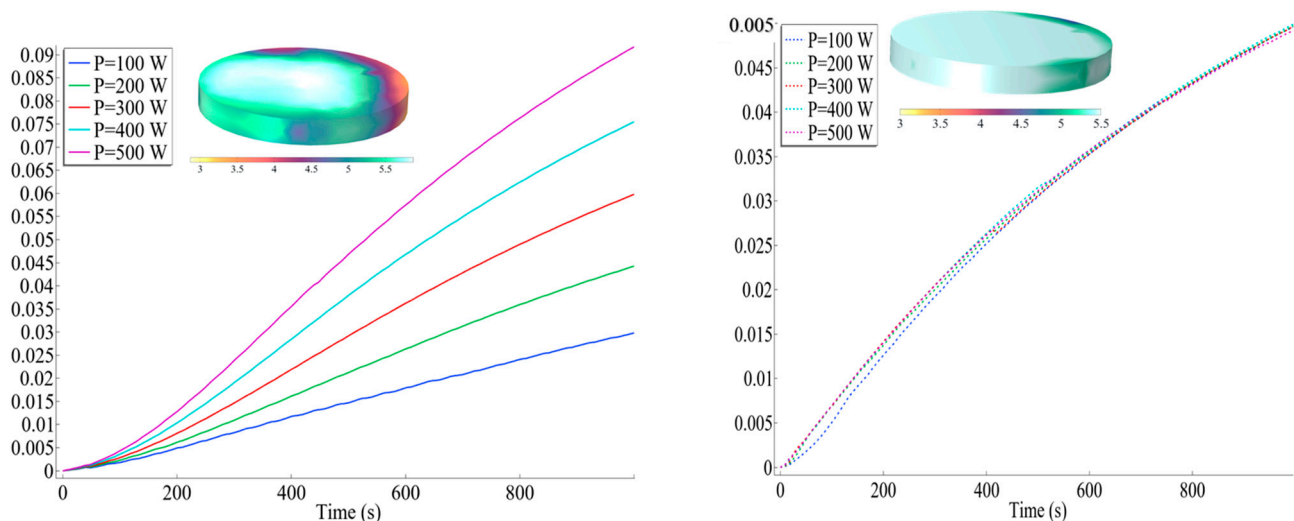


Figure 10. Moisture evolution and COV of moisture content at different MW power.

At higher power levels, the time-based PR approach showed rapid moisture reduction, but with noticeable fluctuations, suggesting uneven drying and potential overheating in localized regions. The COV values further highlight the differences in drying uniformity. The COV analysis highlights the superior uniformity achieved through temperature-controlled PR microwave drying. Under time-based PR, the final COV decreased from 0.11 at 500 W to 0.04 at 100 W, indicating that lower power levels improve uniformity. However, the variation across power levels remains considerable, suggesting inconsistent thermal performance. In contrast, the temperature-controlled PR system maintained a consistently low final COV of approximately 0.035 across all power levels. This uniformity underscores the effectiveness of temperature feedback in keeping a stable thermal environment, which helps even moisture diffusion and evaporation.

Figure 10 presents the drying kinetics and moisture uniformity under the temperature-controlled PR approach for five microwave power levels (100–500 W). Although all power levels are represented, only two distinct curves are clearly visible in each subplot due to substantial overlap among the data. This overlap indicates that the drying behavior and moisture uniformity are largely consistent across different power settings. The effectiveness of the temperature-controlled pulsed ratio (TempPR) approach lies in its ability to dynamically adjust power input based on the material's thermal state. This prevents localized overheating and helps maintain the drying temperature within an optimal range, thereby improving both energy efficiency and product quality.

3.2.3. MW Energy and PR Feasibility

Table 2 shows the energy consumption, energy efficiency, and pulse ratio pattern for both the temperature-controlled PR method and the time-based PR method.

Table 2. MW energy consumption and efficiency during IMCD approaches.

Shape	Magnetron Power (W)	Moisture Content at 1000 s	Total MW ON Time (s)	Total MW Absorption (J)	MW Energy Efficiency (%)	No of Cycle	Avg. ON Time (s)	Avg. OFF Time (s)	PR
Temperature Controlled PR	200	5.7931	518.26	42,182	0.4070	11	47	44	2
	400	5.7604	274.01	44,608	0.4070	17	16	43	4
	600	5.7501	189.15	46,186	0.4070	20	9	41	5
	800	5.7466	141.85	46,185	0.4070	21	7	41	7
	1000	5.7442	112.38	45,741	0.4070	22	5	40	9
Time-Based PR	200	6.0733	250	18,146	0.3629	7	30	120	5
	400	5.8787	250	36,271	0.3627	7	30	120	5
	600	5.6768	250	54,366	0.3624	7	30	120	5
	800	5.4731	250	72,427	0.3621	7	30	120	5
	1000	5.2664	250	90,444	0.3618	7	30	120	5

One of the most notable findings is the remarkable stability of microwave energy efficiency in the temperature-controlled PR system, which remains constant at 0.4070 across all power levels. This consistency reflects a highly optimized energy utilization strategy, where a uniform proportion of energy input is effectively absorbed by the product, regardless of the applied microwave power. In contrast, the time-based PR system exhibits lower and slightly declining energy efficiency, ranging from 0.3629 to 0.3618, indicating less effective energy use.

Moreover, the total microwave energy absorbed in the time-based system increases linearly with power, suggesting greater energy consumption without proportional improvements in moisture removal or thermal performance. The temperature-controlled system, by maintaining relatively constant energy absorption, demonstrates precise thermal targeting and minimal energy waste, reinforcing its superiority in both energy efficiency and process control.

3.2.4. Implications for Drying Uniformity and Process Optimization

The comparison across different power levels reveals a trade-off between heating efficiency and temperature uniformity. While higher MW power accelerates the drying process, it also increases thermal non-uniformity, as shown by the larger gap between average and maximum temperatures in IMCD with timePR. These temperature disparities can negatively impact product quality, leading to overheating or partial carbonization, especially in moisture-depleted regions. From a practical standpoint, these findings suggest that moderate power levels (e.g., 200–300 W) may offer a more balanced approach,

achieving sufficient drying rates while maintaining acceptable thermal uniformity. Therefore, careful optimization of power input and control strategies is essential to maximize drying efficiency and minimize quality degradation. This study shows the promise of the implementation of a temperature-controlled IMCD at an industrial scale, which involves continuous monitoring of the sample temperature and dynamic control of MW power to keep optimal drying conditions.

A key component of this system is the integration of real-time temperature sensors, such as infrared thermometers or thermal imaging cameras, positioned to accurately monitor the temperature of the drying material. These sensors send data to a control unit, which compares the measured temperature with a predefined target range. When the sample temperature drops below the lower threshold, the controller activates the magnetron to supply microwave (MW) power. Conversely, if the temperature exceeds the upper limit, MW power is turned off to prevent overheating. This feedback loop helps maintain the average sample temperature within the desired range, improving both energy efficiency and product quality. The system can be further enhanced using programmable logic controllers (PLCs) or industrial automation platforms, which enable flexible and precise control strategies.

4. Conclusions

This study introduces a novel IMCD-TRPR approach that dynamically regulates MW activation on real-time temperature feedback, ensuring optimum control based on surface and volumetric temperature. The study confirms that TRPR significantly enhances thermal uniformity of the food sample in IMCD. Unlike timePR, which led to overheating with volumetric maximum temperatures rising up to 160 °C, TRPR kept temperatures within the safe range of ≤ 75 °C throughout the drying process. The circular and rectangular samples both benefited from improved thermal uniformity under TRPR, as reflected by the consistently low coefficient of variation (0.035), compared to 0.11 at 500 W in timePR. Moreover, TRPR maintained a stable MW energy efficiency of 0.4070, independent of power level, whereas timePR efficiency declined with increasing power. These results highlight TRPR as a reliable and efficient approach for achieving controlled, uniform, and safe MW drying at an industrial scale. Its real-time temperature feedback system enhances product quality, safety, and process reliability, making it ideal for food, pharmaceutical, and biomaterial drying applications.

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Nomenclature

Symbol/Abbreviation	Description	Unit
CD	Convective drying	-
CMCD	Continuous microwave convective drying	-
IMCD	Intermittent microwave convective drying	-
MC (db)	Moisture content (dry basis)	g/g
M_e	Equilibrium moisture content	g/g
M_0	Initial moisture content	g/g
E	Energy consumption	kJ/kg
T	Temperature	°C
D_{eff}	Effective moisture diffusivity	m ² /s
PR	Pulse ratio	-
T_{max}	Maximum temperature	°C
T_{avg}	Average temperature	°C
ΔT	Temperature gradient	°C

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