Optimizing carrot slices drying: a comprehensive study of combined microwave and convective drying

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Abstract. The integration of both microwave and conventional convective drying techniques (MCD) has notably boosted the efficiency and effectiveness of carrot slice drying. This combination has led to improvements in energy utilization without harmful influence on the quality of the dried carrots. The shortest dehydration time (20 ± 1 min) and the lowest energy consumption (0.220 ± 0.011 kWh), as well as the lowest water holding capacity (705.88 ± 4.97 g H20 g dm-1), had the model of carrot slices dried on 15 seconds of microwave drying on 900W, and 7 seconds of convective drying on 180 °C. The color modification, particularly the change in pigment concentration from its natural state in fresh carrots, was a result of employing the MCD method. The drying time had no impact on color pigment characteristics, unlike the energy model. The values of red, gree and blue color are the highest for the of carrot slices dried on 9 seconds of microwave drying on 900W, and 12 seconds of convective drying on 200 °C.

1 Introduction

Drying is a fundamental unit operation with widespread applications in various industries such as food. The quest for energy-efficient and rapid drying techniques has led to the exploration of innovative approaches to improve the overall drying process. One such advancement is the combination of convective and microwave drying, which synergistically leverages the benefits of both methods to achieve enhanced drying efficiency, reduced drying times, and improved product quality [1].

Carrots rank as the second most widely eaten vegetable on a global scale. They have been recognized for their exceptional health benefits due to their rich content of phytochemical compounds like β-carotene, vitamin C, and various minerals [2]. In newly harvested crops like carrots, the existence of water speeds up the breakdown of phytochemicals due to both enzymatic and nonenzymatic mechanisms. As a result, it's essential to lower the water content by employing drying techniques. This not only enhances the material's manageability and

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reduces susceptibility to microbial deterioration but can also lead to a decrease in beneficial bioactive compounds and flavors. Consequently, the drying procedure should aim for rapid and uniform execution. [3].

Drying is the process of removing moisture or other volatile components from a material to improve its shelf life, and stability. The choice of drying method significantly influences the final product quality, energy consumption, and process duration. Traditional drying methods, such as convective (hot air) drying, are effective but may be energy-intensive and time-consuming, particularly for materials with low thermal conductivity or high moisture content [4, 5]. The microwave drying, on the other hand, offers rapid and volumetric heating, but it can lead to uneven moisture distribution and undesirable thermal gradients. The combined drying process, often referred to as hybrid or integrated drying, emerges as a promising alternative to conventional drying methods. Convective drying provides a gradual, controlled removal of moisture from the surface, preventing the formation of a moisture barrier that can impede further drying. Microwave drying contributes rapid and volumetric heating, leading to the efficient conversion of moisture into vapor [6].

The synergy between these methods allows for improved moisture migration from the interior to the surface, effectively addressing non-uniform drying issues encountered in microwave drying alone. The combined drying process presents several advantages, including reduced drying times, improved energy efficiency, enhanced product quality, and minimized heat-induced damage [1]. Applications span a wide range of materials, including agricultural products. For instance, in the food industry, combined drying has demonstrated the preservation of color, flavor, and nutritional content in fruits and vegetables, such as carrot.

The primary objective of this study was to investigate the dehydration behavior of carrot slices using a combined drying approach involving both convective and microwave methods. The aim was to comprehensively analyze the impact of this combined drying technique on various aspects, including drying kinetics, physical properties (specifically water-holding capacity), and sensory quality (with a focus on color).

2 Material and methodes

2.1 Carrot thin layer microwave/convective drying

Carrots (*Daucus carota* L.) were harvested from the Paraćin area in the Republic of Serbia (coordinates 43°49'57.7"N 21°23'20.3"E). Subsequently, they were promptly stored in a refrigerator set at 4°C, ensuring a storage duration of no more than 1 day. To prepare for the dehydration procedure, the carrots were retrieved from the freezing chamber, treated with cold water, sliced, and then left to reach equilibrium at room temperature over several hour(s).

The microwave oven (Intertronic WD900ESL25RII-2, In-put 1400 W, 230 V, 50 Hz, 1200 W Heater, 1400 W, Convection, 900 W, Output 2450 MHz) was used for the thin-layer combination of microwave and convective drying (MCD). The mass load of fresh carrot slices was 0.38 kg m^{-3} (30 g per tray), with approximately 5 mm thick carrot slices. The MCD was a discontinuous model: 2.30 (9 seconds of MW on 900W, 12 seconds of CD on 230 °C), 2.00 (9 seconds of MW on 900W, 12 seconds of CD on 200 °C) and 1.50 (15 seconds of MD on 900W, 7 seconds of CD on 180 °C). The weight of the trays was measured at intervals of 5 minutes. The drying kinetic was based on mass losses of carrot slices [1].

2.2 Modeling of thin layer microwave/convective drying

The primary water mass transfer mechanism was diffusional, considering the material deformations and shrinkage during the drying process (carrot thickness). Semi-theoretical modeling of carrots' thin-layer dehydration process is characterized by the temperature of the dehydration process, relative humidity, (hot) airspeed, moisture content, material thickness, size, and ability to determine moisture diffusivity while the fit of moisture ratio (MR) vs. drying time. The water loss (MR) could be applied and simplified to $M_t\ M_0^{-1}$ instead of the $MR = (M_t - M_e)\ (M_0 - M_e)^{-1}$, because equilibrium moisture content M_e usually is deficient and can be deleted, without a significant change in MR. The M_t and M_0 are the moisture content achieved after dehydration time t and the initial moisture content [7].

Fick's second low-diffusion model was used to describe the moisture transfer of carrot slices. The used model (Eq. 1, & 2) depends of product geometry (carrot = sphere):

$$MR = A_1 \times \sum_{i=1}^{\propto} \frac{1}{J_o^2} \times e^{-\frac{J_0^2 \times D_{eff}}{A_2}} \tag{1}$$

$$A_1 = \frac{8}{\pi^2}; \quad A_2 = 4 \times L^2 \tag{2}$$

where D_{eff} [$m^2\ s^{-1}$] is the effective moisture diffusivity, t [s] – the time, J_0 – the roots of the Bessel function, A_1, A_2 are the geometric constants, and L is the thickness of the carrot slices.

For the D_{eff} = const and t ~ ∞, the previous equations could be simplified into linear equation ln (MR) = ln (a) – k × t. The slope (Eq. 3) is equal to the constant drying k, and the D_{eff} could be calculated (Eq. 4).

$$k = -\frac{\pi^2 \times D_{eff}}{A_2} \tag{3}$$

An Arrhenius equation (Eq. 4), describes the temperature effect on D_{eff}.

$$D_{eff} = D_0 \times e^{-\frac{E_a}{R \times T}} \tag{4}$$

where E_a [kJ mol^{-1}] is the activation energy, R [8.3143 J mol^{-1} K^{-1}] – the universal gas constant, T [K] – the absolute air temperature, and D_0 [$m^2\ s^{-1}$] – the pre-exponential factor of the Arrhenius equation. The previous equations could be simplified into linear equation ln (D_{eff}) = ln (D_0) – 10^{-3} × k × $(T + 273.15)^{-1}$, and the E_a could be calculated (Eq. 5).

$$k = -\frac{E_a}{R}. \tag{5}$$

2.3 Energy consumption of thin layer microwave/convective drying

Energy input (energy consumption, E) of MCD was measured by using Prosto PM 001 (230 V, 50 Hz, 0–16 A, 2–3680 W, 0–9999 kWh, −10 ◦C to +40 ◦C, ≤85% of relative humidity, the altitude of use max 2000 m). Mathematical relationships were established between the E and the emitted CO_2 levels during MCD (1 kWh of E, approximately releases 0.998 kg of CO_2) [8].

2.4 Water-Holding Capacity of microwave/convective dehydrated carrot slices

The ability of dehydrated carrot slices to retain water, known as water-holding capacity (WHC), was evaluated. This was achieved by combining 10 g of dehydrated carrot slices with 100 mL of distilled water and allowing them to hydrate for 12 hours at room temperature. Subsequently, any excess water was removed and weighed. The measurement was expressed in grams of water per unit of dry solids. Dry matter content in the rehydrated carrot slices was determined using the gravimetric method following the guidelines outlined in the AOAC method [9].

2.5 The color of microwave/convective dried carrots

The digital camera (Triple Camera 48 MP 11.8/27 ASPH, Huawei P30 lite) and the image were processed by Adobe Photoshop Cs 21.0 (RGB and HSL method, [10]. The RGB color coordinate system relies on three primary colors: red (R), green (G), and blue (B). Additional colors are created by blending these three basic colors with varying weights. In the RGB color coordinate system, the relative value of R, G, and B are known and could be calculated for r, g, and b (the chromaticity coordinates): $r = R \times (R + G + B)^{-1}$, $g = G \times (R + G + B)^{-1}$, and $b = B \times (R + G + B)^{-1}$. RGB color images were acquired and saved in PNG format on a computer. As part of the image processing procedure, the background of the digital image was deliberately eliminated to mitigate the impact of "image noise". HSL stands for Hue, Saturation, and Lightness. Hue represents the actual color itself (measured in degrees on a circle, where 0° corresponds to red, 120° corresponds to green, and 240° corresponds to blue.), saturation determines the intensity or vividness of the color (0 % is a completely desaturated or grayscale color, and 100 % is the most vibrant, fully saturated version of that color), and Lightness refers to how bright or dark a color is (0% is completely black, 50% is the original color, and 100% is completely white).

2.6 Statistic method

RStudio 1.4.1106 program was used for the color correlation graph between the obtained independet variables (MCD parameters) and the responses of t, E, CO2, WHC and the color parameters [1].

3 Results and discussion

The initial moisture content of carrot slices was about 87.50 ± 0.64 %. The results of microwave/convective drying are shown in Table 1.

Table 1. Average values of MCD for t, E, CO_2, WHC, and E_a

Model	t (min)	E (kWh)	CO_2 (kg)	WHC (g H_20 g dm^{-1})	E_a (kJ mol^{-1})
2.30	24 ± 2	0.497 ± 0.016	0.496 ± 0.016	750.00 ± 8.51	19.97
2.00	21 ± 2	0.490 ± 0.013	0.489 ± 0.013	733.33 ± 6.74	
1.50	20 ± 1	0.220 ± 0.011	0.220 ± 0.011	705.88 ± 4.97	

The t of the MCD has a lesser role compared to the required E for the process itself. Specifically, in model 1.50, the E_{min} (0.220 ± 0.011 kWh) is needed for drying carrot slices. Considering the mathematical dependency of E – CO_2, that model will also emit a minimal amount of emitted CO_2. The MCD drying process takes the same amount of time as microwave drying at 240 W (the carrot slice thickness was 6 mm), but significantly shorter

than convective drying at temperatures up to 70 °C. In terms of energy, it requires approximately 2 times more energy compared to microwave drying at 80 W, or about 4 times more energy at 240 W [4, 6].

WHC pertains to the capacity of a dried material to retain water. In the realm of plant (vegetables, fruits) dehydration, the WHC has an impact on both the duration of drying and the extent of plant contraction during this procedure. Plants with a substantial WHC necessitate an extended drying period and might experience comparatively less contraction than plants with a lower WHC. This distinction is attributed to the higher initial moisture content of high-WHC plants, rendering their drying process more intricate. Furthermore, the selection of the drying technique and the input energy significantly influence the outcomes of WHC [1]. This statement was also confirmed during this experimental MCD drying, where model 1.50 had the lowest WHC value, likely as a result of higher microwave energy input and lower convective drying temperature. The *Saleh* experimental work showed that a higher rehydration ratio indicates a better product greatly affected by the carrot slices [2]. If we represented WHC through the rehydration ratio for MCD, we would obtain values of 0.53 for model 2.30, 0.50 for model 2.00, and 0.56 for model 1.50. These values are slightly higher compared to convective drying (0.48) in *Saleh*'s study.

The E_a illustrates the degree of sensitivity (the energy required to initiate water diffusion) of diffusivity with respect to temperature variations. A greater E_a indicates an increased susceptibility of effective diffusivity (D_{eff}) to temperature adjustments. The E_a for MCD (19.97 kJ mol^{-1} for 3 – 6 – 9 mm carrot slice thicknes dried on 35 – 50 – 70 °C) is lower that E_a for the convective drying of carrot slices (28.51 – 31.31 kJ mol^{-1}, [4] and higher than microwave drying (15.079 W g^{-1} for 5 mm carrot slices thickness, [11]). A reduction in E_a signifies enhanced efficiency in moisture diffusivity (higher D_{eff}) and an increase in moisture diffusion alongside carrot thickness. This suggests that lower E input leads to the disruption of the intermolecular bonds among the water molecules in the sample.

Figure1 and 2 show that there is an exponential and polynomial dependence of parameters d and D_{eff} in relation to t, with a high degree of correlation ($R^2 > 0.94$). These statements are in accordance with previous research [4, 6, 12]. D_{eff} quantifies how swiftly moisture permeates a substance. It's influenced by multiple aspects, encompassing material characteristics (such as thickness of carrot slices d, Figure 2), environmental temperature and humidity, and potential coatings or obstructions on the material. Generally, at elevated temperatures and energy inputs, the effective moisture diffusion coefficient tends to be greater, since heightened temperatures prompt swifter movement of moisture molecules. From Figure 2, it can be concluded that most efficient MCD model is 1.50, likely due to the longer exposure to microwave drying (15 seconds of MD on 900 W), compared to models 2.00 and 2.30, where the exposure time is 12 seconds of MD on 900 W.

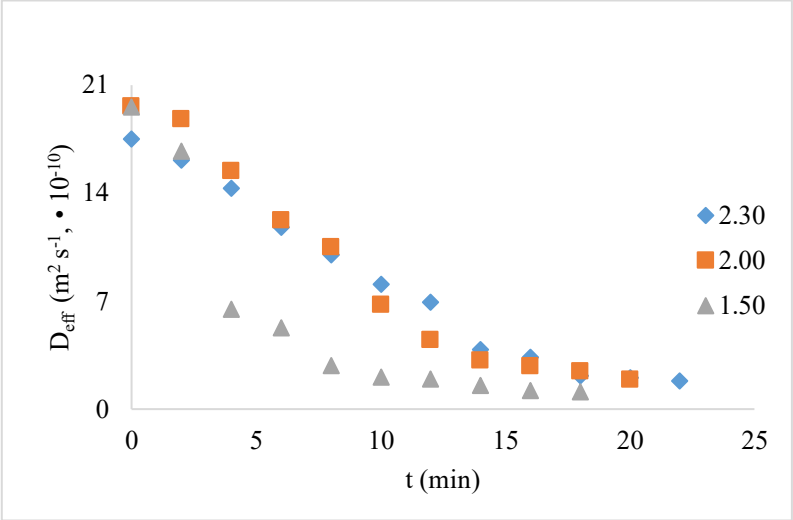


Fig. 1. The D_{eff} values as a function of t

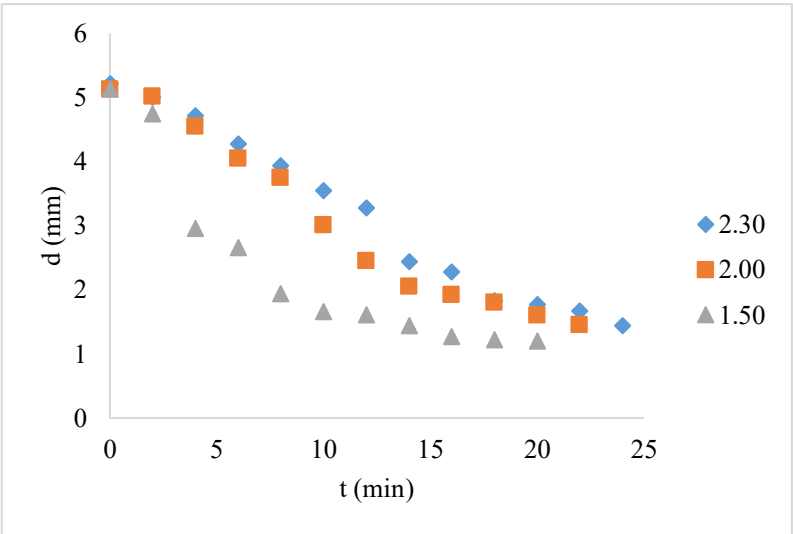


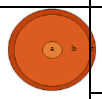
Fig. 2. The d values as a function of t

The D_{eff} primarily fluctuates based on internal factors like the product's temperature, moisture content, (micro)energy input and plant structure, as well as external factors such as the speedof the drying air, the amount of material being dried, and the thickness of the plant slices [8, 13].

Color pigment levels in carrot were assessed through the utilization of digital image processing and color analysis techniques. *Cai* et al. [14] found out that G/R and r were the prime color characteristics of some color pigments (carotenoid) content in vegetables. The experimental results (Table 2.) exhibit a minor fluctuation in H values, while S and L values demonstrated an increase in the range of 2.30 to 2.00 to 1.50. The values of R, G and B are the highest for the 2.00 model of dehydration. It could be generally concluded that the drying time t has no impact on color pigment characteristics, unlike the (energy) model. The values of r, g, b, G/R, B/R, R/G, B/G, G/B and R/B exhibit a strong correlation with the experimental findings of *Gong* et al. [9] for the freeze, microwave and cooked vacuum drying. The

alteration in color, specifically the shift in pigment content from its original state in fresh carrots, was brought about by the MCD technique. The experimental outcomes didn't establish any specific validity concerning this shift. However, it is possible to explore this transformation further using approaches like CieLab or Computer Vision System techniques, in conjunction with the already available suitable analytical methods.

Table 2. The variation of the color characteristic in different parts of carrot slices

Model	HSL/RGB model		H	S	L	R	G	B	r	g	b	G/R	B/R	R/G	B/G	G/B	R/B
2.30		a)	17.33 ± 0.58	185.00 ± 4.00	121.00 ± 2.20	223.33 ± 4.73	116.00 ± 2.81	34.00 ± 3.00	0.60 ± 0.02	0.09 ± 0.01	0.09 ± 0.02	0.52 ± 0.02	0.15 ± 0.03	1.93 ± 0.09	0.29 ± 0.04	3.49 ± 0.55	6.76 ± 1.42
		b)	13.00 ± 1.00	178.67 ± 3.02	119.00 ± 2.94	216.33 ± 3.81	95.67 ± 2.14	36.33 ± 1.07	0.62 ± 0.02	0.10 ± 0.01	0.10 ± 0.02	0.44 ± 0.02	0.17 ± 0.04	2.27 ± 0.12	0.38 ± 0.08	2.74 ± 0.60	6.24 ± 1.59
		c)	13.33 ± 3.21	160.33 ± 2.95	97.33 ± 3.72	175.33 ± 4.92	81.00 ± 1.08	34.33 ± 2.45	0.60 ± 0.04	0.12 ± 0.03	0.12 ± 0.03	0.46 ± 0.07	0.20 ± 0.06	2.22 ± 0.37	0.43 ± 0.11	2.43 ± 0.69	5.34 ± 1.34
2.00		a)	20.67 ± 0.58	187.00 ± 4.36	136.67 ± 3.02	229.00 ± 3.46	139.33 ± 3.08	47.33 ± 2.89	0.51 ± 0.02	0.18 ± 0.04	0.18 ± 0.02	0.61 ± 0.03	0.20 ± 0.04	1.65 ± 0.07	0.34 ± 0.04	3.01 ± 0.37	4.97 ± 0.81
		b)	15.33 ± 2.08	184.33 ± 4.04	114.33 ± 3.33	214.67 ± 4.01	100.00 ± 2.33	28.67 ± 4.04	0.63 ± 0.03	0.08 ± 0.02	0.08 ± 0.04	0.46 ± 0.06	0.12 ± 0.01	2.18 ± 0.28	0.29 ± 0.02	3.48 ± 0.23	7.55 ± 0.65
		c)	13.33 ± 1.53	196.67 ± 0.58	95.33 ± 2.51	182.67 ± 3.50	79.33 ± 4.43	20.33 ± 4.16	0.65 ± 0.02	0.07 ± 0.06	0.07 ± 0.01	0.43 ± 0.02	0.11 ± 0.02	2.31 ± 0.12	0.26 ± 0.04	3.97 ± 0.53	9.20 ± 1.63
1.50		a)	15.67 ± 0.58	199.67 ± 1.53	76.67 ± 2.31	207.67 ± 4.16	94.00 ± 1.73	19.00 ± 1.00	0.65 ± 0.01	0.06 ± 0.01	0.06 ± 0.00	0.45 ± 0.01	0.09 ± 0.00	2.21 ± 0.05	0.20 ± 0.01	4.95 ± 0.19	10.94 ± 0.44
		b)	13.00 ± 0.00	184.00 ± 1.73	118.00 ± 2.65	222.00 ± 3.31	91.00 ± 2.00	29.33 ± 1.53	0.65 ± 0.00	0.09 ± 0.00	0.09 ± 0.00	0.41 ± 0.00	0.13 ± 0.00	2.44 ± 0.02	0.32 ± 0.01	3.11 ± 0.09	7.58 ± 0.28
		c)	13.67 ± 1.53	186.33 ± 3.06	104.00 ± 2.65	196.00 ± 3.46	82.33 ± 3.21	24.67 ± 2.08	0.65 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.42 ± 0.02	0.13 ± 0.01	2.38 ± 0.12	0.30 ± 0.03	3.36 ± 0.34	7.98 ± 0.52
		a)	11.33 ± 0.58	135.00 ± 10.58	117.33 ± 4.16	194.00 ± 2.65	94.33 ± 9.07	55.33 ± 8.02	0.56 ± 0.03	0.16 ± 0.01	0.16 ± 0.02	0.49 ± 0.04	0.29 ± 0.04	2.07 ± 0.19	0.58 ± 0.03	1.71 ± 0.10	3.56 ± 0.53
Fresh		b)	12.00 ± 1.73	144.33 ± 4.04	121.67 ± 0.58	205.00 ± 1.73	99.67 ± 6.66	54.00 ± 3.46	0.57 ± 0.02	0.15 ± 0.01	0.15 ± 0.01	0.49 ± 0.04	0.26 ± 0.02	2.06 ± 0.15	0.54 ± 0.03	1.85 ± 0.09	3.81 ± 0.29
		c)	13.33 ± 2.08	174.33 ± 10.02	116.67 ± 12.74	210 ± 24.33	95.00 ± 16.46	37.67 ± 4.73	0.61 ± 0.01	0.11 ± 0.01	0.11 ± 0.01	0.45 ± 0.03	0.18 ± 0.02	2.23 ± 0.15	0.40 ± 0.05	2.52 ± 0.35	5.60 ± 0.60

*H – hue ; S – saturation; L – lightness; R – red; G – green; B – blue; r, g, b – the chromaticity coordinates

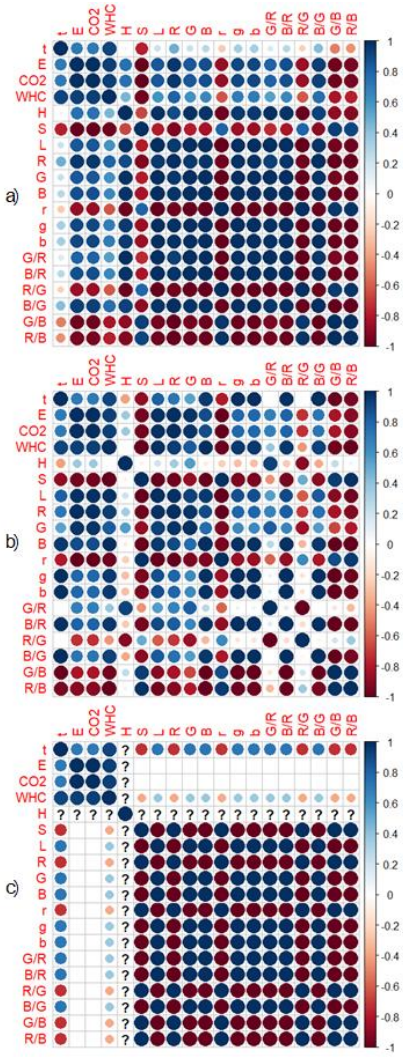


Fig. 3. Color correlation diagram between the parameters of the independent variables (MCD parameters) and the responses of t, E, CO_2, WHC and color parameters (a, b, c – part of the carrot slice, as in Table 2)

The correlation coefficients between the analyzes parameters are visually represented by the variation of the size and the lightness of the circles and using different colors (blue for positive correlation and red for negative correlation). The highest level of positive correlation (r = 0.8–1, statistically significant at $p < 0.05$), including all parts of carrot slices (a, b, c), was shown between t – WHC, E/CO_2 – WHC, R, G, B, r, g, b, R/G, G/R, and B/R, H – G, G/B and G/R, L – B/G, R – r and R/G, G – g and g/R, B – g, b and G/R, r – R/G, g – b, B/R and B/G, b – B/R and B/G. In contrast, the highest level of negative correlation, including all parts of carrot slices (a, b, c), was shown between E – r and R/G, H – L, S – g, b, B/R and B/G, L – g and B/G, R – G and G/R, G – r and G/R, B – r, G/B and R/B, r – g, b, G/R, B/R and B/G, g and b – RG, G/B and R/B.

4 Conclusions

The combined convective and microwave (MCD) drying process of carrot slices offers a novel avenue to enhance drying energy efficiency and product quality (such as color stability) across various industries. By capitalizing on the synergies between these techniques, researchers and practitioners are presented with an opportunity to revolutionize conventional drying methodologies. Continued research and development in this field will not only expand our understanding of the underlying mechanisms, but also pave the way for more sustainable and efficient drying practices.

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