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Convective Drying of Apple Enhanced with Microwaves and Ultrasound—Process Kinetics, Energy Consumption, and Product Quality Approach

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Abstract: This research explores the drying kinetics of apples, evaluating the impact of convective drying (CV), ultrasonically assisted convective drying (CVUS), and convective–microwave processes (CVMW1 and CVMW2) on energy consumption, drying time, temperature profiles, and product quality. Ultrasound-assisted convective drying (CVUS) exhibited a 10% reduction in drying time and a distinct "heating effect". Convective–microwave processes (CVMW1 and CVMW2) significantly reduced drying times (47% and 66%, respectively, compared to CV), raising concerns about potential deteriorative processes due to elevated temperatures. Numerical analysis, using the Midilli–Kucuk model, highlighted its robust fit and emphasized the influence of microwave and ultrasound on the effective diffusion coefficient. Quality assessment indicated enhancements in polyphenolic compounds, particularly in convective–microwave processes. The convective–microwave process at higher power (CVMW2) emerged as a balanced option, displaying improved kinetics, energy efficiency, and product quality. The findings underscore the potential of judiciously applying microwave and ultrasound technologies for significant energy reduction and process enhancement, with a recommendation for further exploration of new parameters. This study emphasizes the importance of considering both drying kinetics and product quality in evaluating drying processes for fruits and vegetables, providing valuable insights for industrial applications.

Keywords: drying kinetics; ultrasound-assisted drying; convective–microwave drying; polyphenolic compounds; effective diffusion coefficient

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1. Introduction

Fruits and vegetables are natural products that provide humans with important and essential nutrients such as sugars, vitamins, minerals, etc. Therefore, fruits and vegetables are of great commercial importance, and their cultivation is an important part of the agricultural industry [1]. Usually, fruits and vegetables contain more than 80% water. That's why they are highly perishable [2]. Therefore, one of the most important issues in vegetable and fruit processing is protecting them against spoilage. For this purpose, various techniques are used, such as freezing, canning, or dehydration. The last of these techniques is probably the oldest method of food preservation. The basic dehydration technique is drying. The most commonly used dehydration technique is hot air drying. The advantages of this drying method are the high efficiency of the process and the simplicity of the equipment used. However, this method also has disadvantages. It is usually energy-intensive and time-consuming and leads to a loss of nutritional value of fruits and vegetables.

Therefore, for many years, researchers' attention has been focused on searching for alternative dehydration methods. The aim of the research is to reduce energy consumption, shorten process time, and use low temperatures. Reducing energy consumption obviously reduces the costs of the process and, at the same time, has ecological significance. Reducing the process time directly affects the cost of the process and, additionally, reduces the loss of nutritional value of the fruit. Lowering the temperature usually lengthens the process time but may have a positive effect on the product quality. All of these strategies together can improve the process from an economic point of view. These include osmotic dehydration, freeze drying, or microwave drying [1]. This last technique seems to be particularly promising. Microwave energy is delivered directly to the moisture inside the material being dried. For this reason, drying takes place quickly and with little heat loss [3]. The hybrid technique, combining convection and microwave drying, is the most commonly used. As research shows [4], the use of microwave energy allows the drying time of fruits and vegetables to be shortened by as much as 90%. Thanks to this, there is huge potential for the use of microwave drying in industry. The use of microwaves increases investment costs, but in the long run, it leads to a significant reduction in operating costs, increasing the economic efficiency of the process. However, continuous microwave drying may cause overheating and deterioration of the quality of the dried material. This can be overcome, for example, by intermittent microwave–convection drying [5]. Another disadvantage of using microwaves is uneven heating due to the standing wave pattern. This disadvantage can be overcome by moving the material to be dried inside the drying chamber [6].

Another hybrid drying technique is convection–ultrasonic drying. In this case, ultrasound practically does not serve as an additional source of energy but improves heat and mass transfer [7,8]. This drying method has been used to dry various fruits and vegetables, such as strawberries [9], green peppers [10], persimmon [11], potatoes [12] and carrots [13]. Convection drying, aided by airborne ultrasound, was also used to dry apples [14–17]. In all cases, the use of ultrasound resulted in a shortening of the drying time and a certain improvement in the quality of the dry material compared to convection drying. According to Konopacka et al. [18], application of ultrasound as a pre-treatment operation for drying carrot slices led to a higher sensory appreciation of the product color. The use of ultrasound requires a new approach for designers because it is not yet used in industrial drying. However, research to date shows that conducting the process using ultrasound can lead to improved process economics.

In this work, it was decided to investigate a hybrid drying technique combining three methods of energy supply: convection, microwave, and ultrasonic. The tests were performed in a drum dryer, which allowed us to avoid the influence of non-uniform distribution of microwaves and ultrasound in the drying chamber. Apple was chosen as the dried material. This is because apples are one of the most widely cultivated fruits in the world. In the 2021/2022 season, global apple production amounted to 81.8 million tons. The largest apple producer in the world was China (45 million tons), followed by the European Union (11.9 million tons) and the USA (4.4 million tons). Poland is the leader of the apple market in the EU, where the harvest in the 2021/2022 season amounted to approximately 4.2 million tons [19].

The aim of this work is to check how the use of microwaves and/or ultrasound affects the process of convective drying of apples. In particular, the process time, its energy consumption, and the quality of the obtained dried apple are examined.

2. Materials and Methods

2.1. Material

Apples (*Malus domestica* cv. Ligol) were bought at a local market and stored for at least 24 h under refrigeration at 277 K before analysis. Samples for the drying operation were then prepared from the raw material. Apple fruits were cleaned and peeled with a ceramic knife to avoid interaction between biomaterial and the blade. Next, fruits were cut in the form of cubes with 10 mm sides and immersed for 2 min in the aqueous solution of sodium pyrosulfite ($Na_2S_2O_5$; 0.12% *w*/*w*) and citric acid ($C_6H_8O_7$; 0.25% *w*/*w*) at room temperature. After that, samples were drained for 2 min on a sieve, placed in the dryer's drum, and dried.

2.2. Drying Procedure

The apple cubes were dried using a hybrid drum dryer constructed by Promis-Tech (Wrocław, Poland). A scheme of the dryer is presented in Figure 1.

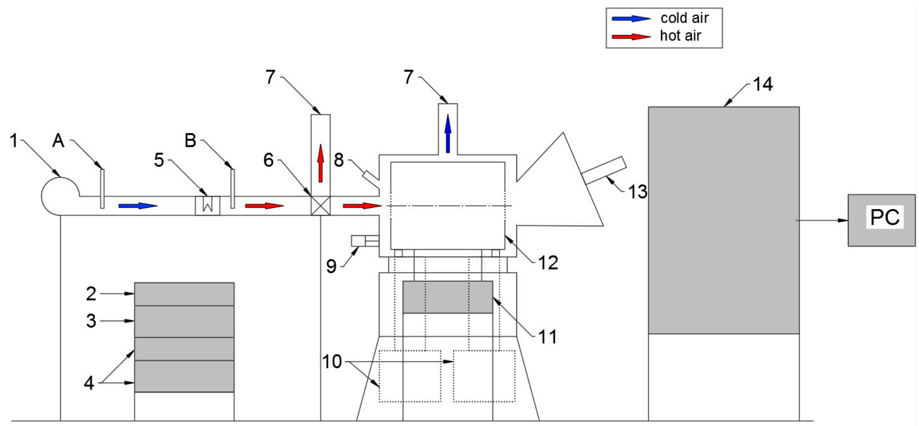


Figure 1. Scheme of drying system: 1: Blower (Fan), 2: AUS controller, 3: AUS preamplifier, 4: Microwave feeders, 5: Heater, 6: Pneumatic valve, 7: Air outlet, 8: Pyrometer, 9: Drum drive, 10: Microwave generators, 11: Balance, 12: Rotatable drum, 13: AUS transducer, 14: Control unit.

This apparatus enables convective (CV) and microwave drying (MW) separately as well as in different combinations (hybrid processes), with ultrasound (US) enhancement. The acoustic waves are generated by the Airborne Ultrasound System (AUS) developed and delivered by Pusonics (Madrid, Spain). The transducer (Figure 1(13)) is assembled at the door of the dryer, and emits a focalized acoustic field directly at the material placed in a rotatable drum (Figure 1(12)). It means that the waves' intensity converges with increasing distance from the transducer, and at about 420 mm from the radiator; it attains a maximum (160–170 dB). The distance between the emitter and samples was fixed at about 415 mm to ensure that samples stayed in the focusing area during the treatment. The intensity of the ultrasound may be adjusted continuously in the range of 1 W to 200 W. However, this value does not refer to the acoustic power delivered to the material but to the current consumed by the generator.

The mass of the sample was measured automatically during the process with the use of a balance (Figure 1(11)). During measurement, the balance was raised with a pneumatic lift, and the stream of hot air was forwarded to the outlet (Figure 1(7)) with a pneumatic valve (Figure 1(6)) to avoid disturbances. The temperature of the material was measured with two methods. For convective processes (CV, CVUS), this parameter was recorded automatically during the process with the use of an HTDL-30 autonomic recorder, produced by Dwyer (Michigan, IN, USA), and placed inside the drum. In the case of microwave programs (CVMW, CVMWUS), the temperature of the material was measured with the use of a Flir ThermaCAM B2 IR camera (ATEC, San Diego, CA, USA). Because this measurement requires direct access to the material being dried, the drying operation was periodically interrupted (for about 30 s for each 10 min of the process) while the thermogram of the samples was captured. Such interruptions did not meaningfully influence the overall kinetics of the process, which was checked through comparison with continuous processes without temperature measurements (interruptions).

Five different programs of drying were carried out in triplicate and the average values of measured parameters were calculated and utilized for further processing. Detailed descriptions of the particular schedules are provided in Table 1.

Table 1. Description of the drying schedules.

No	Symbol	Description
1	CV	convective drying at T_a = 343 K, with air flow velocity v_a = 2 m/s
2	CVUS	convective drying as in schedule No. 1 assisted with ultrasound of power P_{US} = 200 W
3	CVMW1	convective drying as in schedule No. 1 assisted with microwaves of power P_{MW} = 100 W
4	CVMW2	convective drying as in schedule No. 1 assisted with microwaves of power P_{MW} = 250 W
5	CVMWUS	convective drying as in schedule No. 1 assisted with microwaves of power P_{MW} = 100 W and ultrasound of power P_{US} = 200 W

The kinetics of each process were assessed on the basis of the evolution of the relative moisture content (MR) and temperature (T) of the samples. Relative moisture content at a given time of process was calculated in accordance with Equation (1):

$$MR(t) = (MC(t) - MC_{eq})/(MC_0 - MC_{eq}), \quad (1)$$

where MC(t) is the moisture content at a given time of the process (kg/kg_{db}); MC_{eq} and MC_0 are equilibrium and initial moisture content, respectively (kg/kg_{db}).

Equilibrium moisture content was constant for each variant of the process (MC_{eq} = 0.05), while the moisture content at a given time in the process (MC(t)) and initial moisture content (MC_0) were calculated with the use of Equations (2) and (3):

$$MC_0 = (m_0 - m_s)/m_s, \quad (2)$$

$$MC(t) = (m(t) - m_s)/m_s, \quad (3)$$

where m_0 and m_s are the mass of the fresh samples and the mass of the dry matter, respectively (kg), and m(t) is the mass of the samples at a given time in the process (kg). The mass of dry matter (m_s) was determined using the gravimetric method by drying to a constant weight at 343 K under vacuum ($3{\cdot}10^3$ Pa), according to ISO 1026:1982 [20].

Additionally, average drying rate (DR) was determined as a ratio of mass of evaporated moisture to the time in which this process proceeded, in accordance with Equation (4):

$$DR = (m_0 - m_{eq})/DT, \quad (4)$$

where m_{eq} is the equilibrium mass of the samples (kg) and DT is the drying time—duration of the drying operation (h).

Each drying schedule was also judged in terms of specific energy consumption (SEC). The overall energy (SEC) consumed by the drying system was measured during each process with the use of a standard electricity meter. The obtained value was related to the amount of moisture evaporated; thus, the energy consumed per 1 kg of removed water was determined in accordance with Equation (5):

$$SEC = 3.6{\cdot}EC/(m_0 - m_{eq}), \quad (5)$$

where EC is the overall energy consumed by the drying system (kWh) in the particular drying program.

2.3. Approximation of the Experimental Data

Experimental data (moisture ratio) was approximated with the use of four thin-layer drying models (Table 2), in accordance with the method described in [21].

Table 2. Methods applied for the estimation of experimental data [22].

Name	Formula
Newton	$MR = \exp(-kt)$ (6)
Page	$MR = \exp(-kt^n)$ (7)
Henderson–Pabis	$MR = a \cdot \exp(-kt)$ (8)
Midilli–Kucuk	$MR = a \cdot \exp(-kt^n) + bt$ (9)

Additionally, the effective diffusion coefficient D_{eff} was calculated for each drying scheme, in accordance with the method described by Szadzińska et al. in [21].

2.4. Analysis of the Quality of Products

2.4.1. Extraction of Phenolic Compounds

The frozen apple cubes were homogenized into a homogeneous powder in liquid nitrogen using a grinder (IKA A11 basic, IKA-Werke, Staufen, Germany). Extractions of phenolic compounds from apple powder (5 g) were carried out by homogenization for 2 min with a 70% aqueous methanol solution (Ultra Turrax T25 Basic IKA-Werke, Staufen, Germany). The sludge was then transferred to a volumetric flask and filled to the 50 mL mark with 70% methanol. The mixture was filtered through Whatman no. 3 filter paper. Before HPLC injection, all samples were diluted 1:3 in an acetate buffer (mobile phase A).

2.4.2. Analysis of Phenolic Compounds by HPLC

The polyphenolic compounds were determined using a modified version of the HPLC method of Tsao and Yang [23], using a Synergi 4 µm Fusion-RP 80A column (250 mm × 4.6 mm) with a guard column (Phenomenex®, Torrance, CA, USA). An Agilent 1200 series HPLC (Hewlett-Packard, Palo Alto, CA, USA) system equipped with a DAD detector was used. The mobile phase consisted of 10.2% (v/v) acetic acid in 2 mM sodium acetate (solvent A) and acetonitrile (solvent B). The flow rate was kept constant at 0.5 mL/min at 298 K. The analysis was conducted with a gradient program: 0–20 min, 3% B linear; 20–40 min, 17% B linear; 40–65 min, 40% B linear; 65–68 min, 90% B linear; 68–72 min, 90% B isocratic; and 72–73 min, 0% B linear, followed by washing and reconditioning of the column. Phenolic compounds were detected and quantified at 280 nm (flavan-3-ols, dihydrochalcones) and 320 nm (hydroxycinnamic acids) according to external standards. Results were expressed in mg/kg of dry matter (DM).

2.4.3. Analysis of Water Activity

The measurement of water activity took place using AW-Therm 40-RS (Rotronic, Bassersdorf, Switzerland).

2.5. Statistical Analysis

Statistical calculations were performed using Statistica ver. 12.0 computer software (StatSoft; Krakow, Poland). All analyses were carried out in triplicate. The analysis of one-way variance (ANOVA) and Tukey's multicomparison test were performed. Statistically significant differences were reported at $p < 0.05$.

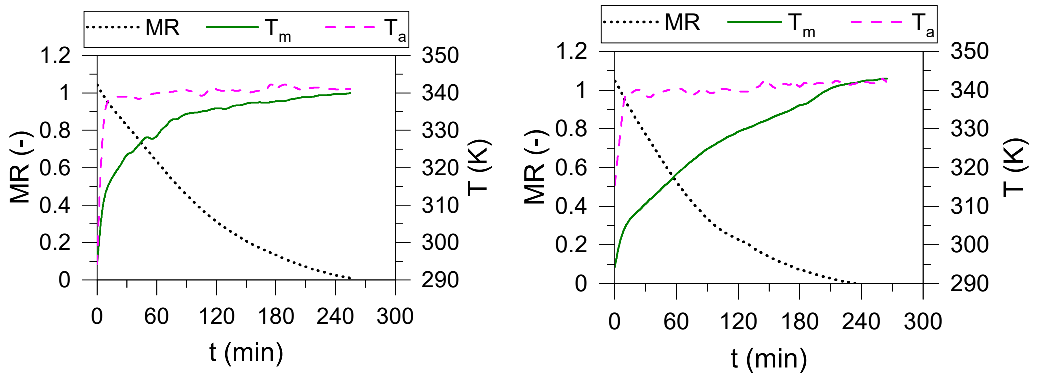
3. Results and Discussion

3.1. Drying Kinetics

In Figure 2 the evolution of relative moisture content (MR) and temperatures of samples (T_m) and drying agent (T_a) are presented for convective (CV) and ultrasonically assisted convective (CVUS) drying of apples.

Comparison of the obtained curves allows us to state that ultrasound visibly influenced the drying kinetics. In the case of ultrasound-assisted convective drying (CVUS), the time of drying was slightly shorter (10% reduction, cf. Figure 5a), and the material attained a higher temperature (Tm) at the end of the process compared to pure convective drying (CV).

Small kinetic advantages may result from the relatively high temperature of the drying agent (T_a = 343 K). It was stated in respective literature that the magnitude of ultrasound's influence on enhancing the drying process depends on the process variables employed. It is maximized when using low temperatures and high ultrasonic power levels. It is usually explained by the changes in air density and stronger attenuation of acoustic waves at higher temperatures. Ultrasound has a greater influence on enhancing the drying process when both external and internal resistances are present. At lower drying temperatures, ultrasound enhances both externally and internally controlled drying behavior [16].



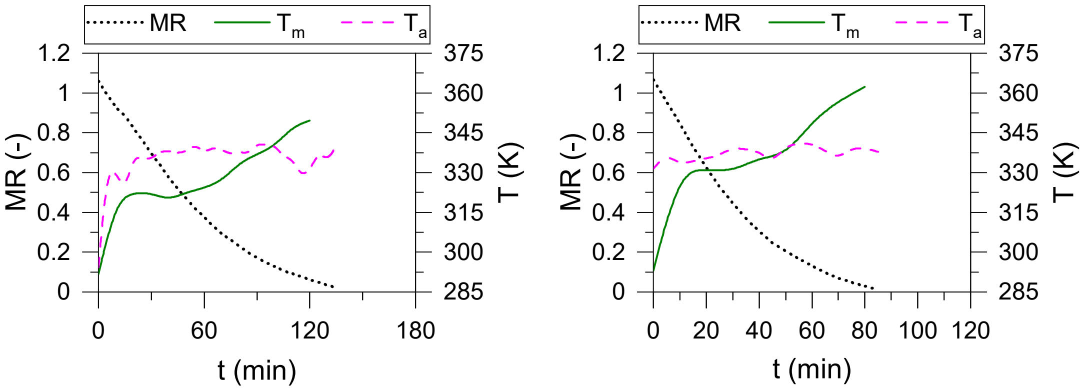
(**a**) (**b**)

Figure 2. Evolution of the relative moisture content (MR) and temperature of samples (T_m) and the drying agent (T_a) during: (**a**) convective drying (CV—schedule No. 1) and (**b**) convective drying assisted with ultrasound of a power P_{US} = 200 W (CVUS—schedule No. 2).

Analysis of the temperature curves revealed the occurrence of the "heating effect" of ultrasound. One can see that the temperature of the material (T_m) exceeded the temperature of the drying agent (T_a—Figure 2b) at the end of the process, which may be attributed to the thermal effect of the acoustic waves. Such a phenomenon was not observed for convective processes (CV), where the temperature of the material during the process increased asymptotically to the value of the temperature of the ambient air. The "heating effect" of ultrasound results from the conversion of mechanical energy carried by the waves into heat. The magnitude of this phenomenon depends on many parameters, both of the material (material structure, density, porosity, chemical composition, etc.) and the process type (temperature and air velocity, flow direction). Properties of materials may affect the action of ultrasound due to their influence on the attenuation factor. The higher the attenuation of ultrasound, the more the waves' energy is converted to heat, the greater the "heating effect". On the other hand, it was stated in [24] that the growth of temperature or velocity of air negatively affects the effectiveness of ultrasound enhancement, thus lowering the "heating effect". Moreover, the growth of material temperature induced by the "heating effect" is usually quite small (does not exceed 5–10 K), thus its influence on the overall temperature of the material decreases with the growth of temperature of the drying agent.

In Figure 3, the evolution of the relative moisture content (MR) and temperatures of samples (T_m) and drying agent (T_a) obtained during the convective–microwave processes (CVMW1 and CVMW2) are presented.

Application of microwaves during the convective process meaningfully influenced the kinetics of the drying operation (compare Figures 2a and 3). Drying times were significantly shortened in comparison to CV or even CVUS processes, and the magnitude of reduction depends on the power of the applied radiation. If the CV schedule is chosen as a reference process, then the drying time reduction equals 47% and 66% for PMW = 100 and 250 W, respectively (cf. Figure 5a). If the drying time of MW1 and MW2 is related to the CVUS schedule, then the advantage equals 41% and 63%, respectively. Additionally, the temperature of the sample surface (T_m), measured with an IR camera, increased violently at the beginning of the process, then stabilized for a short period of drying, and finally increased again, meaningfully exceeding the temperature of the drying agent (Ta). At the end of drying, the temperatures of the sample surfaces were equal to T_a = 350 K and 370 K for the CVMW1 and CVMW2 schedules, respectively. It doubtless resulted from the action of the microwaves, which are recognized as one of the most effective sources of energy. Application of this kind of radiation during drying of products rich in moisture, such as fruits and vegetables, was found to be very advantageous and usually leads to high kinetic benefits [25–27]. Unfortunately, such great increases in the samples' temperature may lead to many deteriorative processes, such as local overheating ("hot spots"); thermal decomposition of nutrients; changes in color, taste, and smell; and texture degradation, deformations, etc. [6,7,9]. For this reason, the quality of the products was analyzed in detail and is discussed in the next section.



(**a**) (**b**)

Figure 3. Evolution of the relative moisture content (MR) and temperature of samples (T_m) and the drying agent (T_a) during convective drying assisted with microwaves of power: (**a**) P_{MW} = 100 W (MW1—schedule No. 3) and (**b**) P_{MW} = 250 W (MW2—schedule No. 4).

In Figure 4, the drying curves obtained for the last and the most complex schedule are presented. In this case, the convective process was enhanced with both microwave and ultrasound radiation of a power P_{MW} = 100 W and P_{US} = 200 W, respectively.

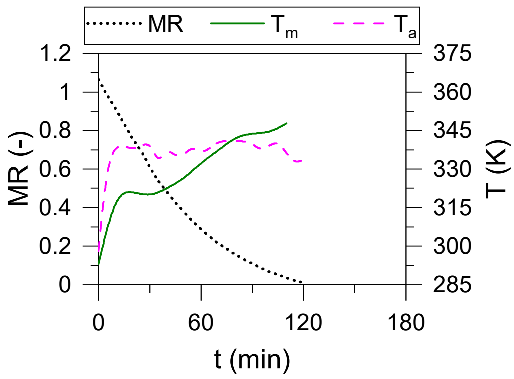


Figure 4. Evolution of the relative moisture content (MR) and temperature of samples (T_m) and the drying agent (T_a) during convective drying assisted with microwaves (P_{MW} = 100 W) and ultrasound (P_{US} = 200 W, CVMWUS—schedule No. 5).

One can see the time of drying was, in this schedule, significantly longer in comparison to CVMW2 (41% growth, cf. Figure 5a) but slightly shorter than that observed during CVMW1 (11% reduction, cf. Figure 5a). Nevertheless, in comparison to convective (CV) or even ultrasonically-assisted convective (CVUS) processes, the drying time was still shorter and the advantages were equal to 52% and 47%, respectively (cf. Figure 5a). If temperature curves are considered, it can be stated that their course is more similar to those observed for CVMW processes than to CV or CVUS ones. At the beginning of the process, the temperature of the material rose rapidly to some equilibrium value; next, it remained stable for a short period of drying, and after the 50th minute of the process, it started to rise again. At about the 90th min of the process, the temperature exceeded the value registered for ambient air and finally attained 355 K, which is 12–15 K higher compared to the temperature of the drying agent. This kind of curved course suggests a dominant influence of microwaves over ultrasound on the kinetics of convective drying.

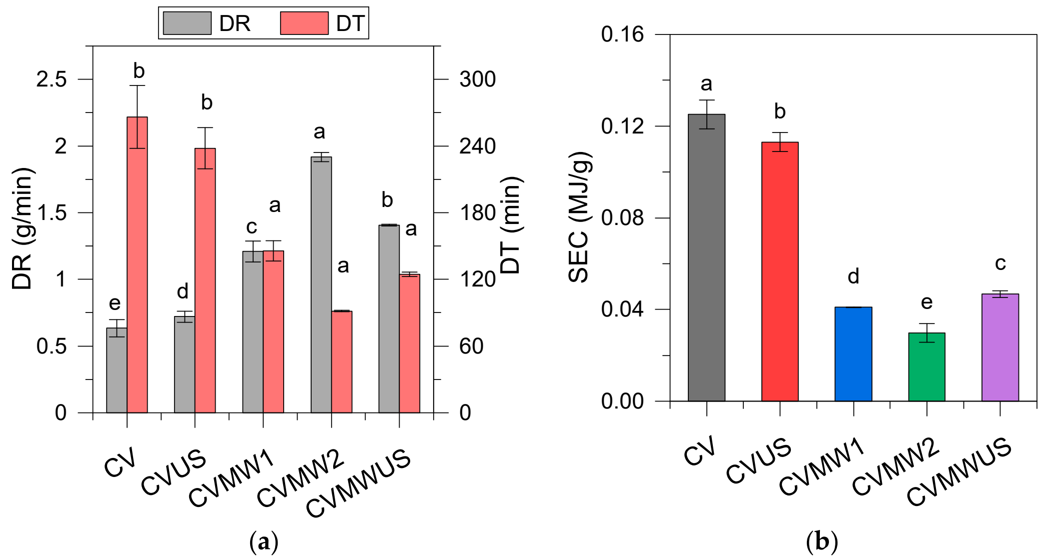


Figure 5. (**a**) Average drying rate (DR) and drying time (DT) for certain processes and (**b**) specific energy consumption (SEC) for particular schedules of drying. Different letters above the bars indicate statistically significant differences at $p < 0.05$, according to Tukey post-hoc test.

In Figure 5 the average values of the drying rate and time, specific energy consumption are presented respectively.

Both presented in Figure 5a parameters exhibited the expected trend observed in the drying kinetics curves (Figures 2–4). The convective-microwave drying process (CVMW2), carried out at higher microwave power, was the shortest drying process, which also had the highest average drying rate. On the other hand, convective (CV) drying took the longest time, which correlates with the lowest average drying rate (Figure 5a).

It can be noticed that the most energy-intensive process was the pure convective one (CV), which resulted due to a long operation time (Figure 5b). Application of ultrasound caused a slight decrease in this parameter, despite a higher power requirement (or instantaneous energy consumption) resulting from the additional energy consumer, which is the ultrasound generation system (AUS). Apparent changes were observed for microwave schedules in which SEC reduction in comparison to CV attained 67%, 76%, and 62% for CVMW1, CVMW2, and CVMWUS, respectively (Figure 5b). So many benefits, despite the use of additional power consumers (ultrasonic and microwave generators), resulted from a significant shortening of the drying time. From an economical point of view, this is a very positive effect of ultrasound or microwave enhancement.

Microwave and ultrasound technologies have been investigated for their influence on energy consumption during drying. Studies have shown that microwave drying can lead to a decrease in specific energy consumption, with higher microwave power levels resulting in lower energy consumption [28]. Additionally, the use of intermittent microwave drying has been found to reduce drying time and decrease energy consumption [29]. Ultrasound treatment has also been shown to reduce energy consumption during drying, as shorter exposure to elevated temperatures can improve the quality of the dried product [30]. Furthermore, the combination of ultrasound with intermittent microwave and low-temperature, hot-air drying has been found to decrease specific energy consumption, making it a suitable alternative for industrial applications [31,32]. Overall, both microwave and ultrasound technologies have the potential to reduce energy consumption during drying processes.

3.2. Aproximation of Experimental Data

The numerical analysis involved fitting moisture ratio curves with four thin-layer drying models. Table 3 shows the parameters determining the goodness of fit of each model. As can be seen, the best fit was obtained for the Midilli–Kucuk model (adj. R^2 of 0.999 and reduced chi-square of 10^{-5}–10^{-6}). The worst fit was observed for the simplest models, i.e., Newton and Page. The Henderson and Pabis model reproduced the drying curves better, thanks to the additional term a.

Table 3. Reduced Chi-square and adjusted R-squared were calculated for the models used in approximation.

No	Symbol	Newton		Page		Henderson–Pabis		Midilli–Kucuk	
		red χ^2	adj R^2	red χ^2	adj R^2	red χ^2	adj R^2	red χ^2	adj R^2
1	CV	$3.01 \cdot 10^{-3}$	0.9689	$1.50 \cdot 10^{-4}$	0.9984	$1.51 \cdot 10^{-3}$	0.9844	$3.09 \cdot 10^{-5}$	0.9997
2	CVUS	$2.18 \cdot 10^{-3}$	0.9775	$2.81 \cdot 10^{-4}$	0.9971	$9.92 \cdot 10^{-4}$	0.9898	$4.26 \cdot 10^{-5}$	0.9996
3	CVMW1	$4.48 \cdot 10^{-3}$	0.9582	$4.48 \cdot 10^{-3}$	0.9582	$1.92 \cdot 10^{-3}$	0.9821	$3.62 \cdot 10^{-5}$	0.9997
4	CVMW2	$3.65 \cdot 10^{-3}$	0.9679	$3.76 \cdot 10^{-4}$	0.9967	$1.42 \cdot 10^{-3}$	0.9876	$6.82 \cdot 10^{-6}$	0.9999
5	CVMWUS	$3.84 \cdot 10^{-3}$	0.9647	$2.98 \cdot 10^{-4}$	0.9973	$1.53 \cdot 10^{-3}$	0.9859	$1.54 \cdot 10^{-5}$	0.9999

red χ^2—reduced chi squared, adj R^2—adjusted R squared.

A comparison of the experimental curves with those approximated by the Midilli–Kucuk model is shown in Figure 6. The model curves coincided with the experimental curves for the entire drying period, as supported by the significantly high coefficient of determination.

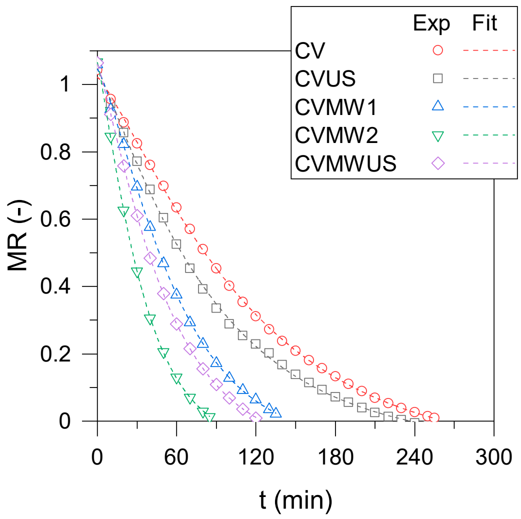


Figure 6. Evolution of experimental (Exp) and numerical (F) moisture ratio (MR) over time, according to the Midilli–Kucuk model.

Table 4 presents the Midilli–Kucuk model parameter values and the effective diffusion coefficient values for each process. The collected data aligns with the analysis of the kinetic data. The CVMW2 program exhibited the highest diffusion coefficient, along with the fastest average drying rate and shortest drying time. The coefficient had a minimum value during the convection (CV) process, indicating it to be slow and energy-intensive. The aid of ultrasound in CVUS marginally improved drying conditions, producing a relatively small (not statistically significant) surge in the effective diffusion coefficient. The CVMWUS process, which utilized all drying techniques, displayed a higher diffusion coefficient than that of convection or ultrasonic-assisted convection, yet lower than that of the convection–microwave process executed at 250 W. A high positive correlation (r = 0.79) was observed between the value of the drying rate k and the diffusion coefficient.

Table 4. Midilli–Kucuk model parameters and effective diffusion coefficient values for individual processes.

Symbol	a	SE	b	SE	k (1/s)	SE	n	SE	D_{eff} (m^2/s)	SE
CV	1.02	$3.72·10^{-3}$	$-3.79·10^{-6}$	$2.39·10^{-7}$	$2.14·10^{-5}$	$2.98·10^{-6}$	1.22	$1.59·10^{-2}$	$7.39·10^{-9}$ a	$2.10·10^{-10}$
CVUS	1.05	$4.83·10^{-3}$	$-3.26·10^{-6}$	$1.88·10^{-7}$	$6.86·10^{-5}$	$9.16·10^{-6}$	1.12	$1.54·10^{-2}$	$9.06·10^{-9}$ a	$3.11·10^{-10}$
CVMW1	1.04	$4.75·10^{-3}$	$-5.05·10^{-6}$	$6.47·10^{-7}$	$2.53·10^{-5}$	$4.53·10^{-6}$	1.29	$2.20·10^{-2}$	$1.33·10^{-8}$ b	$6.26·10^{-10}$
CVMW2	1.07	$2.40·10^{-3}$	$-9.04·10^{-6}$	$5.28·10^{-7}$	$1.16·10^{-4}$	$8.41·10^{-6}$	1.19	$9.58·10^{-3}$	$2.26·10^{-8}$ c	$1.10·10^{-9}$
CVMWUS	1.06	$3.35·10^{-3}$	$-7.80·10^{-6}$	$5.11·10^{-7}$	$6.96·10^{-5}$	$7.45·10^{-6}$	1.19	$1.35·10^{-2}$	$1.57·10^{-8}$ b	$3.95·10^{-10}$

Different letters in the columns indicate statistically significant difference at $p < 0.05$, according to Tukey post-hoc test. a, b, k, n—Midilli–Kucuk model variables, D_{eff}—diffusion coefficient, SE—standard error.

The effective diffusion coefficient during drying is influenced by both microwave and ultrasound. Microwave power significantly affects the total heating time and energy efficiency of the drying processing, and the effective moisture diffusivities follow an Arrhenius-type relationship with microwave power [33]. Ultrasonic power also has an impact on drying kinetics, with a significant linear correlation between the identified effective diffusivity and the applied ultrasonic power for various products [34]. The effectiveness of ultrasound application is determined by the slope of the relationship between diffusivity and power, which is influenced by the porosity, hardness, and acoustic impedance of the material being dried [35]. Additionally, microwave drying accelerates the drying process and increases the dispersibility of materials, with the drying rate being affected by the magnitude of microwave energy and the supply of heated air [36,37].

3.3. Quality of Products

The kinetics of drying is an important parameter that allows the estimation of the operational regimes, times of processes, and costs. However, in the case of fruits and vegetables, the quality of the received products is a key parameter determining the real suitability of a particular drying operation. For this reason, each operation conducted in this research schedule of drying was judged in terms of the quality of the obtained products. A comprehensive analysis of the products' quality was presented in this section.

The amount of total polyphenol compounds in dried apple cubes produced by pure convective drying (CV) was at the level of 1177 mg/kg DM (Figure 7). Application of both ultrasound and microwaves caused enhancement of phenolic compound content in the apple products. In the case of ultrasound-assisted convective drying (CVUS), the increase in phenolic compounds was about 17%, but it was not a statistically significant difference. Application of microwaves (CVMW1 and CVMW2) during the convective process meaningfully influenced the polyphenol content, causing the greatest increase in these compounds, about 26%.

Three classes of polyphenols were detected in the investigated dried apple cubes (Table 5). It is noticeable that flavan-3-ols, represented by (+)-catechin, (−)-epicatechin, and oligomeric procyanidins, were the dominant class of phenolic compounds in the investigated apple samples, accounting for 70% of the total polyphenols detected. They were in the range of 806 mg/kg DM (CV) to 1055 mg/kg DM (CVMW1). Our results correspond with data reported by other researchers, which also indicated that flavanols are the dominant phenolic group present in different cultivars of apples [38–40]. The second important group is phenolic acid, represented by chlorogenic acid (267 mg/kg DM and 325 mg/kg DM for drying schedule CV and CVMW1, respectively), which accounted for about 22% of the total detected polyphenols. The last dihydrochalcons group, represented by phloridzine and phloretin xyloglucoside, constituted only 8% of the found phenolic compounds. Moreover, these compounds proved to be the most resistant to the impact of ultrasound and microwaves during the drying process.

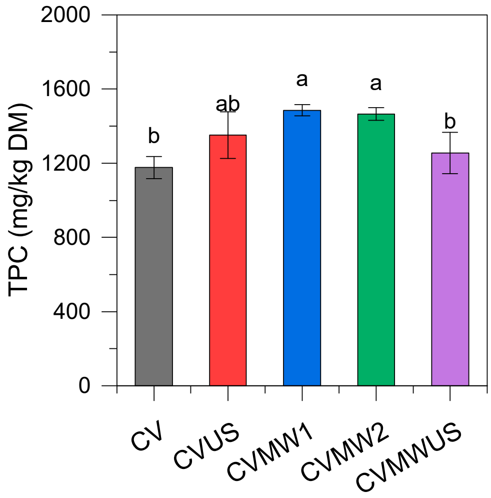


Figure 7. Total polyphenol content of TPC (mg/kg DM) in dried apple cubes produced by particular schedules of drying. Different letters above the bars indicate statistically significant differences at $p < 0.05$, according to Tukey post-hoc test.

Table 5. Effects of particular schedules of drying on polyphenol composition [mg/kg DM] in dried apple cubes.

No	Symbol	Flavan-3-ols			Dihydrochalcons		Phenolic Acid
		Cat	Ecat	Proc	PhXg	Ph	Chl
1	CV	67.3 a	240.0 a	499.0 a	44.4 a	58.6 a	267.5 a
2	CVUS	73.5 ab	277.9 ab	603.4 bc	44.1 a	58.2 a	297.5 a–c
3	CVMW1	87.7 c	303.90 b	663.8 c	47.4 a	57.7 a	325.5 c
4	CVMW2	83.1 bc	276.6 ab	690.5 c	46.0 a	55.6 a	313.9 bc
5	CVMWUS	71.6 ab	248.2 a	557.8 ab	45.8 a	53.0 a	278.7 ab

Different letters in the column indicate statistically significant difference at $p < 0.05$, according to Tukey post-hoc test. Abbreviations: Cat, (+)-catechin; Ecat, (−)-epicatechin; Proc, oligomeric procyanidins; PhXg, phloretin xyloglucoside; Ph, phloridzine; Chl, chlorogenic acid.

The application of ultrasound-assisted convective drying (CVUS) caused better retention of (+)-catechin, (−)-epicatechin, procyanidins, and chlorogenic acid compared to the convective process (CV). The positive effect of microwave application during convective drying was also observed in the case of flavan-3-ols and phenolic acid retention in dried apple cubes. The CVMW1 and CVMW2 schedules caused significant increases in the content of (+)-catechin (about 30–23%), (−)-epicatechin (27–15%), procyanidins (38–33%), and chlorogenic acid (22–17%) compared to convective drying (CV). When used separately, ultrasound and microwave during the drying of apple cubes had a better effect on the content of phenolic compounds than the program that combined both ultrasound and microwave (complex schedule).

Figure 8 shows a radar chart summarizing the evaluation of each drying program in terms of kinetics (drying rate and diffusion coefficient) and energy intensity (specific consumption). Each program was scored on a 1–5 point scale (worst–best) in each of the scored categories. The farther a given program was from the center of the graph, the better the score it received in the evaluation.

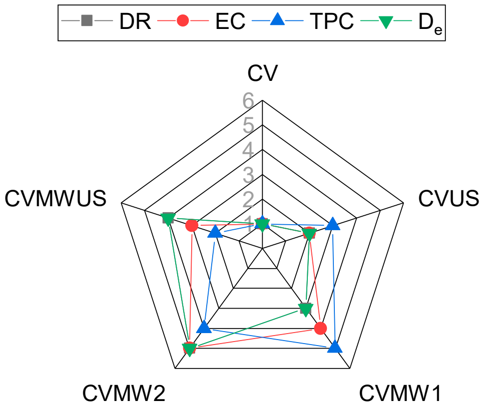


Figure 8. Radar chart showing process evaluation points (the higher the point value, the better).

The location of the points on the graph is important, but so is the distribution of the points within the different categories for a given process. The smaller the spread, the more balanced the process. The balance can be positive if all the points are around a rating of 5–6, or negative if they are 1–2. An example of a positive process is CVMW2, which scored 5 in almost all categories. Only the TPC scored lower than the CVMW1 process. A negative balance is observed for the CV convection program, in which all parameters received the lowest rating. The influence of ultrasound (CVUS) is indirect, and most of the parameters were rated 2–3. The results obtained clearly indicate that microwaves are a positive factor in the evaluated areas (kinetics, energy intensity, and quality). Obviously, the study should be expanded to include new parameters to obtain a more complete picture of the effects of radiation. It is worth noting the slight difference between the CVMW1 and CVMW2 processes. However, the use of lower microwave power does not bring any advantages, so it can be concluded that running the processes at higher microwave power will be more beneficial.

4. Conclusions

The presented study investigated the drying kinetics of apples under different conditions, focusing on the impact of ultrasound-assisted convective drying (CVUS) and convective microwave processes (CVMW1 and CVMW2) on drying time and temperature profiles. We used the Midilli–Kucuk model for numerical analysis and found it suitable for describing the drying process. We also evaluated the quality of the dried apples, particularly the content of polyphenolic compounds. The study indicates that the higher-power convective microwave process (CVMW2) was a balanced and favorable option, and we recommend further exploration of new parameters to better understand the effects of radiation.

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