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Effects of Drying Conditions on Dehydration Characteristics and Quality Attributes of Crab Apple Slices Under Continuous Microwave Drying

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Abstract: Traditional drying methods often result in significant loss of flavor, color, and bioactive components in food products. One effective method of improving the nutritional value of foods and shortening the drying process is to apply heat via continuous microwave drying. Understanding continuous microwave drying of crab apples is key to boosting efficiency and energy savings. In this study, crab apple slices were dried under continuous microwave drying and thoroughly investigated in terms of dehydration characteristics and quality attributes. The effects of drying conditions, including slice thickness (1–5 mm), microwave power (11400–19000 W), air velocity (0–2 m/s), and drying time (12–16 min) on the changes in temperature, moisture content, color, texture, total phenolic content, and microstructure were analyzed. Results showed that increased microwave power and decreased slice thickness significantly reduced moisture content; increasing air velocity reduced the temperature increase, whereas prolonging drying time decreased moisture content and increased drying temperature. As the slice thickness increased, the color values showed a decreasing trend while texture and total phenolic content increased. The application of higher microwave power resulted in changes in the overall color and texture, which decreased while the total phenolic content increased, additionally damaging the surface structure. Higher air velocity increased the color and texture while reducing the total phenolic content. Moreover, heightened air velocity may lead to more apparent structural changes. As the drying time increased, the color and hardness values decreased while the total phenolic content increased; prolonged drying times can significantly change the microstructure. To ensure the quality of the dried product, it is recommended that high microwave power, excessive air velocity, and extended drying times be avoided. Therefore, the appropriate conditions for continuous microwave drying of crab apple slices are a slice thickness of 1.5 mm, microwave power of 15200 W, air velocity of 0.5 m/s, and drying time of 13 min. This study may offer guidance for understanding and improving the continuous microwave drying of dried products, such as crab apples.

Keywords: crab apple slices; continuous microwave drying; dehydration; quality attributes; microstructure

1. Introduction

Crab apple is a small tree of the Rosaceae family, classified within the genus Malus, and is renowned for its ecological and economic importance. Crab apples are extensively found in colder regions, including North America, Europe, and East Asia [1]. The global cultivation of crab apples has grown, especially in horticultural contexts, owing to their various applications, including ornamental purposes and fruit production [2]. In China, fruits with diameters ranging from 3 to 5 cm usually mature in September and are mainly found in the provinces of Heilongjiang, Jilin, Liaoning, and Inner Mongolia, where environmental conditions are favorable to their growth [3]. The mature

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fruits exhibit a yellowish-red color and a tart-sweet flavor with a mild astringency, making them palatable and nutritious [4]. Most crab apple fruits are suitable for direct consumption or can be dried for subsequent use, except certain ornamental varieties [5]. Crab apples are rich in various nutrients and beneficial constituents, including polyphenols, fibers, terpenoids, antioxidants, and trace elements [6,7]. Moreover, these fruits are rich in vital vitamins and minerals, such as vitamins, iron, zinc, and calcium, rendering them an exceptional source of trace elements that are advantageous for overall health [8]. The components of crab apples exhibit a range of functional properties, including antioxidant, anticancer, lipid-lowering, anti-diabetic, and anti-inflammatory effects [9,10].

Studying crab apple fruits via animal models has shown they offer safeguards against cardiovascular diseases, asthma, and diabetes [11]. In addition, consuming these fruits may help reduce the risk of gastrointestinal disorders in children, including constipation, diarrhea, and dysentery [4]. Therefore, crab apples are gaining increasing recognition for their exceptional nutritional properties and pharmacological and medicinal benefits [12]. However, fresh crab apples are prone to rot and product deterioration due to a moisture content exceeding 80% (*w.b.*), which leads to decay, reduced nutritional value, and economic loss. Therefore, efficient processing methods are crucial for maintaining product quality and prolonging shelf life. Drying is a vital function in food preservation technology, reducing moisture content in food products, and has numerous uses in the food processing industry [13]. Although drying offers numerous advantages in the processing and preservation of food and agricultural goods, employing improper techniques under adverse conditions may reduce the overall quality of the final product, leading to high energy consumption and higher production expenses [14,15]. Currently, dehydrated apple slices are a popular and healthy snack for people across various age groups [16]. However, dried foods have various drawbacks, such as a significant decrease in nutritional value and sensory characteristics, such as color, texture, and taste, compared to fresh products. Therefore, selecting an appropriate drying method can help to reduce the shortcomings mentioned earlier in the dried product. Several factors influence the drying process selection, including the nature of the product, its economic value, the intended physical form and characteristics, and the desired physical shape. The drying method is required to be viable from both technological and economic standpoints.

Numerous studies have analyzed fruit drying techniques; various methods demonstrate distinct drying characteristics. Traditional methods are predominantly employed for fruit drying, which requires considerable time; this results in reduced drying speed and a heightened risk of microbial growth increase [17]. One of the most common and cost-effective methods for dehydrating products in the food industry is the hot-air cabinet, which is easy to set up and functions effectively for drying products that need prolonged, low-level drying with minimal purchase and operational expenses [18]. However, it is related to various drawbacks, including inconsistencies in the drying process through various parts of the dryer, significant heat loss throughout loading and unloading, difficulties in process control, and extended drying durations [18]. Recent advancements in innovative technologies have markedly improved the preservation of the qualitative attributes of fruits post-processing. The microwave drying technique has garnered increased attention in the food industry compared to conventional drying methods, owing to its higher energy efficiency, quicker heating rate, and reduced drying time [19]. However, microwave drying efficacy depends on the size and shape of the sample, resulting in varying impacts on the texture and sensory attributes of the dried product. Therefore, it is essential to determine the microwave drying conditions for the production of superior quality final product.

Existing research on microwave drying of apple slices mainly investigates the laboratory-scale microwave equipment, such as microwave ovens [20–24]. Despite these studies providing fundamental insights into the drying mechanism and changes in product quality, understanding the practical application of these processes in large-scale industries remains lacking. In terms of industrial application, the continuous microwave belt dryer demonstrates a superior processing capacity and aligns more closely with industrial production standards compared to laboratory-scale equipment [25]. Consequently, the current investigation aims to assess the dehydration

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characteristics and quality attributes of crab apple slices (CAS) using a large-scale continuous microwave belt dryer. Understanding the product dehydration characteristics is essential to comprehending the drying process, evaluating quality changes, and developing optimal processing technology to attain the desired product quality [26]. The comprehensive analysis of dehydration characteristics and quality attributes of CAS, including color, texture, and total phenolic content (TPC) in relation to final quality under continuous microwave drying (CMD), is yet to be extensively documented. Moreover, the effect of various microwave drying conditions on microstructure was studied. The objectives of this study are as follows: (1) to investigate the dehydration characteristics of CAS during CMD, considering factors including slice thickness, microwave power, air velocity, and drying time; (2) to evaluate the changes in quality regarding color, texture, TPC, and microstructure of the final dried CAS following CMD; and (3) to establish appropriate CMD conditions for controlling the quality attributes of CAS.

2. Materials and Methods

2.1. Sample Preparation

Fresh crab apples were provided by the Institute of Food Processing, Heilongjiang Academy of Agricultural Sciences, Harbin, China, with an equal level of maturity. The samples were selected for uniform sizes and meticulously preserved in the laboratory refrigerator (Model SC/SD-332, Haier Refrigeration Division, Qingdao, China), maintained at a temperature of 4 ± 1 °C to preserve the freshness till subsequent processing. Before the test, the sample is removed from the refrigerator and placed at room temperature, allowing the sample temperature to gradually approach room temperature. The samples were properly cleaned, washed under running water and wiped with muslin cloth. The crab apples were sliced in samples of differing thicknesses utilizing an electric stainless-steel slicer (Model: 2139AL, China). The thickness of the slices was controlled by adjusting the gap between the blades using manual slide calipers, which had a precision of 0.02 mm. The slices were then dipped in a potassium metabisulphite ($K_2S_2O_5$) solution, an anti-browning agent. The solution had a concentration of 1000 ppm, and the slices were soaked for 10 min for color protection, after which the excess water was removed. The average initial moisture content of the samples was 86.04 ± 0.19% (*w.b.*).

2.2. Microwave Drying of Fresh Crab Apple Slices Using a Continuous Microwave Belt Dryer

The fresh CAS drying experiments were performed employing a continuous microwave dryer (WXD21S, Nanjing, Sanle Microwave Technology Development Co. Ltd., Nanjing, China), as depicted in Figure 1. The device comprises a drying chamber, magnetron, control unit, conveyor belt, fan, and frame. Twenty-one magnetrons, positioned above the drying chamber, function at 2450 MHz, each providing a rated output power of approximately 1 kW. A control system facilitates the regulation of conveyor belt speed, fan ventilation velocity, and microwave power. The microwave power, air velocity, and belt speed required for the test were all adjusted before the experiment. The CAS sample was uniformly placed on the conveyor belt using a feeding device with a dryer. Subsequently, the sample gradually moved into the drying cavity. An infrared thermal camera was employed to acquire the thermal image of the sample surface at the dryer outlet. Each test used the same batch of raw material to ensure uniformity and minimize errors.

Figure 1.

The experimental factors consist of slice thickness, microwave power, air velocity, and conveyor belt speed or drying time. A single-factor test was carried out on fresh CAS with a slice thickness of 1–5 mm, microwave power of 11400–19000W, air velocity of 0–2 m/s, and drying time of 12–16 min. The nutritional quality change of CAS was investigated using various slice thicknesses, microwave

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power, air velocity, and drying time to determine the optimal process range. The experimental factors and levels are presented in Table 1.

Table 1.

The drying experiments carried out in this study included CAS samples with varying thicknesses, ranging from 1 to 5 mm. During the initial phase of the experiment, it became apparent that samples with a thickness exceeding 2 mm underwent combustion, as displayed in Figure 2. As a result, the drying experiments conducted in this study involved various levels of thickness of 1 to 2 mm, microwave power of 11400 to 19000 W, air velocity of 0 to 2 m/s, and drying time of 12 to 16 min.

Figure 2.

The evaluation indexes were subsequently determined using the CAS samples, which were stored in sealed plastic bags. The fresh CAS is needed to attain the desired moisture content of approximately 12–14.0% (*w.b.*). As shown in Figure 3, the experimental procedure and evaluation indexes for CAS under CMD.

Figure 3.

2.3. Determination of Evaluation Indexes

2.3.1. Determination of Surface Temperature

To determine temperature distribution, a thermal infrared camera (FLIR E95, FLIR Systems Inc., USA) captured a thermal image of the CAS surface immediately following microwave drying. The heat loss during sampling is within acceptable limits and does not have a significant impact on the results [27]. The overall temperature of the sample was then determined using FLIR Tools software based on the obtained thermal images.

2.3.2. Determination of Moisture Content

The samples used to determine the moisture content of dried CAS were collected from the material layer at the outlet of the drying chamber and stored in airtight polyethene bags. The moisture content of the CAS at 105 °C was determined using the hot air oven method, as described in AOAC Method 930.15 [28]. The measurements were carried out three times, and the findings were expressed as mean ± standard deviation (SD).

2.3.3. Determination of Surface Color

The surface color of fresh and dried CAS was measured at room temperature with a colorimeter (CR-20, Minolta Chroma, Japan) using the CIELab method. While performing color measurements, the instrument underwent a calibration procedure using a black-and-white standard. The L^*, a^*, and b^* values represent the levels of brightness to darkness (0–100), greenness (- a^*) to redness (+ a^*), and blueness (- b^*) to yellowness (+ b^*) [29]. To ensure test reliability, each test was repeated three times, and the mean value was used.

2.3.4. Determination of Texture (Hardness and Brittleness)

The texture analyzer (TA. XT Plus, Stable Micro Systems Ltd., Surrey, UK) was used to determine the hardness and brittleness of the CAS at room temperature. In this case, the material was punctured using a 5 mm-diameter cylindrical P/5 probe. The operational parameters for the test were configured with a pre-test speed of 1 mm/s, test speed of 1 mm/s, post-test speed of 1 mm/s, compression strain of 50%, and a force threshold of 0.8 N. Six slices of crab apple were randomly selected, and a test was performed by stacking them on top of each other, as each slice was very thin.

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Following the superimposing of the six pieces, the texture analyzer was utilized to determine hardness and brittleness. The measurement process was conducted three times, and the average value was recorded. The texture analyzer software computed the peak force value on the time-force curve to determine hardness and evaluated the amounts of peaks to determine brittleness. The peaks of CAS with softer flavors are smaller, whereas the peaks of CAS with crisper flavors are larger.

2.3.5. Determination of Total Phenolic Content

The TPC of the samples was assessed using the Folin-Ciocalteu method [30]. Measuring 2 g of dehydrated CAS and place it in a test tube. The TPC of a 2 g sample of dried CAS was determined using this methodology. This method involves mixing 250 μL of Folin-Ciocalteu reagent with 0.25 mL of dilution solution and allowing the reaction to occur at room temperature for 6 min. After adding 2 mL of a sodium carbonate solution with a concentration of 7.5% at room temperature, along with 2 mL of distilled water, the mixture was placed in a light-free environment for 90 min. The spectrophotometer (UV-Vis spectrophotometer model 19; Hanon Advanced Technology Group Co., Ltd., Jinan, China) was selected according to the absorbance value obtained from the sample, which exhibited a wavelength of 765 nm. To generate the standard curve from a gallic acid solution, a gradient dilution concentration of 1 mg/mL was applied. To generate the standard curve from a gallic acid solution, a gradient dilution concentration of 1 mg/mL was applied. The sample was analyzed for TPC, which was expressed as milligrams of gallic acid per 100 grams of dry mass.

2.3.6. Scanning Electron Microscopy

Scanning electron microscopy (SEM) was applied to investigate the surface structure of CAS to determine changes due to different drying conditions under CMD. The microstructure of fresh and dried CAS was analyzed using scanning electron microscopy (S-3400 N, Hitachi, Ltd., Tokyo, Japan) at an accelerating voltage of 5 kV in a vacuum atmosphere. The samples were attached to aluminum stubs with double-sided tape, sputter-coated using a thin layer of gold, and subsequently examined for microstructure at 100 × magnification.

2.4. Statistical Analysis

All experiments with different treatments were repeated in triplicate, and the data were expressed as mean ± SD. Significant differences between different treatments were evaluated by analysis of variance (ANOVA) with the Fisher LSD test (p<0.05) using Origin Pro software (Version 2024b, Origin Lab, Northampton, Massachusetts, USA). Heatmap and hierarchical cluster analysis were used to identify the correlation and clustering of all experimental factors on the evaluation indexes. Principal component analysis was applied to determine the influence of four experimental factors on the evaluation indexes. Hierarchical cluster analysis and principal component analysis were conducted using R studio version 2023.12.1+402. Subsequently, the results of the data analysis are presented in Tables and Figures.

3. Results and Discussion

3.1. Analysis of Dehydration Characteristics of Crab Apple Slices Under Continuous Microwave Drying

The dehydration characteristics of CAS during CMD were assessed through changes in average temperature and moisture content across different processing parameters, including slice thickness, microwave power, air velocity, and drying time, as illustrated in Figure 4.

3.1.1. Effects of Slice Thickness on the Dehydration Characteristics of Crab Apple Slices

Figure 4a,b illustrated the effects of slice thickness in the range of 1–2 mm on the average temperature and moisture content of CAS at a fixed microwave power of 15200 W, air velocity of 1 m/s, and drying time of 14 min. Overall, increasing slice thickness showed a significant (P<0.05)

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increase in average temperature, as illustrated in Figure 4a, and a decrease in moisture content, as depicted in Figure 4b. The temperature of CAS did not consistently increase during each drying cycle but started to decrease gradually after reaching its highest point. The decrease in temperature is attributed to inadequate heat dissipation from water evaporation and convective cooling from airflow across the material layer surface, which is necessary to counterbalance the heat generation through microwave energy absorption [29]. The findings revealed that decreasing the slice thickness may immediately reduce the moisture transfer between the interior and the surface, resulting in a significant reduction in the average temperature of CAS. A reasonable explanation for this phenomenon is that the thicker samples result in the greater distance for water molecules to travel from the inside to the outside. The reduced moisture content in 1.5 mm and 2 mm slices, relative to 1 mm slices, can be ascribed to their increased thickness, which absorbs and retains more microwave energy. This leads to improved heating and a highly efficient internal vaporization process during drying. Microwaves penetrate deeper into the thicker slices, providing the more uniform and efficient moisture removal. Conversely, thinner slices (1 mm) may undergo localized overheating at the surface, resulting in rapid crust formation. This crust prevents moisture from migrating from the interior to the surface, thereby decelerating the drying process. As expected, the temperature for drying the slices increased, resulting in a significant reduction in drying time. This phenomenon arises from the significant difference in vapor pressure between CAS and the ambient environment at elevated temperatures. Therefore, the rate of water migration exhibited a gradual decrease from the interior to the exterior of the sample [31]. The moisture content of CAS with a thickness of 1.5 and 2 mm was within the desired range of 12–14% (*w.b.*). However, the moisture content of the 1 mm slice exceeded the target level.

3.1.2. Effects of Microwave Power on the Dehydration Characteristics of Crab Apple Slices

Figure 4c,d demonstrate the changes in average temperature and moisture content of CAS subjected to microwave power ranging from 11400 to 19000 W with a fixed slice thickness of 1.5 mm, air velocity of 1 m/s, and drying time of 14 min. Overall, increasing microwave power resulted in a significant ($P<0.05$) increase in average temperature, as shown in Figure 3c, and decrease in moisture content, as displayed in Figure 4d. The increase in microwave power from 11400 to 19000 W resulted in an elevation in the temperature of CAS. This indicates that elevated microwave power levels can raise the temperature, thereby reducing drying time. Microwaves produce heat mainly via dielectric heating, a process in which electromagnetic energy stimulates polar molecules, such as water, inside the material. High microwave power results in enhanced absorption of microwave energy and the production of heat within the dielectric material, leading to a rapid increase in temperature and the subsequent evaporation of water from the material [32]. As microwave power increases, the moisture content of CAS gradually decreases due to increasing temperatures. The temperature increase accelerates the process by which water molecules evaporate from the sample. The findings indicate that increasing the microwave power levels leads to reduced drying times for CAS to achieve the desired moisture content. The microwave drying of germinated red adzuki beans exhibited comparable results, indicating that increased microwave power levels reduced drying time and attained the desired moisture content [33]. Nonetheless, there was a minor fluctuation in the moisture content of CAS at microwave power levels of 17100 W and 19000 W. The observed phenomenon may be related to the sampling deviations of CAS from the dryer outlet, as the distribution of temperature and moisture inside the material layer exhibited unevenness due to the non-uniform characteristics of microwave drying [34,35].

3.1.3. Effects of Air Velocity on the Dehydration Characteristics of Crab Apple Slices

Figure 4e,f presents the changes in average temperature and moisture content at the air velocity of 0–2 m/s, under the microwave power of 15200 W, slice thickness of 1.5 mm, and drying time of 14 min. As shown in Figure 4e, during the initial drying phase, the temperature increased more rapidly in the absence of ventilation compared to the other levels of air velocity. The findings demonstrated an inverse relationship between air velocity and temperature, indicating that as air velocity increases, temperature decreases. This phenomenon arises because the higher air velocity effectively dissipates the more heat from the layer of material, thereby preventing an increase in temperature. Conversely, the higher air velocity facilitated the greater transfer of heat through air convection. The results of this study are consistent with the findings of [33], who discovered a negative correlation between air velocity and sample temperature, indicating that higher air velocity results in lower sample temperatures during CMD of germinated red adzuki beans. This clearly indicated that the average temperature decreased when the air velocity increased from 0 to 2 m/s. The maximum average temperature of the CAS was without ventilation, which quickly led to serious burning in the final dried material [29], whereas the temperature decreased significantly with an air velocity of 1.5 m/s. As illustrated in Figure 4f, the moisture content of CAS declined more rapidly during air velocities of 0 and 0.5 m/s compared to other air velocity levels. Alongside the increased temperature of the CAS at reduced air velocity, additional heat was available for moisture removal. Similar fluctuations were observed in the moisture content of germinated red adzuki beans at the air velocity level of 0–2 m/s during CMD [33]. Furthermore, the CAS exhibited a higher temperature at a low air velocity, resulting in an enhanced heat supply for water extraction. The results of this study align with the findings of [36] who studied the microwave drying characteristics of corn.

3.1.4. Effects of Drying Time on the Dehydration Characteristics of Crab Apple Slices

Figure 4g,h displays the changes in temperature and moisture content at the drying time of 12–16 min, respectively, under the fixed slice thickness of 1.5 mm, microwave power of 15200 W, and air velocity of 1 m/s. In Figure 4g, exhibited the effects of drying time on the average temperature of CAS during CMD. The findings demonstrate that an increase in drying time correlates with an increase in the average temperature of the slices. The observed phenomenon occurs due to the gradual absorption of microwave energy through the slices, leading to increased internal temperatures over time. As the drying time increases, the average temperature generally increases, reaching its maximum at 15 min and then dropping slightly at 16 min. The average temperature changes exhibited an initially quick increase (12–13 min), followed by a gradually decreasing trend (13–14 min), then another increase (14–15 min), and finally a decrease (15–16 min). During the initial drying period, the higher moisture content causes the material to absorb microwave energy, resulting in a progressively rising temperature. The variations in temperature of the sample depend upon the thermal accumulation within the material, resulting from the microwave energy absorbed by the material [26]. As illustrated in Figure 4h, increasing the drying time from 12 to 16 min resulted in a significant decrease in moisture content, with the lowest value reaching at 16 min. The moisture content appears to stabilize at the lower levels undergoing 13 min drying, with minor fluctuations in the 14 to 16 min range. The moisture content of the CAS decreases with extended microwave exposure as more water evaporates from them. The process continued until it reached equilibrium, which had the benefits of extra drying time for the reduction of moisture content. The explanation behind this is that during drying, the transition of water from liquid towards vapor occurs in a unidirectional and irreversible manner; as the thermal driving force shifts to capillary pressure within the material, water persistently migrates from the interior to the exterior, ultimately decreasing the material moisture content through surface convection [29].

3.2. Analysis of Quality Attributes of Crab Apple Slices Under Continuous Microwave Drying

The analysis of drying conditions (slice thickness, microwave power, air velocity, and drying time) on the quality attributes of the dried CAS, including color changes, texture, TPC, and microstructure, was evaluated as presented in Tables 2 to 5.

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3.2.1. Effects of Slice Thickness on the Quality Attributes of Crab Apple Slices

Table 2 present the changes in color (L^*, a^*, b^*), hardness, brittleness, and TPC of CAS at the slice thickness of 1–2 mm, respectively, under the microwave power of 15200 W, air velocity of 1 m/s, and drying time of 14 min.

Figure 4.

(1) Effect of slice thickness on the color (L^*, a^*, b^*) of crab apple slices

Consumers evaluate the surface color of food as a major quality criterion before tasting it, which significantly impacts their approval of the product. Several factors contribute to color changes, the most significant of which are the Maillard reaction, chlorophyll degradation, and non-enzymatic browning [37]. A higher L^* value signifies a lighter color that is more appealing to consumers. The color values of fresh crab apple slices were recorded as L^* 61.00, a^* 8.50, and b^* 29.80, respectively. The color values for 1 mm samples were L^* 75.67, a^* 7.27, and b^* 30.70, respectively. The color values for 1.5 mm samples were L^* 68.33, a^* 8.13, and b^* 29.30, respectively. The color values of 2 mm samples were L^* 60.13, a^* 9.87, and b^* 27.83, respectively. The L^* values for the 1 mm and 1.5 mm slices were higher than those of the fresh sample, whereas the 2 mm slices were lower. The a^* values of the 1 and 1.5 mm slices were lower, while the 2 mm slices were higher than those of the fresh sample. The b^* values of the 1 mm were higher than those of the fresh sample but lower than those of the 1.5 and 2 mm. Based on the color values of the dried CAS, as the slice thickness increases, the L^* value decreases, the a^* value increases, and the b^* value decreases. The results aligned with the prior findings of [38], which indicated that as the slice thickness increases, the L^* values decrease, the a^* values increase, while the b^* values exhibit an opposite, increasing trend during the microwave drying of apple slices. The decrease in L^* values suggests that there was a non-enzymatic reaction in the final product, resulting in a reduction in the sample brightness [39]. Thicker slices exhibit a higher level of redness (a^*), while thinner slices display a lower level of redness. The interaction between light and slice thickness may influence color perception or retention. Thinner slices dry faster and more evenly, reducing moisture and heat exposure and preserving or enhancing yellowness. Although thicker slices retain moisture longer during microwave drying, prolonged heat exposure may cause more browning (Maillard reactions or caramelization), reducing yellowness (b^*) and uneven drying.

(2) Effect of slice thickness on the hardness and brittleness of crab apple slices

Texture is critical for assessing the quality of processed products and influencing consumer acceptance of dried products. Consumers consider the hardness of dried apples as an essential indicator of their texture preferences [40]. Hardness denotes the highest force applied to a sample force deformation curve. The higher hardness values result in the firmer slices, whereas the lower hardness leads to the softer slices. Brittleness is another significant characteristic of dehydrated products. The number of peaks serves as an indicator of the brittleness of the sample. The higher brittleness values indicate a greater degree of fragility in the slices, making them more prone to breaking or crumbling. Conversely, lower values indicate a reduced level of brittleness, meaning that the slices are less likely to break or crumble. The findings regarding the effect of different slice thicknesses (ranging from 1–2 mm) on the hardness and brittleness value of CAS. The hardness values of the CMD dried CAS were 0.62, 0.66, and 0.74 g for thicknesses of 1, 1.5, and 2 mm, respectively. The hardness value increased proportionally as the slice thickness increased. Similar findings were observed by [41] indicating that an increase in slice thickness increased the hardness during microwave intermittent drying of apple slices. The phenomenon occurs because thicker slices (2 mm) have a more extended heat transfer pathway. This may cause a slower rate of moisture removal, resulting in the distribution of internal moisture gradients. These gradients play an essential role in the possibility of case hardening. Case hardening occurs when the surface of the slices, a key aspect, dries and becomes more arduous, retaining moisture inside and increasing hardness. While thinner slices (1 mm and 1.5 mm) have less resistance to heat transfer, they dry more uniformly and

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have less structural resistance, therefore reducing hardness. The brittleness values for dried CAS were measured at 14.53, 12.27, and 9.47 for slice thicknesses of 1, 1.5, and 2 mm, respectively. Overall, as the slice thickness increased, the brittleness of the CAS decreased. The findings showed that the brittleness value decreased significantly as the slice thickness increased. Thin slices (1 mm) exhibit an increased surface area-to-volume ratio, facilitating faster moisture removal. A swift reduction in moisture undermines the structural integrity of cells and intercellular spaces, leading to heightened brittleness. The 1.5 mm slices have slightly lower moisture extraction than the 1 mm slices, and their structural integrity reduces the possibility of brittle fractures. The 2 mm slices demonstrated the lowest brittleness among the different thicknesses. Thicker slices retain moisture longer during drying, leading to reduced cellular collapse and a softer texture.

(3) Effect of slice thickness on the total phenolic content of crab apple slices

The preservation of TPC during drying is crucial due to the established antioxidant properties of phenolic compounds. The CMD dried CAS with thicknesses of 1, 1.5, and 2 mm had TPC values of 5.34, 5.76, and 5.78 mg/g, respectively, whereas the fresh sample had a TPC value of 7.32 mg/g. Drying resulted in a reduction of total phenolic content across all slice thicknesses. The TPC values exhibited reductions of 27.05%, 21.31%, and 21.04%, respectively, compared with the fresh sample and the dried slices of 1-, 1.5-, and 2-mm thickness. The TPC of red flesh apples decreased by 20% during vacuum-microwave pretreatment with convective drying compared to fresh samples [42]. Thinner slices dry faster due to their higher surface area to volume ratio. Phenolic compounds degrade faster when moisture is removed quickly due to oxygen and heat. Thicker slices may dry slowly, delaying phenolic compound breakdown. Additionally, thicker slices with reduced surface area may protect phenolic compounds from oxidation and thermal degradation. The maximum TPC value was found at a slice thickness of 2 mm, while 1 mm had the lowest value. The TPC value did not exhibit a significant difference between the slice thicknesses of 1.5 and 2 mm ($p<0.05$). According to the findings, TPC values increase proportionally with slice thickness. The thickest papaya slices exhibited the highest TPC values, while the thinnest slices showed the lowest during the oven drying process [43].

Table 2.

Therefore, the previous discussion regarding the effects of slice thickness on the quality attributes of crab apple slices demonstrated that the optimal slice thickness for CMD was 1.5 mm, which was suitable to achieve the desired moisture content of 12–14% (*w.b.*), better color, moderate texture, and maximum TPC.

3.2.2. Effects of Microwave Power on the Quality Attributes of Crab Apple Slices

The changes in color (L^*, a^*, b^*), hardness, brittleness, and TPC of CAS at the microwave power of 11400 to 19000 W, under the slice thickness of 1.5 mm, air velocity of 1 m/s, and drying time of 14 min (Table 3).

(1) Effect of microwave power on the color (L^*, a^*, b^*) of crab apple slices

The L^* values of dried CAS under CMD ranged from 77.63, 75.87, 68.00, 48.49, and 38.23 for microwave power levels of 11400, 13300, 15200, 17100, and 19000 W, while fresh CAS had L^* values of 61.00. The observed pattern indicates that increasing microwave power initially lightens the sample, but as power levels increase, the sample darkens, probably because of thermal degradation or browning reactions. Therefore, an increase in microwave power resulted in a more significant difference in L^* value between dry and fresh apples, causing the apples to darken when exposed to higher microwave power [44,45]. The appearance of a brown pigment due to the Maillard reaction is one possible explanation. The results showed that an increase in microwave power levels corresponded to a proportional decrease in the L^* value. Previous studies observed similar patterns of reduction in L^* values [20]. The dried samples had a^* values of 3.93, 6.20, 8.23, 8.77, and 9.50, corresponding to microwave powers of 11400, 13300, 15200, 17100, and 19000 W, whereas the fresh

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CAS had 8.50. The increase in a^* value with high microwave power levels is probably due to a combination of intensified Maillard reactions, elevated thermal degradation, alterations in moisture content, and chemical transformations in the material. Overall, as the microwave power increased, the a^* value increased correspondingly. Similar changes in a^* value increased with the increase of microwave power during the microwave drying of green peas [46]. The fresh sample b^* value of 29.80, while microwave power levels of 11400, 13300, 15200, 17100, and 19000 W yielded b^* values of 32.47, 31.80, 28.33, 19.87, and 11.93. The observed pattern indicates that the application of high microwave power results in a notable decrease in the yellow color, due to pigment degradation or Maillard reactions. Overall, as microwave power increased, the b^* value decreased. A similar pattern was found in the rotary plate microwave dryer of apple cubes and the microwave dryer of orange slices [23,47].

(2) Effect of microwave power on the hardness and brittleness of crab apple slices

The hardness of CAS dried at 11400, 13300, 15200, 17100, and 19000 W was approximately 0.68, 0.74, 0.64, 0.55, and 0.48 g. The findings indicated that an increase in microwave power resulted in a decrease in hardness value. Similar findings were reported by [48], who found that increased microwave power levels reduced the hardness values of sea cucumbers during the microwave drying. The decreasing pattern in hardness with increasing microwave power suggests that the higher energy levels remove more moisture and break down the structure in the CAS, rendering them softer. The brittleness of dried CAS was found to be 8.22, 7.10, 11.53, 12.51, and 13.57 at microwave power levels of 11400, 13300, 15200, 17100, and 19000 W. Based on the findings, the brittleness value increased as microwave power increased. A similar result was obtained by [49], who reported that the brittleness value increased as the microwave power increased during infrared drying of apple slices. The explanation for the increase in brittleness as microwave power increases is that the drying rate accelerates, resulting in rapid moisture gradients, internal stresses, and structural rigidity and brittleness.

(3) Effect of microwave power on the total phenolic content of crab apple slices

The TPC values of dried CAS ranged from 4.95 to 6.15 mg/g, whereas the TPC of fresh CAS was 7.32 mg/g. The findings showed that the TPC value of the CMD dried sample exhibited a decrease when compared to the fresh sample. [50] reported the opposite results, observing that TPC values increased during microwave drying of apple slices compared to fresh samples. It appears that raising the microwave power from 11400 to 19000 W initially increases TPC, but it subsequently decreases as the power increases. The decrease in TPC with increasing microwave power is primarily due to elevated temperatures and enhanced drying process, both of which contribute to the thermal degradation and oxidation of phenolic compounds. The microwave power of 11400 W resulted in the highest TPC value due to the high moisture content. The results clearly indicate that the TPC exhibited a significant increase as the microwave power increased. Similar findings were reported by [51], who found that increasing the microwave power increased the TPC value of apple slices during microwave drying.

Table 3.

(4) Effect of microwave power on the microstructure of crab apple slices

Scanning electron microscopy (SEM) analysis can elucidate the effect of microwave drying on hardness, thereby influencing product quality. As shown in Figure 5, the microstructure of fresh and dried CAS samples at different microwave power levels. As displayed in Figure 5a, the fresh CAS cellular structure was dense and unblemished, exhibiting no visible indications of collapse or damage. In Figure 5b–f, illustrated the cellular structures of dried CAS under different microwave powers. At the microwave power of 11400 W, the sample demonstrates the initial indications of cellular shrinkage and breakdown. Small holes and irregularities manifest, indicating the beginning of moisture reduction and structural degradation due to microwave energy. The cellular structure exhibited an increased tendency to break down at a microwave power level of 13300 W. Large holes

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and cracks are evident, reflecting increased drying intensity and a rapid moisture loss rate. These conditions reduced the integrity of intercellular bonds. At the microwave power of 15200 W, structural degradation intensifies compared to the microwave power of 13300 W. The cell walls exhibit large deformation, which increased porosity. It indicates an accelerated drying process, resulting in increased microstructure collapse. At the microwave power of 17100 W, the cellular structure exhibits additional degradation, reflected in the prevalence of large, irregular holes within the microstructure. The sample demonstrates significant deformation, probably resulting from quickly evaporated moisture and changes in internal pressure. The cellular structure was almost completely disrupted at the maximum microwave power of 19000 W. The porosity appears enhanced, exhibiting large fissures and collapsed areas, indicative of excessive drying and possible thermal damage. The findings revealed that high microwave power levels cause severe damage to the cellular structure of CAS. The observed structural changes align with prior studies investigating the effects of microwave power levels on the microwave drying of apple slices [52]

Figure 5.

Previous discussions regarding the effects of microwave power on the quality attributes of CAS concluded that CMD dried slices are suitable for a microwave power of 15200 W; other microwave power levels were unable to meet the moisture content requirements of 12–14% (*w.b.*).

3.2.3. Effects of Air Velocity on the Quality Attributes of Crab Apple Slices

As presented in Table 4, the changes in color (*L**, *a**, *b**), hardness, brittleness, and TPC of CAS at the air velocity of 0–2 m/s, under the fixed slice thickness of 1.5 mm, microwave power of 15200 W, and drying time of 14 min.

(1) Effect of air velocity on the color (*L**, *a**, *b**) of crab apple slices

The *L** values of dried CAS varied between 61.97 and 72.90 at air velocities ranging from 0 to 2 m/s, whereas the freshly obtained CAS exhibited an *L** value of 61.00. The *L** value of dried CAS is greater than that of fresh CAS. The difference in *L** values for various air velocities is primarily due to the trade-off between drying efficiency and the possibility of adverse effects such as surface hardening or uneven moisture loss. The *L** of CAS initially tended to increase, followed by a decreasing trend as air velocity increased. This phenomenon occurs when water vapor evaporates through the CAS surfaces and remains in the drying chamber, resulting in a prolonged state of wetness in the CAS. As reported by [53] the *L** values changed similarly during infrared-assisted hot air drying at 1–3 m/s. The *a** values of dried CAS ranged from 8.33 to 9.47 at air velocities of 0 to 2 m/s, while fresh CAS had an a* value of 8.50. All dried CAS *a** values exceeded the fresh value, with the exception of the air velocity of 1 m/s. The lower air velocities had less effect on redness compared to the fresh sample, whereas higher velocities (specifically 1.5 and 2 m/s) led to a significant increase in redness. This phenomenon may be attributed to improved moisture extraction, which results in the concentration of pigments and thereby increases the red color of the slices. The *a** value initially reached high levels due to the high temperature, then decreased and eventually increased as air velocity increased. At low air velocities (0 to 1 m/s), the *a** values demonstrate minimal fluctuation, indicating that these conditions are unlikely to significantly influence the color intensity of the slices. A similar change occurred in the *a** value of germinated brown rice during microwave drying as the air velocity changed from 0 to 2 m/s [29]. The *b** values of dried CAS varied from 25.37 to 28.60 at air velocities of 0 to 2 m/s, while the fresh sample displayed a *b** value of 29.80. The interaction between microwave power and air velocity for moisture removal results in changes in the *b** value. As air velocity increases, enhancing the drying rate reduces the duration of thermal degradation and increases b* values. However, the slight decrease in *b** could be attributed to excessive drying at 2 m/s, which caused certain yellow pigments to degrade or over-dry, resulting in a slight reduction in color intensity. The results of this study align with those obtained by [53], who observed a significant

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decrease in the values of *b** as the air velocity increased from 1 to 2 m/s during infrared-assisted hot air drying of apple slices.

(2) Effect of air velocity on the hardness and brittleness of crab apple slices

The hardness of CAS dried at air velocity levels of 0, 0.5, 1, 1.5, and 2 m/s was approximately 0.58, 0.64, 0.74, 0.73, and 0.70 g, respectively. The findings indicated that as air velocity increased, the hardness of CAS initially increased and subsequently decreased. This phenomenon occurs because air velocity enhances moisture removal, particularly at an optimal speed of 1 m/s. It inhibits cellular collapse and improves rigidity, leading to increased hardness. A comparable finding presented by [54] indicated that increasing the air velocity increased the hardness value during the microwave drying of apple slices. In the absence of air velocity, moisture removal depends entirely on microwave energy, resulting in inconsistent drying and softer structures due to inadequate strengthening. At an air velocity of 0.5 m/s, the hardness increased slightly compared to 0 m/s, indicating structural strengthening. Excessive surface drying at air velocities of 1.5 and 2 m/s could lead to case hardening. It produces a firm external layer while limiting moisture transfer, consequently leading to a significant reduction in hardness. The brittleness of dried CAS ranged from 8.50 to 12.93, corresponding to air velocities varying from 0 to 2 m/s. The brittleness values initially increased as the air velocity increased, followed by a subsequent decrease. The measured brittleness value at an air velocity of 0.5 m/s represents the highest among all levels. Increased air velocity may improve moisture extraction from the surface, leading to rapid drying and increased brittleness. At an air velocity of 1 m/s, brittleness reduces relative to 0.5 m/s. Increased air velocity may lead to a decreased moisture gradient within the slices, thereby reducing the hardening of the outer layer. The increase in air velocity can improve moisture removal from the surface, leading to rapid drying and reduced brittleness.

(3) Effect of air velocity on the total phenolic content of crab apple slices

The TPC values were 6.03, 5.75, 5.67, 5.70, and 5.29 mg/g for air velocities of 0, 0.5, 1, 1.5, and 2 m/s, while fresh CAS had 7.32 mg/g. The TPC value of the dried sample appears lower than that of the fresh sample. The TPC values changed during the drying period, showing an initial decrease, followed by an increase, and then a final decrease. The variations observed in TPC throughout the drying process can be explained by the intricate interactions among air velocity, moisture loss, and heat-induced degradation. Reduced air velocities maintain TPC by promoting slower and more uniform drying, thus preserving the TPC from excessive heat exposure. Conversely, increased air velocities expedite moisture loss, resulting in the deterioration of TPC due to higher temperature exposure. The results of the study demonstrated a decrease in TPC with an increase in air velocity. Opposite findings were presented in the studies by [51,53] which indicated that as air velocity changes from low to high levels, the TPC increases during hot air and infrared-assisted hot air drying of apple slices.

Table 4.

(4) Effect of air velocity on the microstructure of crab apple slices

As depicted in Figure 6, the effect of air velocity on the microstructure of fresh and dried CAS. In Figure 6a, the fresh CAS showed distinct cellular structures and a smooth, undamaged surface structure. There were no indications of tissue deformation or collapse. As presented in Figure 6b–f, the cellular structures of dried CAS under different air velocity levels. In the absence of air velocity, the sample demonstrated significant shrinkage and the appearance of large, irregular holes. The lack of ventilation likely led to inconsistent moisture removal, which caused damage to the structure. The surface exhibited a moderate decrease in porosity at an air velocity of 0.5 m/s compared to the air velocity of 0 m/s condition. The microstructure demonstrated reduced shrinkage, indicating a more uniform drying process with minimal structural damage. Increasing the air velocity to 1 m/s reduced the number of holes and preserved a larger portion of the sample microstructure. The surface seemed less damaged, signifying enhanced heat and mass transfer efficiency throughout the drying process.

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At the air velocity of 1.5 m/s, the microstructure exhibited minimal shrinkage and enhanced uniformity in porosity. The combined application of microwave drying with increased air velocity efficiently retained the structural integrity of the cell walls, probably due to improved moisture evaporation. At the air velocity of 2 m/s, the microstructure exhibited indications of excessive drying. Several regions displayed cellular collapse, potentially due to excessive moisture extraction, which led to structural weakness.

Figure 6.

Therefore, the previous discussions regarding the effects of air velocity on the quality attributes of CAS have determined that CMD dried slices achieved optimal results with an air velocity of 0.5 m/s.

3.2.4. Effects of Drying Time on the Quality Attributes of Crab Apple Slices

As shown in Table 5, the changes in color (*L**, *a**, *b**), hardness, brittleness, and TPC of CAS at the drying time of 12 to 16 min, respectively, under the fixed slice thickness of 1.5 mm, microwave power of 15200 W, and air velocity of 1 m/s.

(1) Effect of drying time on the color (*L**, *a**, *b**) of crab apple slices

The *L** values of the dried sample ranged from 64.87 to 73.60, while the fresh sample measured at 61.00. The *L** value increases with prolonged drying time, reaching its highest at 15 min, which indicates a gradual lightening of the slices during the drying process. The lightness decreases after 15 min, indicating that over drying or browning may occur, leading to a darker color. The decrease in *L** values signify a non-enzymatic reaction occurring in the final product, which decreases sample lightness [39]. Overall, as the drying time increased, the *L** value decreased. As drying time increased, olive slice *L** values decreased under microwave drying [55]. The dried samples showed the *a** value ranging from 6.70 to 9.07, while the fresh sample had a value of 8.50. The drying time increased from 12 to 15 min, and the a* reached its maximum value of 9.07, while the lowest recorded value was 6.70 at the drying time of 16 min. The difference in *a** value during microwave drying demonstrates a balance of moisture content, pigment concentration, degradation, and potential browning effects at various drying durations. Overall, as the drying time increases, the color *a** value correspondingly increases. Increasing drying time yielded the maximum *a** value for apple slices during microwave drying [38]. The dehydrated CAS ranged from 25.53 to 28.90, whereas the fresh samples had a *b** value of 29.80. The *b** value of the dried samples under different drying times was lower than that of the fresh ones. As drying time progresses, the color *b** value decreases, indicating a reduction in yellowness. The change in the color *b** value is probably attributable to the degradation of pigments such as carotenoids and alterations in the Maillard reaction during microwave drying. Extended exposure to heat can deteriorate color pigments, decreasing yellowness.

(2) Effect of drying time on the hardness and brittleness of crab apple slices

The hardness of CAS dried at drying times of 12, 13, 14, 15, and 16 min was approximately 0.65, 0.75, 0.71, 0.62, and 0.58 g, respectively. The hardness value began at the low level of 12 min, increased to 13 min, and then gradually decreased as the drying time extended to 14 to 16 min. A significant change in hardness results from the rapid removal of moisture, particularly from the surface layers, during the initial drying stage (12-13 min). Rapid removal results in case hardening, a process in which the surface becomes more rigid, and the core retains moisture, thereby increasing the hardness. At the drying time of 15 to 16 min, the slices undergo more consistent moisture loss, leading to shrinkage and reduced elasticity. The cellular walls deteriorate, leading to a softer texture as the internal structural support of the CAS decreases. The results showed that the hardness decreased with increasing drying time. The results are consistent with those reported by [40,41], who found that the hardness of apple slices decreased with increased drying time during ultrasound and microwave intermittent drying. The brittleness values were 8.20, 8.77, 9.90, 11.73, and 12.83, respectively, at the drying times of 12, 13, 14, 15, and 16 min. The results demonstrated that the dried CAS shows the

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highest brittleness at a drying time of 16 min, followed by 15 min, with the lowest brittleness observed at 12 min. The findings indicated that extending the drying time results in an increase in brittleness. The observed increase in brittleness correlates with the drying time due to a decrease in moisture content, which results in a denser and more compact structural composition in the CAS.

(3) Effect of drying time on the total phenolic content of crab apple slices

The TPC of dried CAS at 12, 13, 14, 15, and 16 min was 4.06, 5.46, 5.74, 5.68, and 5.49 mg/g, while the fresh TPC was 7.32 mg/g. The TPC exhibited an initial increase, subsequently followed by a decrease as the drying time increased. The fluctuation in TPC may result from the deterioration of phenolic compounds attributed to heat and oxidative reactions throughout drying, where extended drying durations may initially cause more significant degradation, resulting in a stabilization effect during intermediate durations. The result indicates that extended drying time could lead to the degradation or loss of TPC. The TPC increased due to shorter drying times during infrared-assisted hot air drying of apple slices [53].

Table 5.

(4) Effect of drying time on the microstructure of crab apple slices

The SEM images illustrated the structural changes in CAS during CMD at increasing time intervals, as illustrated in Figure 7. In Figure 7a, the fresh sample's microstructure was compact and undamaged, with notable cellular structures reflecting the natural moisture and preserved tissue integrity. Figure 7b–f displays the cellular structures of dried CAS at various drying times. During 12 min of drying, the initial structural damage became apparent as the cellular walls collapsed, probably due to the early phases of moisture evaporation. The sample surface reveals minor wrinkling, while the structural integrity remains partially preserved. At the drying time of 13 min, a further breakdown of the microstructure becomes apparent, which leads to increased shrinkage and surface wrinkling. The breakdown of cellular walls exhibits increased uniformity, indicating gradual moisture loss. After 14 min drying, the structure exhibited significant shrinkage and enhanced surface wrinkling. The visible holes within the tissue indicate severe damage to the cellular structure, likely due to the evaporation of retained water. The sample displays a rough, irregular surface as a consequence of severe structure collapse during the 15 min drying period. The structure appeared brittle, exhibiting visible microcracks, indicating extensive dehydration and possible thermal stress. Following a drying period of 16 min, the microstructure attains its maximum deformation, displaying a highly wrinkled and fractured appearance. The cellular integrity appears nearly entirely weakened; thereby, the matrix seems completely dried, indicating extended exposure to microwave energy. Overall, as drying time increases, cell microstructure gradually degrades, resulting in cellular wall collapse, surface wrinkling, and eventually fragmentation.

Figure 7.

Based on the previous discussion on the quality attributes of CAS, the drying durations of 13 and 15 min achieved the desired moisture content. Considering CAS quality attributes, a drying duration of 15 min resulted in better texture and higher TPC, while a drying duration of 13 min appeared more suitable than 15 min due to the higher color rendering capacity and less breakdown of the surface microstructure.

3.2.5. The Hierarchical Clustering and Correlation Heatmap Under Various Drying Conditions

The hierarchical clustering and correlation heatmap (HCA) graph present a visually structured analysis of the relationships between parameters, providing a clear and organized view of the data. Color mapping represents the strength of correlations, with darker shades indicating stronger positive or negative correlations, while lighter shades signal weaker correlations. Cluster analysis is applied to rows and columns, grouping indicators with similar correlation patterns, making it easier to interpret relationships between parameters. Each cell in the heatmap displays a correlation

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coefficient and a significance marker. Correlation coefficients closer to 1 or –1 denote stronger linear relationships, while those near 0 indicate weaker ones. Significance markers (*, **, ***) highlight the statistical relevance of these correlations, with more stars representing higher levels of significance. A heatmap and hierarchical cluster analysis of different evaluation indexes throughout drying conditions are displayed in Figure 8.

Figure 8.

3.2.6. Principal Component Analysis of Crab Apple Slices Under Different Drying Conditions

The principal component analysis (PCA) was determined the influence of four experimental factors on the evaluation indexes of CAS, as shown in Figure 9. PCA biplot presents the relationship between four experimental groups: (a) slice thickness (green), (b) microwave power (orange), (c) air velocity (blue), and (d) drying time (pink) and their effects on various indicators. The arrows indicate the direction and strength of the correlations between the properties: average temperature (AT), moisture content (MC), color *L**, color *a**, color *b**, hardness, brittleness, and TPC. These properties are visualized in terms of their contributions to the separation of the experimental groups, helping to understand the underlying influences on the product characteristics across different experimental conditions. The first principal component (PCA1) accounted for 49.04% of the total variance. In comparison, the second principal component (PCA2) contributed an additional 21.28%, resulting in a total explanation of 70.32% of the total variance in the analysis. The data points related to slice thickness (highlighted in green) are predominantly clustered near the center of the PCA plot, suggesting that this factor exerts a moderate influence on most variables without an obvious directional effect.

The correlation between slice thickness and variables, including hardness and color parameters, indicates that changes in slice thickness influence these attributes, though not as significantly as other factors. This group partially corresponds with indicators involving color *a** and color *L**, signifying its influence on the samples' visual attributes and surface texture. The microwave power cluster (depicted in orange) exhibits a stronger correlation with variables positioned in the positive axis of PCA1 and PCA2. The clustering of points and arrows serves as evidence for MC and brittleness. The extension of the MC and brittleness vectors to microwave power indicates that higher microwave power significantly influences moisture retention and the structural integrity of the samples, probably resulting in increased brittleness and reduced moisture content. The air velocity cluster (shown in blue) exhibits a distribution near the PCA center, with a slight extension toward hardness and AT in the negative axis of PCA1. This positioning indicates that air velocity had a moderate impact on these variables. The influence of air velocity could relate to drying kinetics, impacting drying uniformity and changing sample hardness and average temperature. The drying time (demonstrated in pink) was located between the lines representing TPC and color parameters, particularly in the negative direction of PCA2. It indicated that prolonged drying affects color parameters (*L**, *a**, *b**) and reduces TPC. Drying time findings emphasize color changes and phytochemical preservation, suggesting prolonged drying may lower phenolic content and change sample appearance. S

Figure 9.

In summary, each group displayed differing levels of influence on the evaluated indexes, with slice thickness having a moderate impact on various properties, microwave power being a principal factor for moisture and brittleness, air velocity influencing texture, and drying time affecting TPC and color.

4. Conclusion

In this study, we analyzed the effects of slice thickness, microwave power, air velocity, and drying time on the dehydration characteristics and quality attributes of CAS under CMD. The experimental factors exerted varying influences on dehydration characteristics (temperature and moisture content) and quality attributes such as color, texture, TPC, and microstructure. The findings indicated that reducing slice thickness and increasing microwave power can effectively reduce the total drying time required to reach the desired moisture content; higher air velocity mitigates the temperature increase in the slices, while prolonged drying times lead to a reduction in moisture content and an increase in drying temperature. As the slice thickness increased, the color values showed a decreasing trend while the texture and TPC increased. The increase in microwave power decreased the overall color and texture, whereas the TPC increased. Moreover, the higher microwave power damaged the surface structure. As the air velocity increased, the color and texture increased while the TPC decreased. In addition, at lower air velocities, the microstructure exhibited less shrinkage, indicating more uniform drying with minimal structural degradation. As drying time increased, color, texture, and TPC decreased, while extended drying times significantly changed the microstructure of dried CAS. Based on the dehydration characteristics and quality attributes of the final product, the optimal drying conditions for CMD of CAS are a slice thickness of 1.5 mm, microwave power of 15200 W, air velocity of 0.5 m/s, and a drying time of 13 min. This study enhances the comprehension of the dehydration process and quality changes of CAS during CMD, facilitating the development of suitable technology for dried products, like crab apples.

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