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Convective Drying of Apple Peel as a Preservation Procedure in Fruit Waste Valorization

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Abstract

This study investigated the convective drying process of apple peels, focusing on drying kinetics, energy consumption, and product quality. The apple peels were dried under forced convection at temperatures of 40, 50, 60, and 80 °C, and with microwave assistance of 100 W. The key process parameters that were evaluated included the drying rate, the diffusion coefficient, the activation energy, and the specific energy consumption. Quality of the products was assessed based on moisture content, water activity, overall color change, browning and yellowness indexes, and ascorbic acid content. The results showed that all drying processes occurred during the falling drying rate period. The drying rate and effective diffusion coefficient were positively correlated with the temperature of the drying agent and/or microwave assistance (growth from 2.22×10^{-3} to 7.25×10^{-3} g/s and from 2.64×10^{-10} to 7.80×10^{-10} m^2/s respectively). The drying time was negatively correlated with those process parameters (a decrease from 5300 to 1800 s). The lowest energy consumption was recorded for convection-microwave drying (~81 MJ per kg of evaporated moisture). The water activity of the peels dried at lower temperatures (40 and 50 °C) or with microwave assistance (CVMW) was about 0.4 and about 0.2 for those dried at higher temperatures (60 and 80 °C), ensuring microbial stability. Products that dried convectively at 50 and 60 °C, as well as those dried with the assistance of microwaves, showed a slightly higher overall color change compared to products dried using other processes. Ascorbic acid retention was similar in convectively dried products but decreased significantly in the convective-microwave process. In consideration of the positive effects on drying kinetics and the absence of adverse effects on the energy intensity of the process and the quality of the products, it was concluded that high-temperature drying can be the preferred method of preservation of apple peels in the course of valorization.

Keywords: forced convection; microwaves; effective diffusion coefficient; ascorbic acid; color; water activity

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1. Introduction

Fruit and vegetable by-products are rich in valuable bioactive compounds, including phenolic compounds, carotenoids, minerals, and dietary fiber. These compounds have been found to possess antitumor, antibacterial, cardioprotective, and antimutagenic activities [1,2]. Therefore, they can be used as natural functional ingredients in the design of new functional foods, providing additional health benefits beyond basic nutrition [3].

The utilization of fruit and vegetable by-products in a variety of food products, including dairy products, meat and fish products, oil, wine, pasta, and bakery products, is primarily aimed at enhancing the quality of these products [2]. This results in the development of high-value products in the food and feed industry due to their enhanced nutritional profiles and robust antioxidant activity [3].

However, by-products of fruits and vegetables contribute to global greenhouse gas emissions and constitute a substantial portion of total food waste, posing significant environmental challenges [2]. Effective management and utilization of these by-products can help reduce waste and contribute to a circular economy, thus mitigating adverse environmental impact [4]. The reuse of vegetable and fruit by-products to obtain biologically active phytochemicals has the potential to provide economic incentives for the industry, thus solving environmental problems and increasing competitiveness [1]. Furthermore, the valorization of fruit waste can promote economic growth and minimize waste production, thus contributing to a circular economy [4].

The moisture content in fruits and vegetables plays a significant role in maintaining their sensory quality and normal physiological metabolic processes. However, the high moisture content predisposes raw fruits and vegetables to rapid weight loss, mechanical damage, and potential microbial spoilage [5]. Water activity has been shown to be a critical factor in limiting microbial organism growth and regulating the level of spoilage in foods, including fruits and vegetables [6]. Therefore, regulation of moisture content is crucial to extend the shelf life of fresh horticultural produce, as uncontrolled transpiration can lead to defects in external appearance and promote decaying processes [7].

The drying of fruit peels is a fundamental step in the valorization of agricultural by-products, enabling the conversion of unstable waste into high-value functional ingredients. The literature extensively documents the drying of various fruit residues, highlighting diverse findings for citrus peels (orange, lemon, grapefruit) [8,9], apple [10], banana [11], pineapple [12], peach [13] and others. Several drying methods are employed: Microwave drying—effective for preserving color and phenolic content in citrus peels [9]; convective drying (hot air)—can lead to browning and is usually efficient in terms of drying rate [8]; freeze drying retains the highest levels of bioactive compounds and is particularly effective for citrus peels [9]; however, it is extremely expensive. Vacuum drying allows the quality of dried products to be maintained by reducing the drying temperature and preventing thermal degradation [8]; infrared drying has shown promise in preserving phenolic compounds while being energy efficient [14].

Despite these advancements across multiple fruit matrices, most of the current research remains focused on citrus peels, often utilizing relatively expensive technologies such as freeze-drying or vacuum-microwave systems. While these methods offer superior quality, their high capital and operating costs can be prohibitive for large-scale industrial by-product upcycling. In contrast, apple peels [10] represent a massive industrial waste stream that differs structurally from the oil-rich citrus matrices. Therefore, there is a significant research need to improve simpler, more accessible methods, such as convective hot-air drying, which remains the industrial standard due to its ease of implementation and lower cost. However, the long duration and high energy intensity of convective drying remain major drawbacks.

The strategic importance of apple peel valorization lies in the efficient recovery of its unique bioactive profile, which is highly sensitive to thermal processing. Beyond simple dehydration, the stabilization of this matrix is a prerequisite for high-value industrial applications, including the extraction of pharmaceutical-grade pectin [15], the formulation of specific nutraceuticals [16], and the development of functional edible coatings [17]. To ensure the viability of these end-uses, it is critical to employ control markers that objectively

reflect the degree of thermal degradation, thereby bridging the gap between raw waste management and high-precision ingredient manufacturing.

However, the transition from laboratory findings to industrial-scale upcycling faces significant industrial challenges, primarily related to high energy intensity and the complexity of process optimization for heterogeneous by-product streams [18,19]. The current literature emphasizes that energy costs and scale-up barriers remain the most prohibitive factors in the circular economy of fruit processing [16]. Consequently, a robust comparative energy assessment is not merely a technical requirement but a necessity to validate the economic feasibility of hybrid drying solutions and define the optimal 'technological window' for large-scale apple peel recovery [20].

The objective of this study was to evaluate the efficacy of convective drying across a practical temperature range (40–80 °C) for apple peel valorization. Furthermore, a single hybrid process (convective drying at 40 °C supplemented with a low-intensity microwave load of 100 W) was investigated to evaluate the efficacy of minimal microwave assistance in enhancing drying rates. This approach aims to assess whether a moderate energy supplement can effectively overcome internal mass transfer resistance at low temperatures, thereby reducing thermal stress on sensitive bioactives and preventing product degradation often associated with high-power microwave treatments. The research focuses on finding a balance between process simplicity, energy consumption, and the retention of critical quality parameters such as ascorbic acid and color. By analyzing the kinetics and energy intensity through a mechanistic lens, this study aims to provide a robust and economically viable drying solution.

2. Materials and Methods

2.1. Material

The research material was apple (*Malus domestica*) peels from the Jonagold cultivar. Apples were purchased from a local orchardist (geographical location of the orchard: 52.3838147003593 N, 17.099227595312577 E) and stored under refrigeration conditions (4 °C). Before the drying process, the apples were washed and then peeled with an automatic peeler. The resultant peelings, which exhibited comparable thickness (approx. 5 mm), were cut into strips measuring approximately 40–50 mm in length and arranged in a single layer (skin side down) on a perforated round weighing pan (diameter approximately 210 mm). The length and thickness of the slices were measured with the use of a digital caliper. The weight of a single batch was approximately 16 g. The initial moisture content of the peels was determined using a XM120 moisture analyzer (Precisa Gravimetrics AG, Dietikon, Switzerland) with an accuracy of 0.01%. On average, the moisture content equaled 0.8126 ± 0.0098 kg/kg (wet basis) or 4.3361 ± 0.0523 kg/kg (dry basis).

2.2. Drying Procedure

The prepared peels were subjected to a drying process in a laboratory-scale hybrid dryer designed and constructed by PROMIS-TECH (Wrocław, Poland), the scheme of which is presented in Figure 1.

The experimental apparatus consists of a multisource hybrid dryer capable of integrating convective, microwave, and ultrasonic techniques, either simultaneously or as independent drying modes. The system is equipped with an air heating system (Figure 1—(1, 3)) and an Air-borne Ultrasound System—AUS (Pusonics, Madrid, Spain) (9). This ultrasonic unit operates at a frequency of 26 kHz with a maximum power output of 200 W, facilitating the generation of sound pressure levels exceeding 170 dB. Furthermore, microwave radiation is supplied at 2.45 GHz with a peak power of 500 W, generated by a magnetron (10) (Muegge, Reichelsheim, Germany).

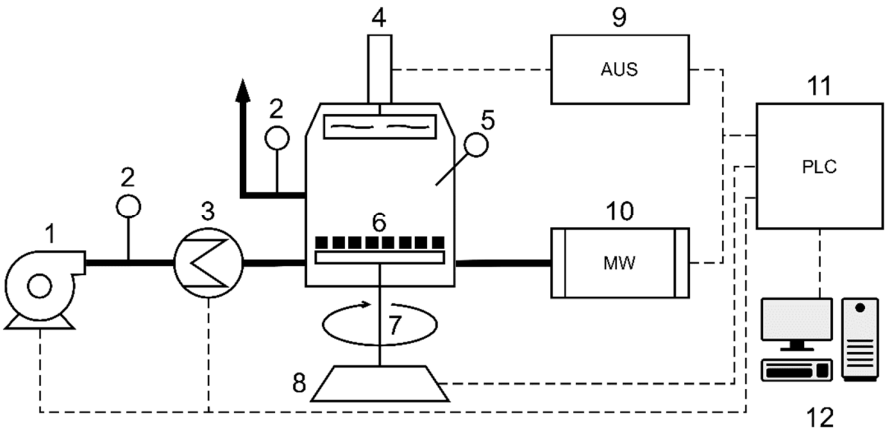


Figure 1. Scheme of hybrid dryer [21]: 1—fan; 2—hot-wire thermo-anemometer, temperature and humidity sensor; 3—heater; 4—ultrasound transducer; 5—pyrometer; 6—samples; 7—rotatable balance pan; 8—balance; 9—air-borne ultrasound generation system; 10—microwave generation system; 11—control cabinet; 12—control and data acquisition workstation.

The ambient air is drawn through a fan (1) into a heating conduit. Subsequently, the heated air enters the drying chamber from the bottom of the sample pan. (6). Ultrasonic energy is delivered from the upper section of the dryer. In the configuration illustrated in Figure 1, a transducer (4) induces vibrations on a specially profiled cylindrical plate with a diameter of 400 mm. These ultrasonic waves are directed through a cone-shaped sleeve toward the material, which is placed on a rotating pan (6) within the drying chamber.

Precise monitoring of the drying kinetics is achieved through high-accuracy instrumentation. The sample mass reduction is recorded using a PS6000.R2 laboratory balance (8) (Radwag, Radom, Poland) with a resolution of 0.01 g. The surface temperature of the material is monitored using an infrared pyrometer, model CT LT15 model (5) (Optris, Berlin, Germany), which has a precision of 0.1 °C. The system is managed by an industrial PLC controller (11) and dedicated computer software (12), which allows for the regulation of process variables, including air temperature (30–90 °C), air velocity (1–5 m/s), microwave power (stepless from 100 to 500 W), ultrasound power (stepless from 50 to 200 W) and drying duration. Furthermore, a comprehensive data acquisition system registers real-time parameters such as air conditions at the inlet and outlet (velocity, temperature, and humidity) measured with HD29371TC1.5 and HD4817ETC1.5 (DLETAOHM, Selvazzano Dentro, Italy) sensors (2) with a precision of 0.01 m/s, 0.1 °C, 0.01%, respectively, material mass, surface temperature, and total energy consumption (kWh).

The studies presented employed drying under forced convection (CV) conditions at varying temperatures, as well as hybrid convection-microwave drying (CVMW) methods. The values of individual process parameters are presented in Table 1.

Table 1. Description of the drying processes.

No.	Process	Type of Process	T (°C)	v (m/s)	P_{MW} (W)	Δt (s)
1	CV40	convection	40	3	0	300
2	CV50		50			
3	CV60		60			
4	CV80		80			
5	CVMW	convection-microwave	40		100	120

T—air temperature; v—air flow velocity; P_{MW}—microwave power; Δt—data recording time interval.

The experimental matrix was intentionally designed using a targeted screening approach to identify the critical stability limits of the apple peel matrix. The convective temperature gradient (40, 50, 60, and 80 °C) was selected to focus on the non-linear degra-

dation zone of ascorbic acid. Based on preliminary studies and literature reports [22], the most significant kinetic changes for this marker occur between 50 °C and 60 °C; therefore, the inclusion of 70 °C was deemed redundant as the trend between 60 °C and 80 °C already followed a predictable, stabilized trajectory.

Furthermore, the hybrid microwave-assisted treatment was limited to a single combination (100 W at 40 °C) to serve as a boundary condition for the process. Since this minimum available power setting (100 W) already induced a significant decrease in ascorbic acid content and adversely affected product quality markers at the lowest convective temperature, higher microwave power levels or temperatures were scientifically excluded. This strategic selection of parameters allowed for the precise identification of the 'technological window' while preventing unnecessary thermal stress on the samples, which would inevitably lead to total degradation of the thermolabile compounds investigated.

The adopted experimental design was based on previous experience and the technological capabilities of the dryer. It was assumed that drying would take place within a temperature range from a minimum (40 °C) to a maximum (80 °C). The exclusion of 70 °C from the study was undertaken as the greatest loss of ascorbic acid (one of the quality parameters evaluated during the study) occurs between 50 °C and 60 °C [22]. Furthermore, given the similar values of the evaluated parameters (for kinetics, energy consumption and product quality) observed for processes carried out at 50 °C and 60 °C, it was decided that the latter process would be carried out at the highest possible temperature. The microwave radiation at a frequency of 2.45 GHz, continuously emitted at a power of 100 W—the minimum power setting available on the device—was utilized. To prevent the material from overheating, microwaves were applied at the lowest possible temperature of the drying medium, that is, 40 °C. The adverse effect of microwaves on the quality parameters under evaluation led to the discontinuation of research into higher power levels.

Temperature monitoring during the drying trials was conducted using a pyrometer (Figure 1—(7)). However, due to the experimental setup where the samples were dispersed on a rotating pan to ensure drying uniformity, the pyrometer primarily captured the surface temperature of the pan rather than the discrete samples. Because of this methodological limitation and the resulting interference from the background temperature, the measured values did not accurately represent the sample temperature and were thus excluded from the report.

During each drying process, the process parameters (air flow velocity, temperature, radiation power) and the mass and temperature of the samples were automatically recorded at predetermined time intervals (Δt). The drying process continued until the sample mass change was less than 0.1 g in 3 consecutive measurements, that is, during 900 or 360 s of the process (depending on the data recording interval Δt—Table 1). Each drying process was carried out in triplicate.

2.3. Assessment of the Drying Kinetics

Based on the data obtained, the spatial average moisture content $\overline{X}(t_i)$ (dry basis) over drying time was calculated as follows [23]:

$$\overline{X}(t_i) = \frac{m(t_i) - m_s}{m_s} \quad (1)$$

where $m(t_i)$ (kg) is the sample mass measured at time t_i, and m_s (kg) is the mass of dry matter.

The drying kinetics of apple peels could be assessed in terms of the dimensionless moisture content (Y_i) and the drying rate (DR_i), in accordance with the following equations [23]:

$$Y_i = \frac{\overline{X}(t_i)}{\overline{X}_0} \tag{2}$$

$$DR_i = -\frac{dm_w}{dt} = -\frac{m(t_i) - m(t_{i-1})}{t_i - t_{i-1}} \tag{3}$$

where $\overline{X}_0$ is the initial moisture content, dm_w (kg) is the weight loss of the sample, and dt (s) is the time interval at which the weight loss dm_w occurred.

The average drying rate, DR_{av}, for a given drying process was calculated using the following equation:

$$DR_{av} = \frac{\Delta m_w}{DT} \tag{4}$$

where Δm_w (kg) is the mass of moisture (water) removed from the sample by drying, and DT (s) is the total drying time.

2.4. Determination of the Effective Diffusion and Mass Transfer Coefficients and Activation Energy

Effective diffusion D_{eff} and mass transfer α coefficients were calculated according to the methodology presented by Szadzińska et al. [23] with the following equations:

$$\frac{d\overline{X}}{dt} = -\frac{\pi^2 D_{eff}}{4l^2}\left(\overline{X} - X_e\right) = -k\left(\overline{X} - X_e\right) \tag{5}$$

$$\alpha = k \cdot l \tag{6}$$

where l (m) is the sample half-thickness, X_e is the equilibrium moisture content, and k (1/s) is the drying constant:

$$k = \frac{\pi^2 D_{eff}}{4l^2} \tag{7}$$

The drying constant k was determined by linear approximation of the $-\left(d\overline{X}/dt\right)_i = f\left(\overline{X}\right)_i$ curves, where $-\left(d\overline{X}/dt\right)_i$ is the rate of moisture content change:

$$-\left(\frac{d\overline{X}}{dt}\right)_i = \frac{\overline{X}(t_{i-1}) - \overline{X}(t_i)}{t_i - t_{i-1}} \tag{8}$$

and $\left(\overline{X}\right)_i$ is the average moisture content (averaged over a time period):

$$\left(\overline{X}\right)_i = \frac{\overline{X}(t_i) + \overline{X}(t_{i-1})}{2} \tag{9}$$

The drying constant k is the slope of the obtained lines.

It should be noted that while the theoretical model (5) accounts for the equilibrium moisture content (X_e), this parameter was omitted in the graphical representation of drying rates. From a mathematical standpoint, X_e acts as a constant offset that shifts the experimental curve without altering its slope. Since the determination of the drying constant k (7) is derived directly from the slope of the linear approximation, the exclusion of X_e from the visual plots does not affect the calculated kinetic parameter.

The activation energy E_a was estimated under the assumption that the relationship between effective diffusivity and temperature is of the Arrhenius type [24]:

$$D = D_0 \exp\left(-\frac{E_a}{R \cdot T}\right) \tag{10}$$

where D_0 (m^2/s) is the preexponential factor of the Arrhenius equation, R ($J \cdot mole^{-1} \cdot K^{-1}$) is the universal gas constant, and T (K) is absolute temperature.

A plot of $\ln(D)$ as a function of $(1/T)$ produced a straight line with a slope equal to $(-E_a/R)$; thus, activation energy may be calculated.

2.5. Assessment of the Energy Intensity of the Processes

The total energy consumption (EC) for each drying experiment was measured using a NERIS DVH5161-M (SBE France (ACEAN), Boulogne Sur Mer, France), with an accuracy of ±1%. The measurement covered the entire drying system, including the heating elements, fans, and control units. Data were recorded from the start of the process until the sample reached the constant mass (as defined in Section 2.2). The results were expressed in kilowatt-hours (kWh) and then normalized per unit of initial mass or water removed to allow for comparative analysis [25]:

$$SEC = \frac{3.6 \cdot EC}{\Delta m_w} \quad (11)$$

where 3.6 is the value of 1 kWh in MJ.

2.6. Assessment of the Product's Quality

Quality parameters are critical from the perspective of food products. Material that does not meet stringent requirements cannot be approved for consumption. Therefore, it has no market value. Given the very large number of quality parameters that can be evaluated, in each case, those with the broadest informational spectrum are selected. In the presented studies, the following were selected: water activity, color, and ascorbic acid retention.

2.6.1. Water Activity Measurements (a_w)

Low water activity—which directly indicates the shelf life—inhibits the growth of pathogenic microorganisms such as harmful bacteria, fungi or molds, and reduces the rate of non-enzymatic and enzymatic reactions, as well as fat oxidation [26]. Furthermore, low water activity minimizes physical and chemical changes during storage, such as browning and texture modifications, which are essential to maintain the quality of dried products [6,27].

The water activity of the raw and dried samples was determined using the LabMaster-aw apparatus (Novasina AG, Lachen, Switzerland). Measurement was carried out at a constant temperature of 25 °C until a stable a_w value was obtained. The value was considered stable if there was no change greater than 0.001 of the unit value within 3 min [28].

2.6.2. Color of the Products Measurements

Color is one of the first and easiest sensory parameters to determine for assessing product quality. Desirable color can suggest better retention of nutrients and a less aggressive processing method. On the contrary, significant color degradation, such as browning, can be unpleasant and may imply a loss of nutritional value or poor handling. It can also serve as an indicator of adverse reactions from the safety perspective, such as the formation of potentially carcinogenic compounds [29]. For these reasons, maintaining a color close to that of the fresh product is often a primary goal in the development of drying processes [30,31].

The color of the raw and dried samples was determined using a CR400 colorimeter (Konica Minolta, Tokyo, Japan) equipped with a D65 light source. Before measurement, the device was calibrated on a standard white plate. The absolute color of the samples was then measured on the inner part of the peels, covered with flesh. Based on the measurements, color coordinates in the CIELAB space were determined, such as: L^*—lightness; a^*—

chromatic component for colors from red (+a^*) to green (−a^*); b^*—chromatic component for colors from yellow (+b^*) to blue (−b^*); C^*—chroma; and h—hue. Measured values were used to determine the indices: color change index dE, yellowness YI, and browning BI according to the following equations [32]:

$$dE = \sqrt{\left(L_0^* - L_d^*\right)^2 + \left(a_0^* - a_d^*\right)^2 + \left(b_0^* - b_d^*\right)^2} \quad (12)$$

$$YI = \frac{142.86 \cdot b^*}{L^*} \quad (13)$$

$$BI = 100 \cdot \frac{Z - 0.31}{0.17} \quad (14)$$

where

$$Z = \frac{a^* + 1.75 \cdot L^*}{5.645 \cdot L^* + a^* - 3.012 \cdot b^*} \quad (15)$$

Symbols with index 0 refer to values measured for raw material, with index d for dried samples, without index for raw material or dried samples.

2.6.3. Ascorbic Acid Retention

Ascorbic acid is one of the most sensitive compounds found in food products, as it is susceptible to the effects of light, atmospheric oxygen, and elevated (high) temperatures. For this reason, it is often used as a quality marker in food processing. A high loss of ascorbic acid usually indicates a severe processing method and a potentially negative impact on other quality parameters [33].

The ascorbic acid content AAC was determined using the modified voltammetric method presented by Yu and Chen [34]. The measurements were carried out in a classic, three-electrode quartz vessel with a nominal volume of 10 mL. The working electrode was a glassy carbon electrode modified with sulfuric acid (VI), and its potential was measured against a silver chloride reference electrode. Platinum wire was utilized as an auxiliary electrode. The electrolyte utilized was 0.05 M KNO_3. Ascorbic acid was extracted from ground apple skins into 25 mL of 0.05 M KNO_3. The total ascorbic acid content was determined using the multiple standard addition technique.

The voltammetric method developed for the determination of ascorbic acid was validated through the assessment of its linearity range as well as the limits of detection (LOD) and quantification (LOQ). The LOD was calculated from the parameters of the calibration curve, and the LOQ was defined as three times the LOD. The method demonstrated excellent linearity over the concentration range of 1.6–1000 mg/L. The limit of detection was 0.5 mg/L, whereas the limit of quantification was 1.6 mg/L.

Optimization of the extraction procedure for ascorbic acid from apple peels involved evaluating the influence of KNO_3 concentration and extraction time. The concentrations of KNO_3 examined were 0.005 M, 0.01 M, 0.05 M, and 0.1 M, while the extraction times tested were 5, 10, 15, and 30 min. The best extraction conditions were established as 0.05 M KNO_3 and an extraction time of 15 min, which yielded the highest extraction efficiency.

The precision of the method, expressed as the standard deviation of ascorbic acid content (mg/g) in the analyzed samples, ranged from 0.05 to 0.46, indicating satisfactory repeatability for quantitative analysis.

2.7. Statistical Analysis

The experimental data were processed with OriginPro 2025b (OriginLab, Northampton, MA, USA). The data presented are mean ± standard error of the mean (SEM) [35]. A one-way analysis of variance (ANOVA) and a Tukey post hoc test mean comparison were performed. Statistically significant differences at the level of $p < 0.05$ were marked

with different letters. Furthermore, a correlation matrix was generated, which exhibited Pearson's correlation coefficient for a selected set of parameters. The correlation matrix was generated based on raw data (n = 15).

Linear regression was applied to estimate the slope and intercept of the model, which were used to determine the effective diffusion coefficient, activation energy, and specific energy consumption. The goodness of fit was evaluated using the coefficient of determination (R^2), adjusted R^2, and the root mean square error (RMSE). For each fit, 95% confidence intervals for the regression line and 95% prediction bands were also determined.

All calculations were carried out using Statistica 12 software (StatSoft, Tulsa, OK, USA).

3. Results and Discussion

3.1. Kinetics of the Drying Processes

The obtained drying curves are characteristic of vegetables and fruits, with no distinct period of constant drying rate (Figure 2). The shape and course of the curves indicate that the entire drying process took place during a period of falling drying rate. This is indicated by the nonlinear decrease in the dimensionless moisture curves Y_i (Figure 2a) and the absence of a straight-line segment horizontal to the X-axis (plateau) on the drying rate curve DR_i (Figure 2b).

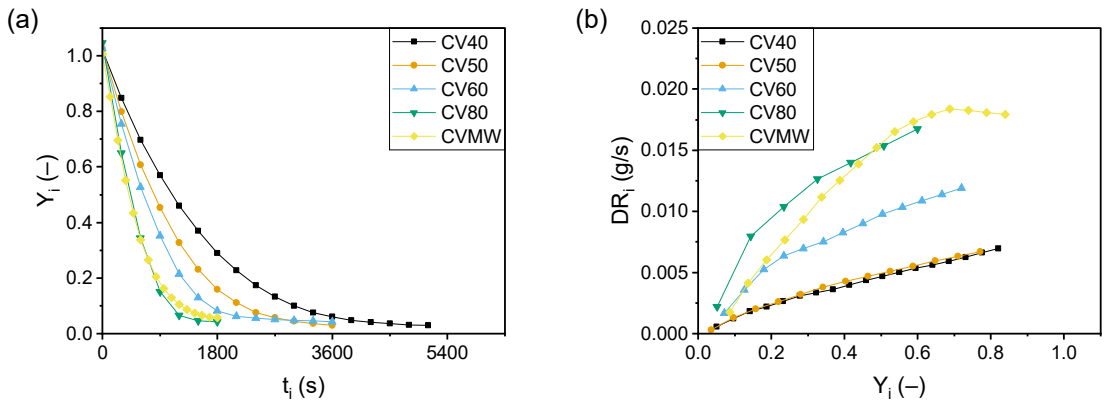


Figure 2. Dependency of the dimensionless moisture content Y on time (**a**) and drying rate DR on dimensionless moisture content (**b**) for particular processes.

The drying curves also demonstrate the impact of the drying conditions on the kinetics of the processes. It can be observed that an increase in air temperature corresponds to an increase in instantaneous drying rate (Figure 2b). The application of microwaves resulted in a substantial influence on drying kinetics. The dimensionless moisture content curve for the CVMW process exhibits a trend similar to the curve obtained for the convection process at 80 °C. However, it should be noted that the convective-microwave process (CVMW) was carried out at the lowest air temperature, that is, 40 °C.

The drying kinetics of the apple peels observed in this study proceeded exclusively within the falling-rate regime, with no visible constant-rate period. This trend indicates that the drying process was governed by internal mass transfer resistance rather than surface evaporation from the outset. This mechanistic behavior can be attributed to the complex cellular structure of the apple peel, where a significant portion of moisture (typically 78–95%) is stored intracellularly [36]. For evaporation to occur, this water must traverse biological barriers such as cell walls and membranes via symplastic or apoplastic routes. The resulting internal resistance prevents the maintenance of a saturated surface layer required for a constant-rate stage [37]. While similar falling-rate behaviors have been observed across various plant matrices [38–41], our data confirms that for apple peels, the internal mass transfer remains the rate-limiting step throughout the entire process,

as the surface cannot be replenished with moisture as quickly as it is removed by the drying medium.

The average values of drying rate (*DR*) and drying time (*DT*) are particularly useful in comparative analyses of drying processes. The values of DR_{av} and *DT* (Figure 3) are consistent with the results of the analysis of drying curves (Figure 2). The convective process exhibited the lowest average drying rate at 40 °C, while the highest rate was observed for the convective-microwave process (CVMW) (Figure 3a). The impact of drying conditions is evident: an increase in the temperature of the drying agent corresponds to an increase in the average drying rate. However, it should be noted that the increase in drying rate, in relation to the slowest CV40 process, is relatively small in the CV50 and CV60 processes (15 and 57%, respectively), while it is very pronounced in the CV80 process (approx. 200%).

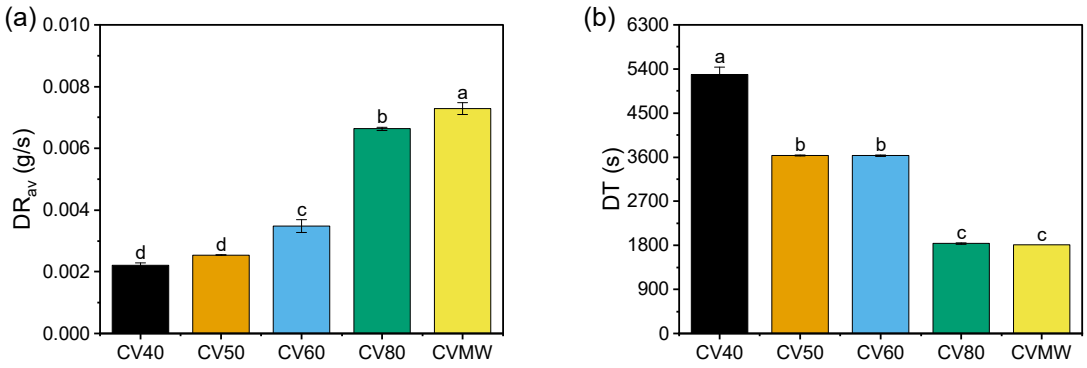


Figure 3. Average drying rate DR_{av} (**a**) and drying time *DT* (**b**) for particular processes (error bars represent the SEM; bars labeled with different lowercase letters are significantly different according to Tukey's HSD test at $p < 0.05$).

An analysis of the average drying time, *DT*, reveals a trend of change similar to that observed for the average drying rate. The convection process at 40 °C demonstrated the longest drying time, while the convective-microwave process (CVMW) had the shortest one (Figure 3b). It can also be seen that the average drying time for the CV50 and CV60 processes was reduced by a similar amount compared to the CV40 process (approx. 31%). Similarly, the CV80 and CVMW processes exhibited comparable drying times, with reductions of 65% and 66%, respectively, when compared to the CV 40 process.

Statistical analysis revealed a significant (at $p \leq 0.05$) strong negative correlation between average drying rate DR_{av} and drying time *DT* (Pearson's coefficient $r = -0.93$, Figure A4).

The experimental data was used to calculate the average moisture content of the material (9) and the rate of moisture content change (8). The values obtained were then plotted as $-\left(d\overline{X}/dt\right)_i = f\left(\overline{X}\right)_i$ and approximated by a linear function (Figure A1). Accordingly, an approximation of the drying constant *k* (that is, the slope of the straight line) was determined. The mass transfer coefficient α (6) and the effective diffusion coefficient D_{eff} (7) were also determined. Adjusted R^2 and RMSE values indicate an adequate fit of the model to the experimental data (Table 2).

All values determined through this analysis demonstrate a consistent trend of change in response to changes in drying conditions. In the context of convective drying, an increase in the temperature of the drying medium has been shown to result in an increase in the drying rate, the mass transfer coefficient, and the effective diffusion coefficient (Table 2). The application of microwaves during convective drying in the CVMW process resulted in a significant increase in the determined parameters, despite the low temperature of the

drying air, that is, 40 °C. The relative change in D_{eff}, compared to the solely convection process carried out at an air temperature of 40 °C (CV40), was in this case nearly 200%.

Table 2. The values of the drying constant k, effective diffusion coefficient D_{eff}, mass transfer coefficient α, adjusted R^2 and root mean square error *RMSE* for particular processes.

Process	k (1/s)	D_{eff} (m^2/s)	α (m/s)	adj. R^2	RMSE
CV40	$6.53 \times 10^{-4} \pm 5.33 \times 10^{-7}$	$2.64 \times 10^{-10} \pm 2.16 \times 10^{-13}$	$6.53 \times 10^{-7} \pm 5.33 \times 10^{-10}$	0.9821	8.90×10^{-5}
CV50	$8.80 \times 10^{-4} \pm 7.01 \times 10^{-5}$	$3.57 \times 10^{-10} \pm 2.84 \times 10^{-11}$	$8.80 \times 10^{-7} \pm 7.01 \times 10^{-8}$	0.9724	1.89×10^{-4}
CV60	$1.15 \times 10^{-3} \pm 1.80 \times 10^{-5}$	$4.67 \times 10^{-10} \pm 7.28 \times 10^{-12}$	$1.15 \times 10^{-6} \pm 1.80 \times 10^{-8}$	0.9471	3.77×10^{-4}
CV80	$1.73 \times 10^{-3} \pm 4.98 \times 10^{-5}$	$7.00 \times 10^{-10} \pm 2.02 \times 10^{-11}$	$1.73 \times 10^{-6} \pm 4.98 \times 10^{-8}$	0.9255	6.22×10^{-4}
CVMW	$1.93 \times 10^{-3} \pm 1.66 \times 10^{-5}$	$7.80 \times 10^{-10} \pm 6.75 \times 10^{-12}$	$1.93 \times 10^{-6} \pm 1.66 \times 10^{-8}$	0.9776	3.49×10^{-4}

Furthermore, statistical analysis based on raw data (n = 15) indicated a significant (at $p \leq 0.05$) strong positive correlation between the effective diffusion coefficient D_{eff} and the average drying rate DR_{ave} (Pearson's coefficient r = 0.99, Figure A4). It should be noted, however, that this exceptionally high correlation is partly a result of mathematical coupling, as both parameters are derived from the same primary drying data. Consequently, this specific relationship should be interpreted as an indication of the internal consistency of the calculation pathway rather than as an independent physical discovery.

The effective diffusion coefficients determined for convective processes allowed the calculation of the energy activation E_a. For this purpose, the obtained values were plotted as $\ln\left(D_{eff}\right) = f(1/T)$ (Figure 4). The value of E_a was then determined from the slope coefficient in accordance with Equation (10). The calculated activation energy value was equal to 22.28 kJ/mol, which is consistent with the results reported in the literature [42,43]. The statistical analysis indicates a very good fit of the model to the experimental data (Figure 4).

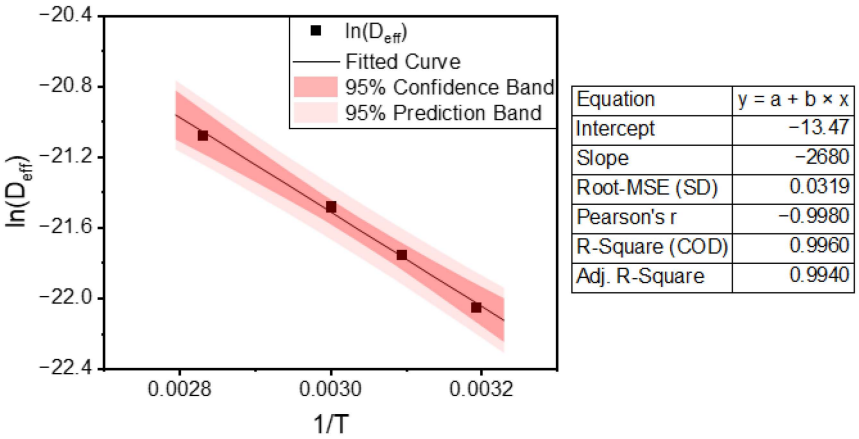


Figure 4. The relationship between the effective diffusion coefficient and air temperature for convectively dried apples.

It is obvious that drying conditions significantly influence the kinetics of the process. Increases in air temperature result in increased drying rates and reduced drying times. The phenomenon can be explained by both the improved vapor pressure difference between the material and the ambient air and the reduction in relative humidity at elevated tempera-

tures, which accelerates the process of moisture evaporation [37]. Furthermore, an increase in air temperature also affects internal mass transport processes. Taking into account that the effective diffusion coefficient is strongly influenced by temperature, a relationship described by the Arrhenius Equation (10), increasing temperature exponentially increases the effective diffusion coefficient, leading to an increase in the drying rate and a shortening of the drying time [24].

In the present study, the application of microwave energy appeared to enhance the drying rate and potentially reduce the overall drying time. This observation could be attributed to the volumetric heating effect of microwaves, which may heat the material more rapidly from the inside to the outside compared to conventional convective methods. Under these experimental conditions, vapor likely forms within the food and spreads through an internal pressure gradient. Due to the penetrability of microwaves, it is plausible that the interior and exterior of the food are heated simultaneously, contributing to an effective temperature rise [44]. During microwave-convective drying, it might be inferred that moisture evaporation is primarily facilitated by microwave energy, while heated air serves to remove moisture from the drying chamber [45]. The observed increase in effective moisture diffusivity may also be linked to microwave energy, as internal heating is suggested to reduce the resistance to moisture movement [37]. Furthermore, the increased mass transfer could potentially result from microwaves disrupting cellular structures and forming microchannels, as reported in similar studies [46].

3.2. Energy Intensity of the Drying Processes

Drying conditions also affected the energy consumption of the processes. In the case of convective processes, an increase in the temperature of the drying agent increased the specific energy consumption (Figure 5). However, an exception was observed in the drying process at 80 °C, where a decrease in *SEC* is visible. This phenomenon can be attributed to the fact that the energy consumption of a given convective process is determined by two factors. Firstly, the electrical power and secondly, the total drying time. Under constant drying conditions, electrical power is typically constant and can be determined from a graph of energy consumption (*EC*) versus time (Figure A2). Electrical power is, in this case, represented by the slope of the straight lines used to approximate the experimental data (points). As can be seen, electrical power (and instantaneous energy consumption) is closely related to the temperature of the drying medium (Figure A2). The higher the temperature of the drying medium, the higher the electric power (the value of the slope coefficient). Thus, two processes carried out at different temperatures can have the same energy consumption only if there is a sufficiently large difference in drying time between them.

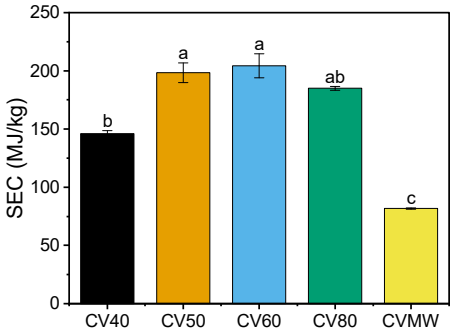


Figure 5. Specific energy consumption *SEC* for particular processes (error bars represent the SEM; bars labeled with different lowercase letters are significantly different according to Tukey's HSD test at $p < 0.05$).

The increase in instantaneous energy consumption in the CV50 and CV60 processes, resulting from the need to elevate the air temperature from 40 to 50/60 °C, was not counterbalanced by a reduction in drying time. Therefore, higher specific energy consumption was observed compared to CV40 (an increase of 36% and 40%, respectively). In the case of the CV80 process, the increase in instantaneous energy consumption was balanced by a reduction in drying time, resulting in a smaller overall *SEC* than CV50 and CV60.

Energy consumption is a critical factor in the assessment of the drying processes of fruits and vegetables, including apples. The effective utilization of energy has been demonstrated to result in a number of key benefits, including a reduction in operational costs, a diminution in environmental impact, and an enhancement in food quality and safety [47]. Traditional drying techniques, such as sun and solar drying, are characterized by their low energy intensity. However, these techniques often result in product deterioration and contamination [47]. For this reason, there is an ongoing endeavor to identify methodologies that are both energy-efficient and quality-preserving [48,49]. Innovations in drying technology, such as microwave and convective-microwave drying, are tested experimentally to address these issues. Hybrid systems (e.g., hot air–microwave, hot air–infrared) have been shown to further reduce *SEC* and emissions. Some studies have reported a reduction in *SEC* of up to 70% in comparison with traditional methods [50–53].

3.3. Quality of Products

3.3.1. Water Activity (a_w)

The water activity, a_w, in all dried products reached a value below 0.6, allowing us to assume that the growth of pathogenic microorganisms, such as yeast, fungi, and molds, is significantly limited [6]. A comparative analysis reveals that products dried using CV40, CV50, and CVMW convection and microwave processes exhibited comparable water activity values, that is, 0.422 (Figure 6). The products that were dried at temperatures of 60 °C and 80 °C were characterized by lower values of water activity, which are 0.219 and 0.181, respectively. This discrepancy is probably due to variations in the relative humidity of the drying air, which was measured at 4–7% for the CV40, CV50 and CVMW processes, and 2% and 1% for the CV60 and CV80 processes, respectively. As the samples were subjected to a drying process until a constant weight was achieved, the final (equilibrium) moisture content of the material may vary slightly, which affected the a_w value.

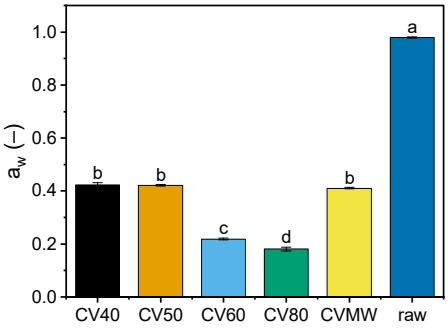


Figure 6. Water activity a_w of raw and dried samples (error bars represent the SEM; bars labeled with different lowercase letters are significantly different according to Tukey's HSD test at $p < 0.05$).

Water activity is one of the most important quality parameters for dried fruits and vegetables. It directly influences microbial growth, spoilage, and the overall stability of food products. One can see that drying conditions may affect the water activity of dried products. In convective drying, a decrease in water activity is typically observed as the temperature of the drying medium increases [54,55]. This is often related to the equilibrium moisture content that the material reaches under the given thermodynamic conditions of

the air. In the case of microwave drying, a decrease in water activity is observed as the power of radiation increases. This may be due to more efficient drying, which involves heating the entire volume and facilitating moisture transport [56]. In effect, lower final moisture content and water activity are observed.

3.3.2. Color of the Products

Analyzing the overall color change dE, it can be concluded that the color of the products obtained in all drying processes was noticeably different from the color of the raw material ($dE > 4$) [32]. In the CV40 and CV80 convection processes, the color change was smaller ($dE \approx 6$) compared to other processes (Figure 7) and resulted mainly from the change in the lightness L^* (Figure A3). In the CV50 and CV60 convection processes and the convective-microwave (CVMW) process, a significant color change was observed ($dE \approx 9$–10). In this case, the dE value was predominantly influenced by alterations in both the lightness (L^*) and the a^* (red-green) component. It is worth noting that, regardless of the drying conditions, dried products were characterized by greater lightness than the raw material (increase in the L^* value, Figure A3), which may have a positive effect on the perception of color [32].

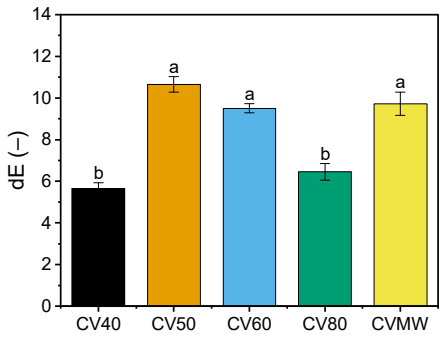


Figure 7. Color change index dE of dried samples (error bars represent the SEM; bars labeled with different lowercase letters are significantly different according to Tukey's HSD test at $p < 0.05$).

The drying conditions also affected the chroma C^* and hue values. Products subjected to drying temperatures of 40 and 80 °C exhibited a C^* value that was comparable to that of the raw material (Figure 8a). In contrast, products exposed to drying temperatures of 50 and 60 °C demonstrated a slightly diminished value of C^*, suggesting a less pronounced color intensity and a shift towards gray shades. Products obtained after drying in a convective-microwave process (CVMW) exhibited the highest C^* value, indicating an increase in color intensity compared to the raw material. When analyzing hue h (Figure 8b), a slight increase in value can be observed for all dried products except those dried by convection at the lowest temperature of 40 °C.

From an analysis of the browning index BI and the yellowness index YI, it can be observed that products dried by convection at 40 and 80 °C, as well as by the convective-microwave process (CVMW), had values of both parameters similar to those of the raw material (Figure 9). In the case of products dried using the CV50 and CV60 processes, a significant decrease in the BI and YI values was observed.

Statistical analysis revealed a significant (at $p \leq 0.05$) strong positive correlation between browning index BI and yellowness Index YI (Pearson's coefficient $r = 0.98$, Figure A4).

The color of dried fruits and vegetables is another important quality indicator. It is one of the first attributes a consumer assesses and is closely related to their perception of its quality, freshness, and flavor [30]. Drying conditions, particularly temperature, air velocity, and the technology used, have a significant impact on the final color of the product, because of their influence on enzymatic and nonenzymatic reactions. Studies on apple drying show

that both air temperature and velocity have a notable effect on color [57,58]. Increasing the drying temperature can accelerate browning reactions that affect overall color change [58]. However, in most cases, higher temperatures also reduce drying time, which can limit the duration of browning reactions and thus the overall color change [30,57,59]. Therefore, finding an optimal temperature is crucial to minimizing browning and overall color change.

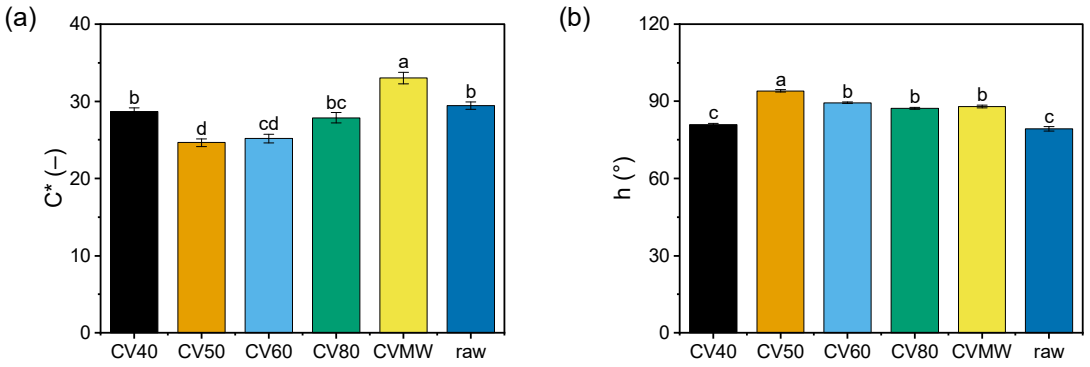


Figure 8. Chroma C^* (**a**) and hue h (**b**) of raw and dried samples (error bars represent the SEM; bars labeled with different lowercase letters are significantly different according to Tukey's HSD test at $p < 0.05$).

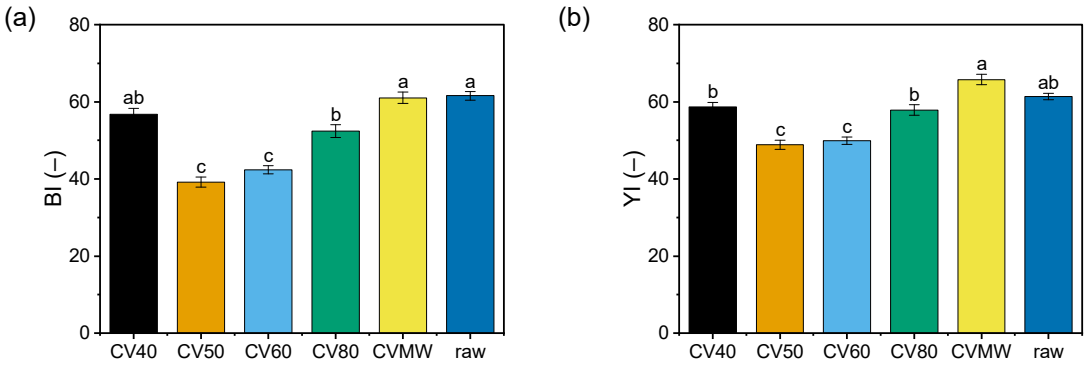


Figure 9. Browning index BI (**a**) and yellowness index YI (**b**) of raw and dried samples. (error bars represent the SEM; bars labeled with different lowercase letters are significantly different according to Tukey's HSD test at $p < 0.05$).

Microwave-assisted drying methods, including vacuum-microwave drying and combined convective-microwave drying, often result in better color retention compared to traditional hot-air drying. This is primarily due to the fact that microwaves generate heat volumetrically within the product, leading to a much faster and more uniform temperature increase. This rapid heating can quickly deactivate the enzymes responsible for browning [58,60].

3.3.3. Ascorbic Acid Content (*AAC*)

Last but not least, the quality parameter evaluated in the studies was the ascorbic acid content *AAC*. In this study, the samples dried at 40 °C (CV40) were strategically selected as the reference baseline for calculating relative ascorbic acid (*AA*) retention. This approach was necessitated by the requirement for a stabilized analytical matrix, as direct voltammetric measurements on raw apple peels are scientifically compromised by the high activity of endogenous ascorbate oxidase and complex matrix interferences. In the raw state, these biochemical factors induce rapid, uncontrolled analyte degradation during the extraction phase, leading to poor measurement reproducibility and an unreliable baseline. By utilizing the mildest drying condition (CV40) as the reference, the enzymatic activity

is effectively neutralized and the matrix is stabilized. This ensures that the comparative analysis reflects the actual impact of process intensity (higher temperatures and microwave energy) on nutrient retention, rather than being confounded by the inherent instability of the raw material.

It was found that products subjected to drying at higher temperatures (50, 60, and 80 °C) and with microwave application (CVMW), exhibited a smaller *AAC*. The relative change for convection processes was approximately 7–8%, while for the convective-microwave process (CVMW) it increased significantly to 20% (Table 3).

Table 3. Ascorbic acid content *AAC* and relative change in ascorbic acid content in dried products.

Process	*AAC* (mg/g DM)	% Relative Change
CV40	4.36 ± 0.21 a	–
CV50	4.02 ± 0.22 ab	−7.87
CV60	4.06 ± 0.19 ab	−7.01
CV80	4.07 ± 0.18 ab	−6.98
CVMW	3.48 ± 0.14 b	−20.35

AAC—ascorbic acid content in mg per 1 g of dry matter; mean ± standard error of the mean (SEM); values within column followed by different lowercase letters are significantly different according to Tukey's HSD test at $p < 0.05$.

The temperature gradients of 40, 50, 60, and 80 °C were strategically selected to investigate the boundaries of the 'energy–quality nexus' in apple peel drying. The exclusion of 70 °C was justified by the observed asymptotic behavior of ascorbic acid (*AA*) degradation. Preliminary tests and the final results confirmed that *AA* content stabilized at a similar level for treatments at 50, 60, and 80 °C, indicating that a degradation plateau is reached within this range. Consequently, the existing matrix effectively captures the transition from the high-retention zone (40 °C) to the stabilized low-retention zone (50–80 °C), making additional sampling at 70 °C redundant for the mechanistic understanding of the process.

The amount of ascorbic acid in dried fruits and vegetable peels is very important due to several aspects, in particular its nutritional value, as a quality indicator, and waste valorization. Ascorbic acid is an essential nutrient and potent antioxidant for the human body, helping to prevent diseases and support overall health. Dried fruit peels, especially apple peels, can be a significant source of these nutrients. Therefore, maintaining a high *AAC* in dried products is vital to maintain their health benefits. It is also known that ascorbic acid is highly susceptible to degradation from heat, oxygen and light; therefore, its retention level is often used as an indicator of overall quality of the processed foods. Significant loss of ascorbic acid often indicates a more general degradation of other sensitive compounds and sensory qualities, such as color and flavor. Finally, fruit peels, such as those from apples and oranges, are often discarded but are rich sources of bioactive compounds, including ascorbic acid. Drying is a key step in valorizing these by-products for use in functional foods or nutraceuticals, making *AAC* preservation a primary goal.

Since ascorbic acid is a highly thermolabile compound, an increase in the temperature of the drying agent generally results in a decrease in the content of this compound in products [61]. However, some researchers have observed a non-linear relationship between *AAC* and the temperature of the drying agent. In this case, intermediate temperatures of 50–60 °C resulted in greater losses of ascorbic acid compared to high temperatures of 70–80 °C [62,63]. This phenomenon can be attributed to the reduction in drying time, which signifies that the material is exposed to unfavorable factors such as high temperature (above 45 °C), light, and oxygen for a more limited duration.

3.4. Practical Implications for By-Product Valorization and End-Use Suitability

The selection of the optimal drying protocol for apple peels must be dictated by the intended application, as process parameters affect quality markers in a non-linear manner. Our results demonstrate the following:

- For Long-term Storage and Microbiological Stability, convective drying at 80 °C (CV80) is the most effective, yielding the lowest water activity (a_w) compared to all other treatments (CV80 < CV60 < CV40 ~ CV50 ~ CVMW $\ll$ raw). This makes it the preferred method for producing stable intermediate products for the animal feed industry or for long-term storage before pectin extraction.
- For Food Ingredients Prioritizing Visual Quality, if the dried peel is intended for use in functional snacks or tea infusions, color stability is paramount. While CV40 and CV80 showed the lowest total color change (dE), the browning (BI) and yellowness (YI) indices were significantly lower for CV50 and CV60. This suggests that moderate temperatures (50–60 °C) are most effective at inhibiting enzymatic browning compared to the raw material and CVMW treatments.
- For Nutraceuticals and Vitamin C Retention, the retention of ascorbic acid (AA) highlights a critical limitation of hybrid drying for this matrix. The results (CV40 > CV50 ~ CV60 ~ CV80 $\gg$ CVMW) indicate that even the lowest microwave power (100 W) induces severe degradation of thermolabile compounds compared to purely convective methods. Consequently, while CVMW accelerates the process, it is suboptimal for applications where the recovery of antioxidant markers is the primary objective.

In summary, the end-use of the by-product defines the 'best' treatment: CV80 for stability and energy efficiency, and CV50/CV60 for superior aesthetic properties, whereas CVMW remains a boundary condition illustrating the maximum tolerable thermal stress for the apple peel matrix.

4. Conclusions

The convective and convective-microwave drying of apple peels were examined regarding process kinetics and their impact on the final quality of the dried product. Convective-microwave drying proved to be the most effective from a kinetics perspective but was associated with the greatest deterioration in material quality. During convective drying, temperature significantly influenced process kinetics: the higher the temperature, the more efficient the drying process. Furthermore, increasing the temperature caused only minor changes in the analyzed quality parameters. Given the positive effects on drying kinetics and the lack of adverse effects on energy intensity or quality, high-temperature convective drying appears to be a promising method for preserving apple peels. However, to fully understand the impact of drying on product quality, future analyses should be expanded to include indicators such as polyphenol content and antioxidant potential—parameters that are important for apple peels.

Integrating the parameters evaluated in each area (kinetics, energy consumption, and quality) is not easy due to their large number and the mutual influence of process conditions. The parameters evaluated for the above-mentioned aspects are closely related, and it is not possible to modify any one of them without affecting others. For example, it is possible to obtain a high-quality product by applying mild drying conditions; however, this will affect both process kinetics (drying rate) and energy intensity. On the other hand, drying under severe conditions can lead to a significant reduction in drying time and (even) a reduction in the consumption of energy, but the products obtained are of poor quality, making them worthless. Considering the interdependence between the particular parameters, the best program should be characterized by a reasonable drying rate and energy intensity of the process, combined with the highest possible product quality.

The good kinetics of convection-microwave drying suggest future research directions. These involve finding convection-microwave drying conditions that do not significantly degrade the kinetics of the process while significantly improving the quality of the resulting dried product. Convective drying assisted by intermittent microwaves may be an appropriate solution.

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Conflicts of Interest: The authors declare no knowledge of existing or possible conflicts of interest.

Appendix A

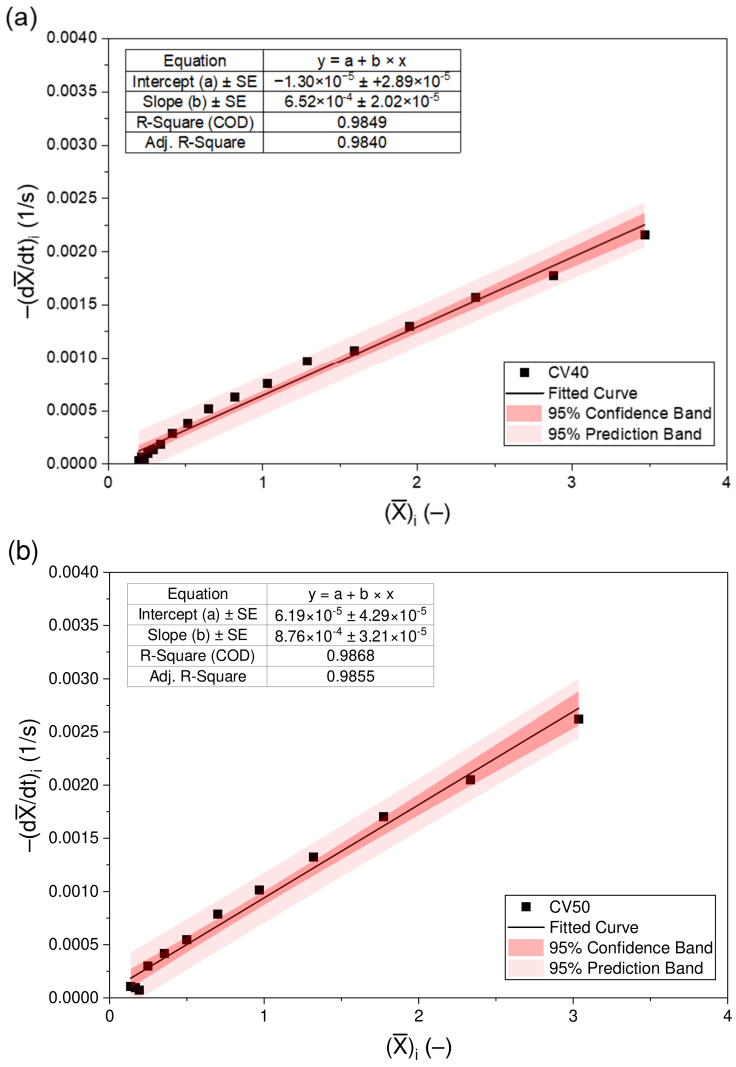


Figure A1. *Cont.*

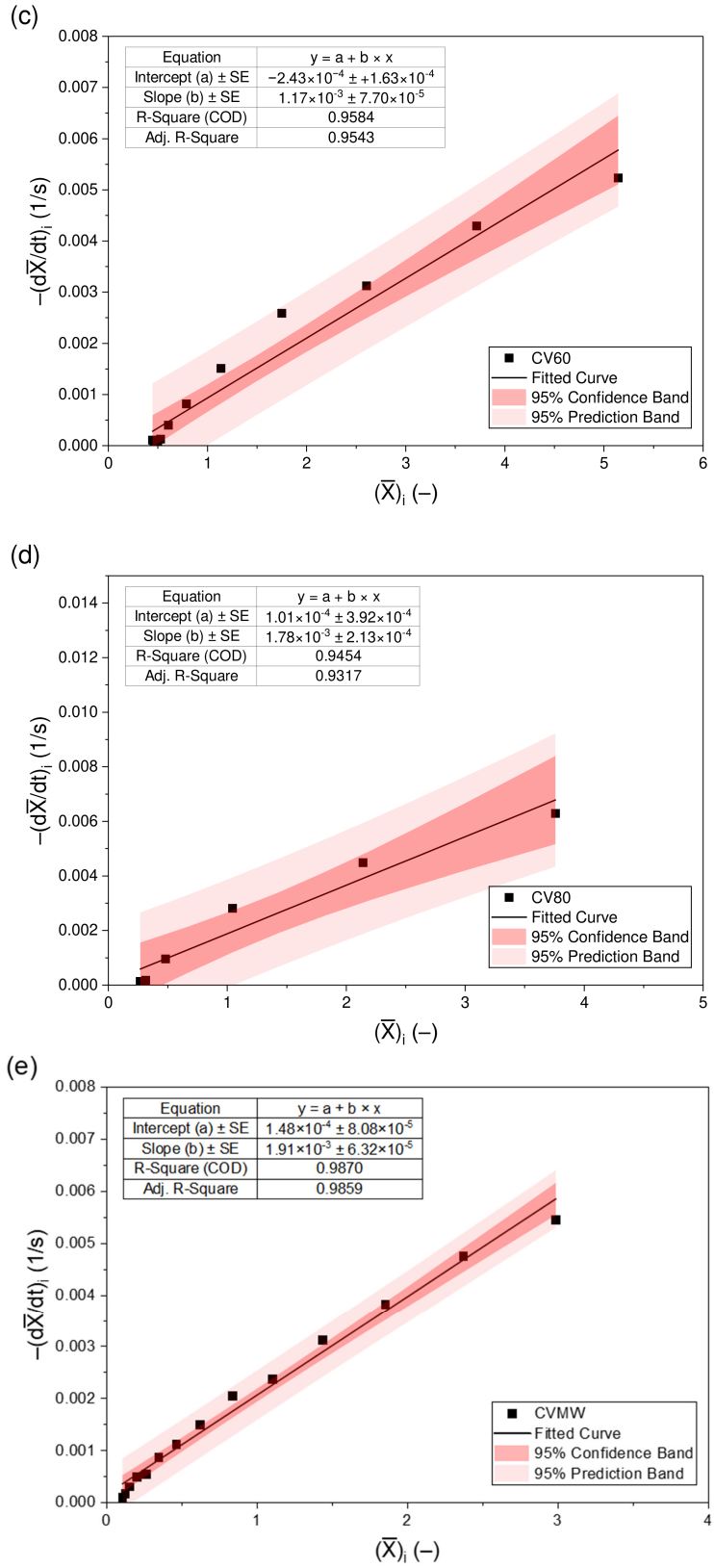


Figure A1. Sample plots of the rate of moisture content change over average moisture content for: CV40 (**a**), CV50 (**b**), CV60 (**c**), CV80 (**d**), and CVMW (**e**).

Equation	y = a + b × x				
Plot	CV40	CV50	CV60	CV80	CVMW
Intercept (a)	0	0	0	0	0
Slope (b) ± SE	$9.64\times10^{-5} \pm 4.03\times10^{-7}$	$1.29\times10^{-4} \pm 5.57\times10^{-7}$	$2.09\times10^{-4} \pm 1.50\times10^{-6}$	$3.39\times10^{-4} \pm 1.45\times10^{-6}$	$1.79\times10^{-4} \pm 1.11\times10^{-6}$
R-Square (COD)	0.9992	0.9992	0.9974	0.9994	0.9988
Adj. R-Square	0.9992	0.9992	0.9973	0.9994	0.9987

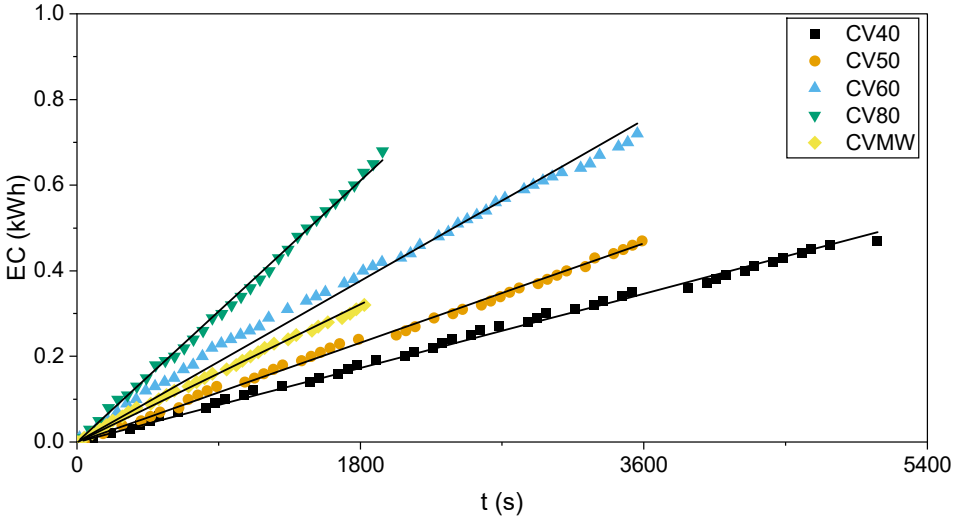


Figure A2. Sample energy consumption (*EC*) versus time (*t*) curves for individual processes: points—experimental data; lines—linear regression ($y = a + b \times x$).

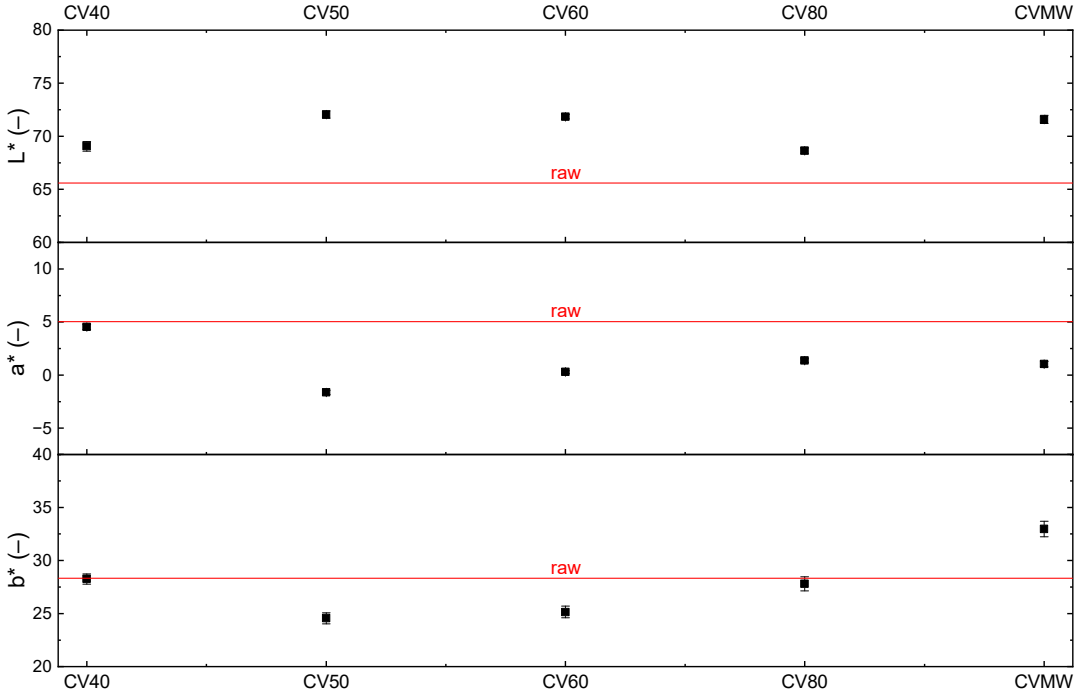


Figure A3. Color components in the CIELAB space: *L**—lightness; *a**—chromatic coordinate from green to red; *b**—chromatic coordinate from blue to yellow (error bars represent the SEM; black squares represent the parameter value for the dried product; red line represents the parameter value for the raw material).

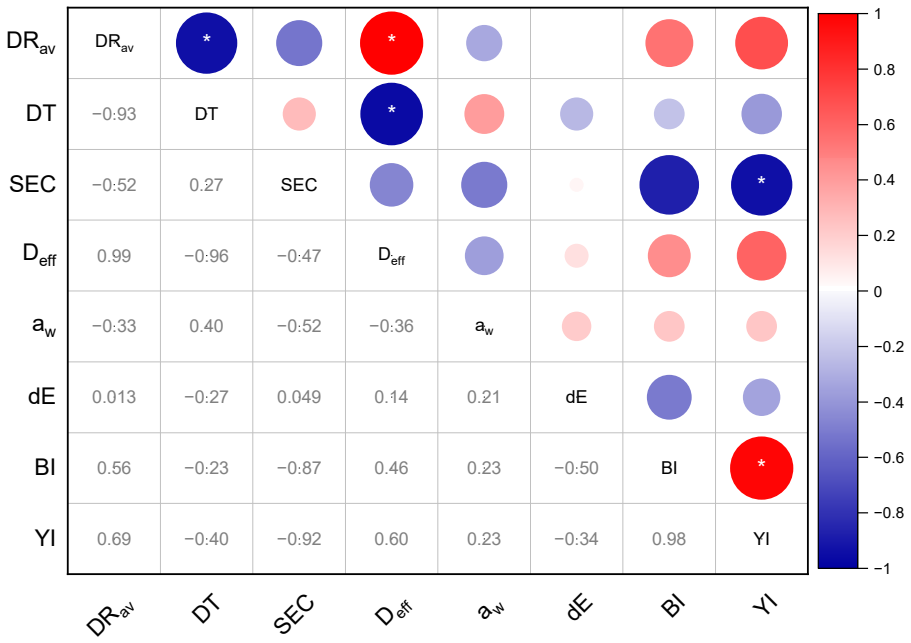


Figure A4. Correlation matrix of the analyzed variables: DR_{av}—average drying rate; DT—drying time; SEC—specific energy consumption; D_{eff}—effective diffiusion diffusion coefficient; a_w—water activity; dE—color change index; BI—browning index; YI—yellowness index (numerical values indicate Pearson's correlation coefficient *r*; circle diameter and color intensity are proportional to coefficient magnitude, with larger and more saturated circles denoting stronger correlations; color hue indicates relationship direction, with red for positive $r > 0$ and blue for negative $r < 0$; asterisks (*) indicating statistically significant correlations at $p \leq 0.05$).

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