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Ultrasound-Assisted Convective Drying of Stinging Nettle (*Urtica dioica* L.): Kinetics, Energy Consumption and Quality Attributes

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Abstract

To extend shelf life and enjoy the aroma and bioactive properties of wild nettle all year long, a drying operation is needed. This research aimed to compare conventional drying with modern drying technology using ultrasound to investigate intensification of the process together with the quality of sensitive leafy herbs. The kinetic, energy, and selected quality attributes typical for dry products of plant origin were analyzed: color, water activity, and polyphenol retention. Drying tests on wild nettle were carried out at two temperatures of 50 and 70 °C, with and without airborne ultrasound (100 and 200 W). The results showed that the application of ultrasound contributed to higher drying rates throughout the moisture content range compared to convective drying at the same air temperature. The higher the ultrasound power, the higher the increase in drying rate and shorter drying time, confirming intensification of moisture diffusion due to ultrasound assistance. The higher temperature and ultrasound level strongly influenced the final appearance and antioxidant properties of dry nettle, leading to color change ($dE00$ = 8.2) and polyphenol degradation (36%). However, all of the analyzed drying variants reduced the risk of microbial development (a_w = 0.444). In conclusion, ultrasound can be effectively applied to intensify the drying of nettle leaves by providing more favorable drying conditions, including a 53% reduction in drying time and a drying rate more than twice as fast as that of convective drying.

Keywords: airborne ultrasound; drying rate; effective diffusion coefficient; mass transfer intensification; specific energy consumption; water activity; color change; polyphenol retention

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1. Introduction

Stinging nettle (*Urtica dioica* L.) is common almost worldwide, especially in Europe, North America, North Africa, and parts of Asia. It can be found near homes, in meadows, gardens, and forests. It grows particularly well in moist soils [1]. Young nettle leaves are nutritious and can be cooked and eaten. For this reason, nettle is used as a vegetable, especially in regions where vegetables are scarce [2]. The high nutritional quality of nettle leaves is due to the high content of various vitamins (C, B1, B2, B3, B6, A, K), microelements, fatty acids, and polyphenols [2,3]. Nettle has been used in herbal medicine for its pharmacological properties for more than 2000 years; however, its medicinal potential was not fully explored until the 21st century, beginning with the identification of its chemical

structure and pharmacological properties [2,4]. These extensive studies have shown that nettle has antihelminthic, antidiabetic, nephroprotective, hepatoprotective, antiobesity, neuroprotective, anticancer, antiaging, cardioprotective, antidiarrheal, antimicrobial, antiviral, and antioxidant activities [4–6].

Nettle can be used both as fresh leaves and as an infusion of fresh leaves [2]. However, like any plant material, fresh nettle cannot be stored for long. The basic method of protecting herbs from degradation is drying [7]. Drying not only protects plant materials against the growth of fungi and bacteria, but also reduces the volume and weight of the material, making it easier to transport and store [8].

Unfortunately, there are few reports in the literature directly related to the drying of nettle leaves. Shonte and de Kock [9] compared infusions obtained from fresh and dried nettle and spinach leaves. In their study, they investigated the effect of drying on the color and sensory properties determined by the panel. The infusion made of dried leaves showed a significant color change compared to the infusion made of fresh leaves. However, drying had little effect on sensory changes in the infusion. Droštinová et al. [10] investigated the effect of three different drying methods on the content of chlorophyll and carotenoids in dried stinging nettle and lemon balm. They examined solar and convective drying (both at 25 °C for 65 h) and microwave drying (800 W for 45 s). Solar drying demonstrated the best retention of the tested components in the leaves of nettle. Of the two remaining methods, convective drying demonstrated better chlorophyll retention, while microwave drying demonstrated better carotenoid retention. Nallan Chakravartula et al. [11] investigated the drying of nettle leaves to produce powders that could be used in the food industry as functional additives. Convective drying and liofilization of unblanched and blanched leaves were compared. According to [11], blanching had a positive effect on mass transfer and reduced the oxidative degradation of pigments during drying, but resulted in a loss of total phenolic content, antioxidant activity, and potassium content. Convective-dried powders exhibited better flow properties, while those obtained by freeze-drying better retained color, pigments, magnesium content, phenols, and antioxidant parameters. On the basis of these studies, the authors concluded that both drying methods should be considered equivalent and the one that provides the desired properties of the resulting powders should be chosen. Garcìa et al. [12] analyzed the effect of three drying methods: liofilization (−50 °C), high-temperature convection drying (105 °C), and low-temperature drying using a heat pump (35 V) on the quality of dried nettle leaves. The authors assumed that the total content of polyphenols and ascorbic acid was an indicator of the quality of the dried material. The results presented in this article should be taken with great caution, as the authors found that after low-temperature drying, the polyphenol content increased more than twice compared to fresh leaves. However, the general conclusions are as follows: the best quality was obtained after low-temperature drying, while the worst quality was obtained after high-temperature drying. This is consistent with the general knowledge available that food and herbs should not be dried at high temperatures [7,8]. Ozola et al. [13] studied the effects of drying and freezing on the quality of selected herbs: stinging nettle, common goutweed, dandelion, and chickweed. They analyzed the retention of pigments (chlorophyll A, chlorophyll B, and carotenoids) in leaves as well as changes in their color. As a result, it was found that freezing had little effect on the change in material properties, while drying significantly reduced the pigment content and changed the color of the material [13]. All of the above-mentioned studies, drying kinetics, and energy consumption during the process were not investigated [9–13].

Alibas compared convective, microwave, and vacuum drying [14] and the convective, microwave, and microwave-convective drying [15] of nettle leaves. He studied drying kinetics, energy consumption, leaf color change [14,15], and ascorbic acid retention [15]. He

approximated drying kinetics using the semi-empirical Pabis model. In [14], microwave drying was found to be the best drying method, with the shortest drying time, the lowest energy consumption, and the smallest color change. Convection drying was second, and vacuum drying was the worst. In [15], convective drying was the slowest and consumed the most energy. Hybrid microwave-convective drying was the fastest, and microwave drying was slightly slower. From an energy consumption perspective, microwave drying was slightly better than hybrid drying. After the impact of the processes on the quality of the dried product (color and retention of vitamin C), microwave-convective drying was considered the best. Lamharrar et al. [16] studied the kinetics of the solar drying of nettle leaves. They approximated the obtained drying curves with nine models, the best of which was Midi. On the basis of these approximations, they determined the effective diffusion coefficient and activation energy in the studied process.

Among the studies that examined the drying of nettle, the research by Mousavi Kalajahi and Ghandiha [17] is also worth mentioning. They analyzed spray drying of the nettle extract from the perspective of optimizing the process parameters.

Ultrasound can inactivate microorganisms that cause food spoilage, improve the bioavailability of bioactive compounds, and enhance sensory properties [18]. Ultrasound used as a pretreatment before food drying has a positive effect on drying kinetics and the quality of the dried product [19]. Wang et al. [20], studying Chinese quince, showed that ultrasound as a pretreatment destroys cell walls, loosens tissue structure, and increases porosity, creating microchannels that favor further drying. The use of ultrasound during the convective drying process also has a beneficial effect, improves the kinetics of the process, can reduce its energy consumption, and positively affects the quality of the material obtained [21,22]. For example, when drying cellulose, the use of ultrasound resulted in a process duration shortening by 2.5 times, and the energy consumed for drying was reduced by more than two times compared to convective drying alone [23]. As demonstrated by Bayati et al. [24], the use of a hybrid convective–ultrasonic dryer resulted in a 41% reduction in total drying time and a 35% improvement in energy efficiency compared to conventional hot air drying systems for drying apple slices. Convective–ultrasonic drying of grains was studied in [25] (paddy rice) and [26] (caraway seeds). In both cases, the use of ultrasound accelerated the drying process. Furthermore, in the case of rice [25], a positive effect of ultrasound on vitamin B-3 retention was observed. In the case of caraway seeds [26], the use of cold plasma as a pretreatment and ultrasound during drying resulted in an improvement of over 50% in color, an improvement of over 40% in rupture force, and an increase of nearly 25% in antioxidant capacity. Convective–ultrasonic drying of henna leaves was studied by Bennaceur et al. [27], who investigated the kinetics of the process and its effect on the extraction of lawsone from dried leaves. They found that the use of ultrasound significantly accelerated drying and increased the rate of extraction of the lawsone.

The aim of this research was to determine the influence of airborne ultrasound on the drying kinetics and quality parameters of nettle leaves. Convective (CV) and ultrasound-assisted convective (CVUS) drying methods at two different temperatures were investigated. The drying kinetics were described using a thin-layer model. To assess the quality of the dried material obtained, water activity, color change, and retention of polyphenolic compounds were used.

2. Materials and Methods

2.1. Material and Drying Procedure

The fresh leaves of the stinging nettle (*Urtica dioica*) were collected in June from wild plants that grow in the Malta area of Poznań, Poland. The material (approx. 20 leaves, ~5 g) was stored at 6 °C in a sealed container prior to analysis to preserve the initial moisture

content (75% in fresh samples). For drying experiments, the leaves were placed on a rotating plate and placed in a laboratory-scale drying chamber until a constant mass (~1.3 g) was reached. The schematic diagram of the dryer is shown in Figure 1. The moisture content was determined using a Precisa XM120 moisture analyzer (Dietikon, Switzerland) with an accuracy of 0.01%, and validated by oven drying at 105 °C for 24 h under free convection.

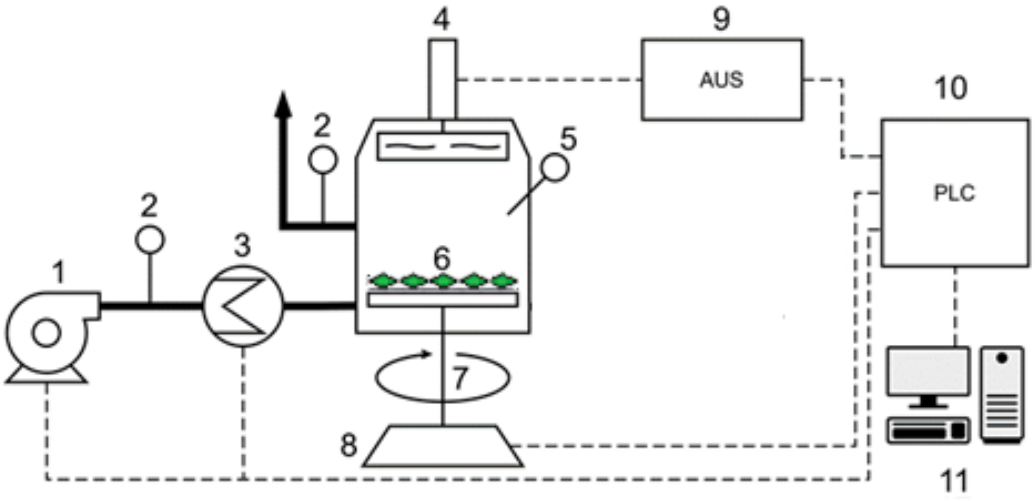


Figure 1. The scheme of the hybrid dryer: 1—fan, 2—hot-wire thermo-anemometer, temperature, and humidity sensor, 3—heater, 4—ultrasound transducer, 5—pyrometer, 6—samples, 7—rotatable balance pan, 8—balance, 9—airborne ultrasound generation system, 10—control cabinet, 11—control and data acquisition workstation.

Drying experiments were carried out in a hybrid laboratory dryer (PromisTech, Wrocław, Poland) that combined forced convection with continuous ultrasonic treatment (26 kHz) at power levels of 100 and 200 W. The ultrasonic power reported in this study refers to the nominal output of the ultrasonic generator. Due to the nature of airborne ultrasound propagation, including high air acoustic impedance and significant attenuation, as well as the irregular and dynamic geometry of the leaf samples during dehydration, direct measurement of ultrasonic intensity on the sample surface (W/cm^2) was not feasible. The applied power levels were chosen on the basis of the technical specifications of the drying system to ensure reproducible experimental conditions.

Two air temperatures (50 °C and 70 °C) were applied as typical conditions to dry leafy materials, allowing a balance between drying efficiency and the preservation of heat-sensitive compounds. Air velocity was set to 2 m/s at the inlet and 0.4 m/s through the plate. The material temperature was monitored using a pyrometer (CT LT15, Optris, Berlin, Germany), and the sample mass was recorded with a precision scale (PS6000, Radwag, Radom, Poland). Each drying trial was carried out in duplicate to ensure that all samples from a single batch were processed in a minimal time frame, thus limiting potential enzymatic degradation or moisture migration during storage; this approach, combined with the high precision of the control system and the negligible variance observed between runs, ensured data reliability and is consistent with established methodologies for the drying of perishable biological materials where sample uniformity is prioritized. Detailed drying parameters are provided in Table 1.

2.2. Drying Kinetics and Energy Consumption

Drying kinetics and energy consumption parameters were determined to evaluate the performance of the drying process. The following indices were calculated: moisture content (X), drying rate (DR), average drying rate (DR_{av}), moisture ratio (MR), and specific energy consumption (SEC).

Table 1. Drying processes and experimental parameters.

Process Code	Air Temperature (°C)	Ultrasound Power (W)
CV50	50	0
CV50US100	50	100
CV50US200	50	200
CV70	70	0
CV70US100	70	100
CV70US200	70	200

CV—convective drying; US—ultrasonic assistance.

The average moisture content $\overline{X}$ (g water/g dry matter) on a dry basis at any given time t of the drying process was calculated using the following formula [28]:

$$\overline{X}(t) = \frac{m\ (t) - m_d}{m_d}. \quad (1)$$

Here, $m(t)$ refers to the sample mass recorded at time t, whereas m_d corresponds to the dry matter.

The drying rate DR (g/s) was calculated as the ratio of the moisture mass removed Δm (g) to the corresponding drying time interval Δt (s), according to Equation (2) [28]:

$$DR = -\frac{\Delta m}{\Delta t}. \quad (2)$$

The average drying rate DR_{av} (g/s) was determined as the ratio of the total amount of moisture removed Δm_{tot} (g) to the total drying time DT (s), according to Equation (3) [28]:

$$DR_{av} = -\frac{\Delta m_{tot}}{DT} \quad (3)$$

The moisture ratio was used to describe the drying behavior of the material and was determined according to Equation (4) [28]:

$$MR\ (t) = \frac{\overline{X}(t) - X_e}{X_0 - X_e} \quad (4)$$

where MR $(-)$ is the moisture ratio, X_0 is the initial moisture content (g water/g dry matter), and X_e is the equilibrium moisture content (g water/g dry matter).

Since the equilibrium moisture content (X_e) is relatively small compared to X_0 and $X(t)$, a simplified form of the equation was also applied (Equation (5)) [29]:

$$MR = \frac{\overline{X}(t)}{X_0} \quad (5)$$

2.3. Determination of the Drying Constant and Effective Diffusion Coefficient

The values of the drying constants (k) and the effective diffusion coefficient (D_{eff}) were determined according to the methodology presented by Szadzińska et al. [30], assuming that the sample has infinite slab geometry (thin-layer model). In this case, the rate of moisture content change may be written as follows:

$$\frac{d\overline{X}}{dt} = -\frac{\pi D_{eff}}{4l^2}\left(\overline{X} - X_e\right) = -k\left(\overline{X} - X_e\right), \quad (6)$$

where k (s^{-1}) is the drying constant and l (m) is the half-thickness of the sample.

The drying constant k can be 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 [30]

$$-\left(\frac{d\overline{X}}{dt}\right)_i = \frac{\overline{X}(t_{i-1}) - \overline{X}(t_i)}{t_i - t_{i-1}}, \quad (7)$$

and $(\overline{X})_i$ is the averaged over time period moisture content [30]:

$$(\overline{X})_i = \frac{\overline{X}(t_i) + \overline{X}(t_{i-1})}{2}, \quad (8)$$

The specific energy consumption SEC (MJ/g) was determined as the ratio of the total electric energy consumed from all energy sources during convective and ultrasound-assisted drying during drying EC (kWh), measured using a standard electricity meter with an accuracy of 0.01 kWh, to the total mass of evaporated moisture Δm_{tot} (g), according to Equation (9) [31]:

$$SEC = 3.6 \cdot \frac{EC}{\Delta m_{tot}}, \quad (9)$$

where 3.6 is the value of 1 kWh recalculated to MJ.

2.4. Physicochemical and Functional Quality Evaluation

To comprehensively assess the physicochemical quality of fresh and dried nettle leaves, a set of analytical determinations was performed. The water activity a_w and the change in leaf color $\Delta E00$ were measured to evaluate the effect of drying on the stability and appearance of the product, while the total polyphenol content was quantified to determine changes in bioactive compounds. All chemical and physical analyses were performed in multiple technical replicates to minimize analytical error. The water activity and the total polyphenol content were determined in 3–4 replicates, while the color was measured in 15 replicates per sample (5 measurements at 3 points on each surface of the sample). The applied methodologies are described below.

The water activity of the fresh and dried leaves was measured using a LabMaster—a_w (Novasina AG, Lachen, Switzerland). The samples were placed in a thermostatically controlled chamber at 25 °C and measurements were recorded after equilibrium was reached. The dried leaves were analyzed after 24 h of storage in a desiccator (without desiccant). The results were obtained with a precision of three decimal places.

Leaf color was evaluated using a CR-400 colorimeter (Konica Minolta, Tokyo, Japan). Both dried and fresh samples were measured on a white ceramic plate to ensure repeatability and eliminate background interference. The color variation between the fresh and dried materials was expressed as the color change ($dE00$). The parameter is described precisely in [32].

The total polyphenol content was determined using the Folin–Ciocalteu method with minor modifications [33]. Fresh (1 g) and dried (0.3 g) samples were ground, weighed, and extracted with 50 mL of 80% methanol under reflux on a hot plate for 5 min. The extracts were cooled, transferred to 50 mL volumetric flasks, and adjusted to volume with methanol. Analytical solutions were prepared by mixing 1.5 mL of extract with 2.5 mL of Folin–Ciocalteu reagent, 5 mL of sodium carbonate solution, and demineralized water in a 50 mL flask. The mixtures were incubated in darkness for 1 h and the absorbance was measured at 750 nm using a U-5100 spectrophotometer (Hitachi, Hitachinaka, Japan) against a blank without extract. The results were expressed as gallic acid equivalents. Polyphenol retention PR was calculated as the ratio of the polyphenol content in the dry (PFC_d) and fresh (PFC_0) nettle leaves according to the equation:

$$PR = \frac{PFC_d}{PFC_0} \quad (10)$$

2.5. Statistical Analysis

All experimental data were expressed as mean ± standard deviation (SD) from two independent repetitions (n = 2). Due to the limited sample size (total number of processes 10), which results in low statistical power for conventional null-hypothesis

significance test (NHST), the magnitude of the differences between the control (CV50, CV70) and ultrasound-treated samples was evaluated using Cohen's effect size d. Cohen's d was calculated as the difference between the means divided by the pooled standard deviation [34]:

$$d = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\left(s_1^2 + s_2^2\right)/2}} \quad (11)$$

where $\overline{x}_1$ and $\overline{x}_2$ are the mean values of the compared groups, and s_1^2 and s_2^2 are the variances of these groups.

The effect size was interpreted according to Cohen's benchmarks: small ($d < 0.5$), medium ($0.5 \leq d < 1.2$), large ($1.2 \leq d < 2.0$), and very large/huge ($d \geq 2.0$) [34]. All calculations and power analysis were performed using Microsoft Excel and G*Power software (version 3.1). The significance level was established at $\alpha = 0.05$.

The relative change with respect to the reference process was determined using the following equation:

$$\%change = \frac{N - N_{ref}}{N_{ref}} \quad (12)$$

where N is the value of the parameter measured/calculated for a particular process, and N_{ref} is the value of the parameter measured/calculated for the reference process (CV50 or CV70).

The goodness-of-linear fit of the experimental data, during determination of the effective diffusion coefficient, was assessed based on the *adjusted* R^2 and the root mean square error (*RMSE*). The fitting procedure was performed using Origin(Pro), version 2025 (OriginLab Corporation, Northampton, MA, USA).

3. Results and Discussion

3.1. Drying Kinetics

The drying material was characterized by kinetic plots showing the evolution of the moisture ratio *MR* and the material temperature T_m in drying time, as well as the evolution of the drying rate *DR* in the moisture ratio. In addition, the average drying rate DR_{ave} and the specific energy consumption *SEC* were determined for each drying process.

Figure 2 presents the drying kinetics of nettle leaves subjected to convective and ultrasound-assisted convective drying, illustrated by three complementary representations: (a) moisture ratio (*MR*) as a function of drying time, (b) material temperature as a function of drying time, and (c) drying rate (*DR*) as a function of moisture content (*MC*).

As shown in Figure 2a, the moisture ratio decreased continuously with drying time for all drying variants. The application of ultrasound clearly accelerated moisture removal compared to convective drying at the same air temperature. Increasing the ultrasound power from 100 to 200 W further intensified this effect, resulting in a faster reduction in *MR* at a given drying time. The influence of ultrasound was more pronounced at a lower air temperature (50 °C), indicating that ultrasonic assistance partially compensates for the reduced thermal driving force by improving internal mass transfer.

The evolution of the material temperature during drying is presented in Figure 2b. In all cases, the temperature of the nettle leaves increased rapidly during the initial stage of the process and subsequently reached a quasi-steady level. A clear effect of air temperature (50 and 70 °C) on the material temperature was observed.

The results indicate that the thermal effect of ultrasound is temperature dependent and becomes less significant as the drying air temperature increases. In the case of the CV50 process, a slight thermal effect was observed, where the sample surface temperature slightly exceeded the drying air temperature (by approximately 2 to 3 °C). However, for the CV70

process, this effect was not observed, and the sample temperature remained below the air temperature throughout the process. This is in agreement with previous studies [35] which reported that the thermal effect of airborne ultrasound generally does not exceed 5 °C and that its relative contribution to the process decreases with higher convective heat fluxes. Therefore, while acoustic energy dissipation provides a minor thermal input, the drying acceleration at 70 °C is almost exclusively governed by mechanical phenomena, such as acoustic streaming and the reduction in the resistance of the boundary layer. Importantly, the application of ultrasound did not introduce additional temperature fluctuations.

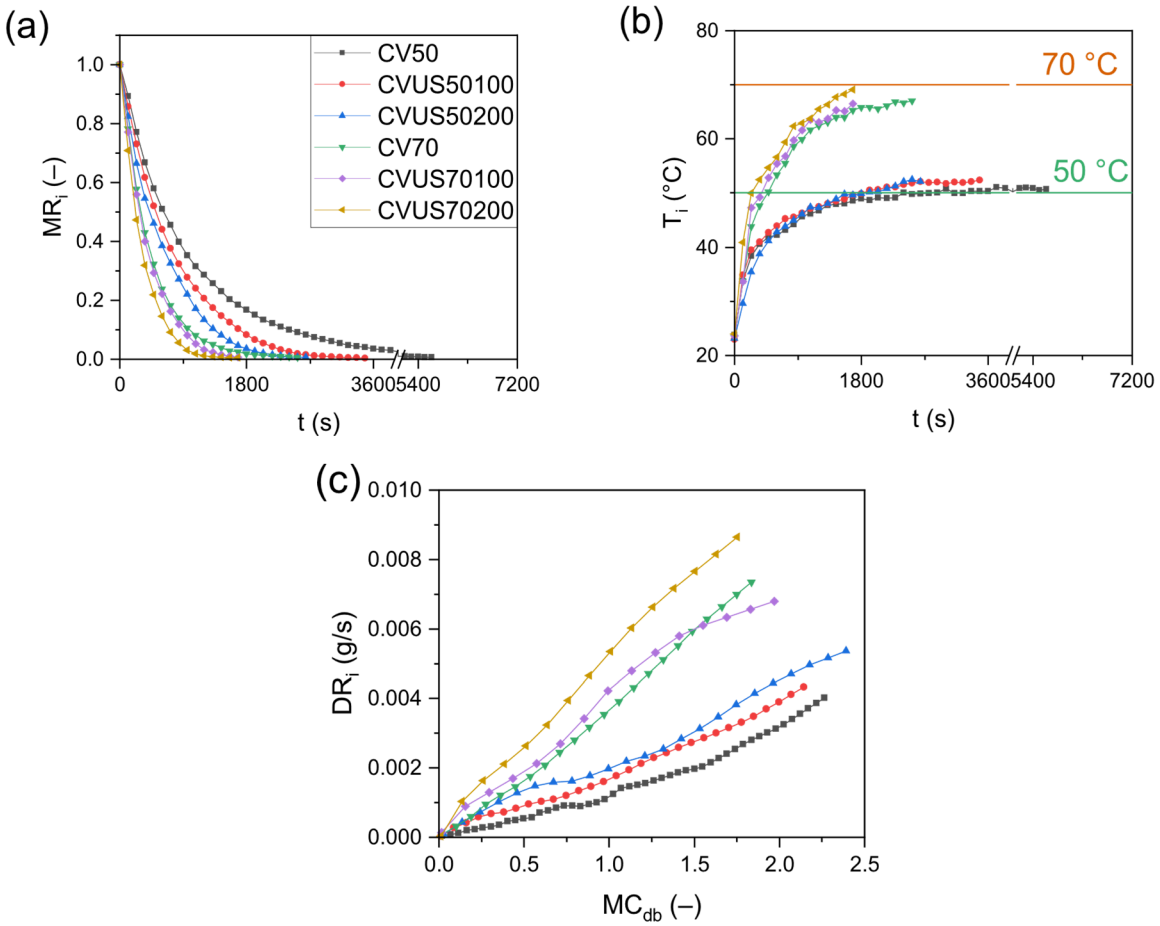


Figure 2. Drying characteristics of nettle leaves subjected to convective drying at 50 °C (CV50) and 70 °C (CV70) and ultrasound-assisted convective drying at ultrasound powers of 100 W and 200 W: (**a**) moisture ratio (*MR*) versus drying time, (**b**) material temperature versus drying time, and (**c**) drying rate (*DR*) as a function of moisture content (*MC*).

The drying rate as a function of moisture content is shown in Figure 2c. In all drying variants, the drying rate continuously decreased with decreasing moisture content, indicating the absence of a constant drying rate period. This behavior suggests that moisture removal was predominantly governed by internal mass transfer resistance.

The application of ultrasound resulted in higher drying rates throughout the moisture content range compared to convective drying at the same air temperature. Moreover, increasing the ultrasound power from 100 to 200 W led to a further increase in the drying rate, particularly at a higher moisture content, confirming the intensification effect of the ultrasound assistance.

The air temperature also affected the drying rate, with higher *DR* values observed at 70 °C compared to 50 °C. However, at both temperatures, ultrasound-assisted variants exhibited drying rates higher than those of the corresponding convective drying processes,

highlighting the synergistic effect of convective heating and ultrasound assistance on moisture transport.

Furthermore, the observed enhancement of the drying rate, combined with the lack of increased or fluctuating temperature, suggests that ultrasound-assisted drying may facilitate moisture transport through mechanical effects, such as acoustic vibrations or slight structural changes within the material, thus reducing resistance to internal mass transfer.

Similar trends were reported for kale leaves subjected to convective drying at 50 and 70 °C, with and without ultrasound assistance (100 W), as well as with and without microwave support. It was demonstrated that the drying rate (*DR*) and its dependence on ultrasound application were strongly influenced by the drying temperature. Specifically, at 50 °C, ultrasound assistance resulted in a pronounced improvement in the drying rate, with quantitative effects reaching up to a 100% increase compared to convective drying. In contrast, at the higher temperature of 70 °C, the effect of ultrasound was less pronounced, and the maximum increase in drying rate was approximately 70%. These results confirm that the intensification effect of ultrasound on drying kinetics decreases with increasing temperature, as convective heat and mass transfer become more dominant [36].

Chen et al. [37] reported that the application of ultrasound power during the convective drying of mint leaves significantly enhanced both heat and mass transfer processes. Moreover, increasing ultrasound power levels led to higher heat and mass transfer coefficients, indicating a stronger intensification effect. The authors attributed this behavior to the increase in energy within the boundary layer induced by ultrasound application. Specifically, the occurrence of airborne cavitation and acoustic perturbations generated by ultrasound disrupted the boundary layer, resulting in its thinning. Consequently, the reduced thickness of the boundary layer facilitated a more efficient heat and mass transfer, thereby accelerating the drying process.

Similarly, Rodríguez et al. [38] investigated the convective drying of thyme leaves in fixed beds with and without ultrasound assistance at various drying temperatures and air velocities. The authors observed that ultrasound exerted a more pronounced effect on drying kinetics, including a reduction in total drying time, at temperatures below 70 °C and air velocities lower than 3 m/s. Under these conditions, ultrasound more effectively intensified moisture removal, whereas its influence diminished at higher temperatures and air velocities, where convective transport mechanisms predominated.

In general, the literature consistently indicates that ultrasound assistance is most effective at lower drying temperatures and air velocities, supporting the trends observed in the present study.

Figure 3 presents the average drying rate (DR_{av}) obtained for dried nettle leaves using different drying methods. For each temperature level, convective drying (CV) was adopted as the reference process. The results clearly indicate that the application of ultrasound significantly increased the average drying rate compared to the corresponding convective drying variants by approximately 75–116% at 50 °C and 44–78% at 70 °C, for 100 and 200 W of US power, respectively. It was also evidenced by the large effect sizes (*d* values reaching 16.39 for CV50 variants, Table A1). Such extreme values ($d \geq 2.0$ confirm that the mechanical effects of acoustic cavitation and the "sponge effect" are the primary drivers to accelerate moisture removal, regardless of the drying temperature.

At 50 °C, the drying rate progressively increased with ultrasound application, with higher DR_{av} values observed for ultrasound-assisted drying at 100 and 200 W compared to CV50. A similar trend was observed at 70 °C, where both ultrasound-assisted variants exhibited higher drying rates than convective drying at the same air temperature.

For both temperatures, increasing the ultrasound power from 100 to 200 W resulted in a further enhancement of the drying rate, indicating a clear dependence of the DR_{av} on

the ultrasound power. These results confirm that ultrasound-assisted convective drying intensifies the drying process relative to the reference convective drying, primarily by enhancing mass transfer rather than by increasing thermal input.

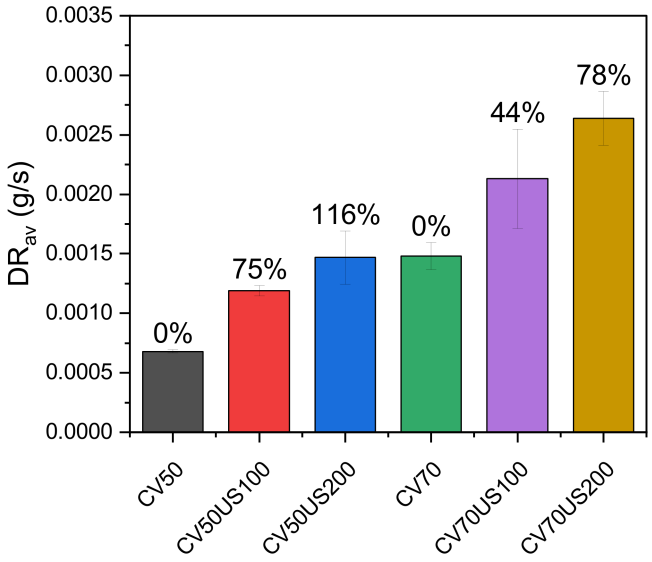


Figure 3. Average drying rate (DR_{av}) under different drying conditions. The value above the columns indicates the relative change (%change) determined in relation to the reference process (CV50 or CV70).

Figure 4 presents the total drying time (*DT*) obtained using different drying processes. The results indicate that ultrasound-assisted drying resulted in a noticeable reduction in *DT* compared to convective drying conducted at the same temperature. A more pronounced effect of ultrasound power was observed at the lower process temperature (50 °C). For drying at 50 °C, *DT* decreased by 43% and 53% when ultrasound powers of 100 W and 200 W were applied, respectively. In the case of drying at 70 °C, reductions of 30% and 44% were recorded for ultrasound powers of 100 W and 200 W, respectively. The reduction in total drying time showed a corresponding huge effect magnitude across all tested conditions, with *d* values significantly exceeding the 2.0 threshold. This indicates that the time-saving benefit of ultrasound-assisted drying is highly reproducible and represents a fundamental shift in process efficiency compared to convective drying (Table A1).

Furthermore, *DT* decreased with increasing ultrasound power, with the 200 W variant producing the shortest total drying time and the 100 W variant showing an intermediate effect. These results suggest that increasing the power of ultrasound contributes to improved process efficiency and shorter drying times.

The observed reduction in *DT* under ultrasound-assisted conditions may be related to ultrasound-induced mechanical vibrations and structural modifications within the material, such as the formation of microchannels, which can facilitate internal moisture transport. The relatively low variability of the results indicates good repeatability of the measurements and confirms the reliability of the observed differences between drying variants.

Figure 5 presents the last parameter used to describe the drying performance of nettle leaves, namely the specific energy consumption (*SEC*), as a function of the applied drying method. The results are shown in relation to the convective drying conducted at the same air temperature, which was adopted as the reference process.

It should be noted that the drying experiments were conducted on a laboratory scale with a partial load on the drying chamber. Consequently, the measured energy consumption (EC) and the calculated specific energy consumption (*SEC*) should be treated as indicative values. Although absolute energy efficiency could vary under full-scale

industrial conditions or different loading capacities, the results obtained in this study remain valid for identifying and comparing fundamental relationships in the efficiency of the drying variants analyzed (Table A1).

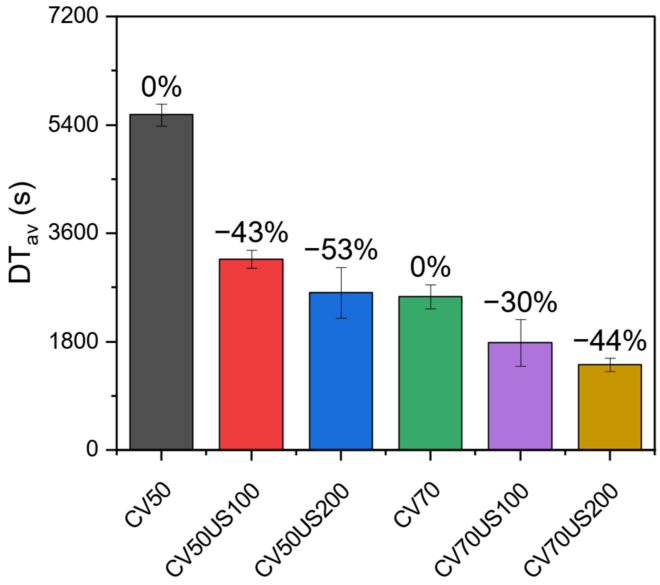


Figure 4. Total drying time (*DT*) for convective drying at 50 °C (CV50) and 70 °C (CV70) and ultrasound-assisted drying at 100 W (100US) and 200 W (200US). The value above the columns indicates the relative change (%change) determined in relation to the reference process (CV50 or CV70).

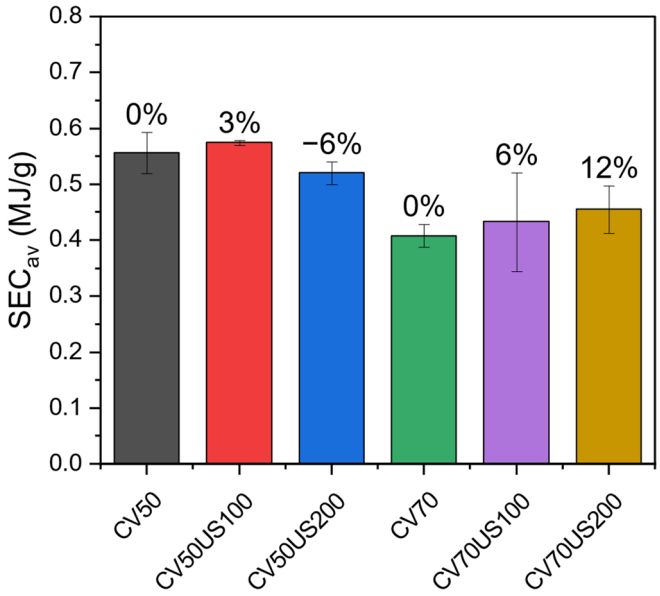


Figure 5. Specific energy consumption (*SEC*) of nettle leaves dried by convective drying at 50 °C and 70 °C and ultrasound-assisted convective drying at ultrasound powers of 100 W and 200 W. The value above the columns indicates the relative change (%change) determined in relation to the reference process (CV50 or CV70).

The results indicate that the application of ultrasound-assisted drying led only to a slight increase in *SEC* compared to convective drying. In particular, in the case of the CV50US200 variant, a reduction in *SEC* was observed. This behavior can be attributed to the very long drying time of the purely convective drying, particularly at 50 °C, where the duration of the process reached up to 5400 s, resulting in a high energy consumption.

Although ultrasound-assisted drying introduces additional energy input, the substantial reduction in drying time effectively compensates for this increase. As a result, the

total energy demand did not increase significantly, and in the case of CV50US200, even slightly decreased. These results demonstrate that intensifying the mass transfer induced by ultrasound-assisted drying can improve the overall energy efficiency of the process, especially at lower drying temperatures. Regarding energy efficiency, ultrasound treatment showed a very large effect of $1.2 \leq d < 2.0$ for the US200 variants, suggesting that higher acoustic power is necessary to achieve substantial energy savings. In contrast, the smaller effect size for CV70US100 indicates that at higher temperatures, the relative contribution of ultrasound to energy reduction may be less pronounced (Table A1).

Ghanbarian et al. [39] reported similar findings when investigating the effect of high intensity acoustic energy on the drying time and energy efficiency of convective hot air drying of peppermint leaves. The authors demonstrated that ultrasound energy can be effectively applied to improve conventional hot air dryers by reducing the duration and energy consumption of the process. However, the influence of ultrasound power on both drying time and energy use was shown to depend strongly on the drying air temperature and the applied acoustic power level. The intensification effect of ultrasound became more pronounced at lower drying temperatures, whereas at higher temperatures, its benefits diminished. In particular, the combination of ultrasound power with hot air at 70 °C did not shorten drying time and instead led to an increase in energy consumption. The authors emphasized that acoustic power has significant potential for integration with industrial and commercial hot air drying systems, particularly for heat sensitive products, such as medicinal and aromatic plants.

In addition, Mierzwa et al. [36] emphasized the influence of ultrasound assistance on specific energy consumption (*SEC*) during convective drying. The authors observed that the application of ultrasound led to a moderate increase in *SEC* compared to convective drying. Importantly, this increase was less pronounced at the lower drying temperature (50 °C) than at 70 °C, indicating that the energetic impact of ultrasound assistance is strongly temperature dependent.

In general, ultrasound-assisted convective drying improved the drying kinetics of nettle leaves by increasing the drying rates and shortening the total drying time without inducing temperature fluctuations, translating into comparable or even reduced specific energy consumption, particularly at lower drying temperatures.

3.2. Drying Constant and Effective Diffusion Coefficient

All experimentally obtained curves $-\left(d\overline{X}/dt\right)_i = f\left(\overline{X}\right)_i$ (Equations (7) and (8)) were approximated linearly according to Equation (6).

Figure 6 shows examples of the experimental curves and lines obtained by linear fitting for individual processes. As can be seen, the linear approximation corresponded satisfactorily to the experimental data obtained, as confirmed by the high *adjusted* R^2 values and low *RMSE* values (Table 2). On the basis of these approximations, the values of the drying constant k and then the effective diffusion coefficient D_{eff} were calculated. The calculation results are also presented in Table 2.

The determined values of the effective diffusion coefficient range between 1.19–2.69 $\times$ 10^{-10} m^2/s for forced convection (CV) and 1.44–3.13 $\times$ 10^{-10} m^2/s for ultrasound-assisted forced convection (CVUS) (Table 2). These values are consistent with those observed for nettle [16,28] and other herbs or leafy materials such as mint [40,41], black tea [42], garden mint [43], and basil [44]. Drying conditions significantly influence the effective diffusion coefficient (D_{eff}) in convective and ultrasound-assisted convective drying of nettle and other leafy herbs [40]. Higher drying temperatures and higher air velocities generally improve D_{eff} [40], while the application of ultrasound further increases the diffusivity of the moisture [45]. Ultrasound enhances mass transfer by creating microchannels and

reducing the resistance of the boundary layer, offering the potential for faster and more energy efficient drying. However, the beneficial effect of ultrasound is most pronounced at moderate temperatures and low air velocities, decreasing at very high temperatures or flow rates [46].

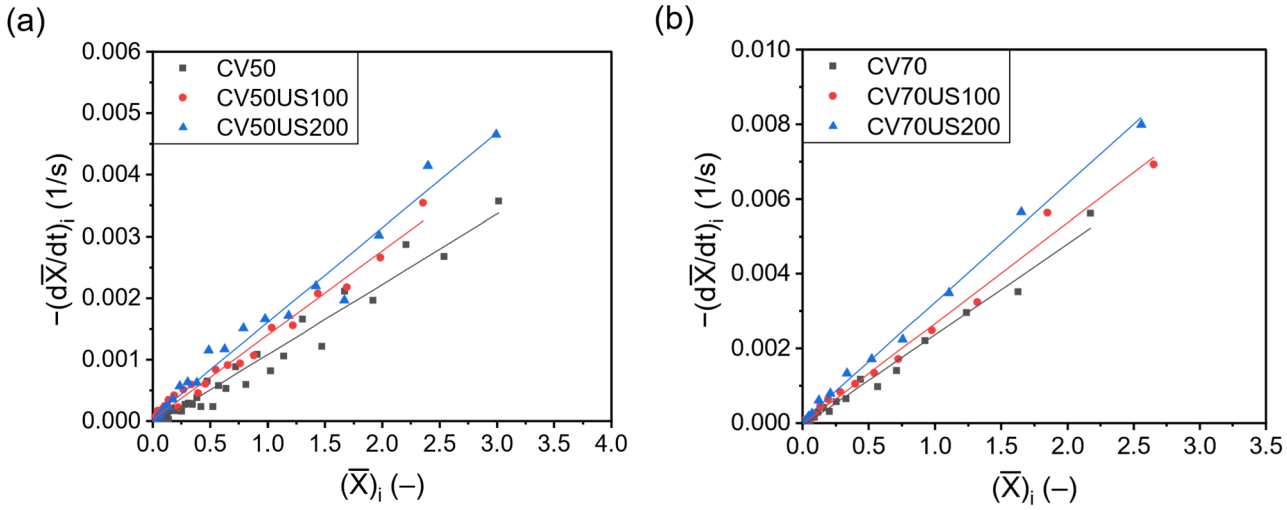


Figure 6. Sample plots of the change in moisture content $-\frac{d\overline{X}}{dt}$ over average moisture content $\overline{X}$ at (**a**) 50 °C and (**b**) 70 °C.

Table 2. Values of the drying constant *k*, the effective diffusion coefficient D_{eff}, *adjusted* R^2, and root mean square error *RMSE* (mean ± standard deviation).

Process	*k* (1/s)	D_{eff} (m^2/s)	*adj.* R^2	*RMSE*
CV50	$1.17 \times 10^{-3} \pm 3.79 \times 10^{-5}$	$1.19 \times 10^{-10} \pm 3.84 \times 10^{-12}$	0.9345	1.98×10^{-4}
CV50US100	$1.43 \times 10^{-3} \pm 8.05 \times 10^{-5}$	$1.44 \times 10^{-10} \pm 8.15 \times 10^{-12}$	0.9782	1.54×10^{-4}
CV50US200	$1.61 \times 10^{-3} \pm 9.51 \times 10^{-5}$	$1.63 \times 10^{-10} \pm 9.63 \times 10^{-12}$	0.9707	2.25×10^{-4}
CV70	$2.66 \times 10^{-3} \pm 3.17 \times 10^{-4}$	$2.69 \times 10^{-10} \pm 3.21 \times 10^{-11}$	0.9888	1.77×10^{-4}
CV70US100	$2.74 \times 10^{-3} \pm 7.22 \times 10^{-5}$	$2.78 \times 10^{-10} \pm 7.31 \times 10^{-12}$	0.9781	2.41×10^{-4}
CV70US200	$3.08 \times 10^{-3} \pm 1.21 \times 10^{-4}$	$3.13 \times 10^{-10} \pm 1.23 \times 10^{-11}$	0.9914	1.98×10^{-4}

k—drying constant, D_{eff}—effective diffusion coefficient, *adj.* R^2—*adjusted* R^2, *RMSE*—root mean square error.

3.3. Quality Parameters

As presented in Figure 7, the water activity (a_w) of the nettle leaves decreased significantly after drying, regardless of the method applied. Fresh leaves exhibited a high a_w value of approximately 0.98, indicating a high level of free water available for microbial and enzymatic reactions. In contrast, all dried samples showed markedly lower a_w values, ranging from 0.42 to 0.46, confirming efficient water removal and reduced risk of spoilage during storage. Among the dried variants, samples processed at 70 °C with ultrasound assistance (CV70US100 and CV70US200) reached slightly lower a_w values than convectively dried leaves, suggesting that ultrasound improved internal water diffusion and facilitated moisture evaporation through cavitation effects.

The application of ultrasound during convective drying improves the efficiency of mass transfer and leads to a more uniform distribution of residual moisture. Lower water activity not only contributes to an extended shelf life, but also minimizes enzymatic and microbial degradation during storage [47]. Therefore, the present results confirm that ultrasound-assisted convective drying is an effective strategy to improve the drying efficiency and stability of nettle leaves while maintaining desirable product quality. Most

ultrasound-assisted variants achieved a very large effect $1.2 \leq d < 2.0$ on final water activity, indicating a consistent improvement in product stability. However, the medium effect size observed for CV50 versus CV50US200 suggests that at lower temperatures, increasing ultrasound power might not further reduce a_w once a certain moisture equilibrium is approached (Table A1).

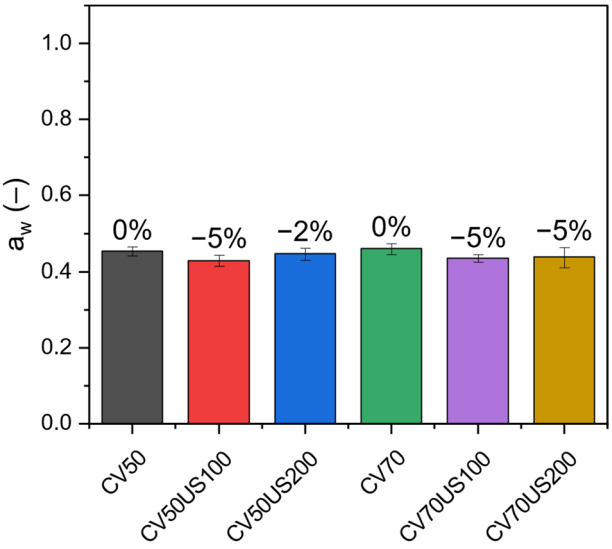


Figure 7. Water activity. The value above the columns indicates the relative change (%change) determined in relation to the reference process (CV50 or CV70).

Similar results were obtained by Jakubczyk et al. [48] for apple samples. The authors demonstrated that both an increase in drying temperature and the application of ultrasound-assisted drying led to a decrease in water activity, thus enhancing the microbiological stability of the dried material. The water activity was low in purslane leaves that were pretreated with ultrasound for 60 min and then freeze-dried, while the untreated, sun-dried sample showed a high a_w value [49].

According to Tapia et al. [50], in the range of 0.4–0.5 a_w, there is no microbial proliferation, which applies to foods such as pasta, spices, and egg powder. However, there is still a risk of accelerated lipid oxidation leading to off-flavors, as well as browning and enzymatic reactions.

Figure 8 presents the color change *dE00* of nettle leaves subjected to different drying methods.

The color change (*dE00*) of the nettle leaves was significantly affected by the drying method applied (Figure 8). Convective drying at 70 °C (CV70) resulted in the highest color deviation compared to fresh leaves (*dE00* = 11.4), indicating pronounced pigment degradation. The application of ultrasound at this temperature (CV70US100 and CV70US200) reduced the color change to *dE00* = 8.2, suggesting a partial protective effect of ultrasonic assistance. In contrast, samples dried at 50 °C exhibited much smaller differences in color. Both CV50US100 and CV50US200 reached a *dE00* value of 2.6 on average, and were lower compared to CV50 alone. These results indicate that the combination of a lower drying temperature with ultrasonic assistance is the most effective in preserving the natural color of the nettle leaves. High-temperature convective drying, both with and without US, led to substantial visual deterioration, indicating a clearly perceivable difference in product color. The total color difference was profoundly affected by the process, with huge effect sizes ($d \geq 2.0$) particularly visible in the CV70 series. This high magnitude of the d values indicates that ultrasound-assisted drying significantly alters the degradation kinetics of the

pigments or the browning reactions, leading to a distinct optical profile of the final product (Table A1).

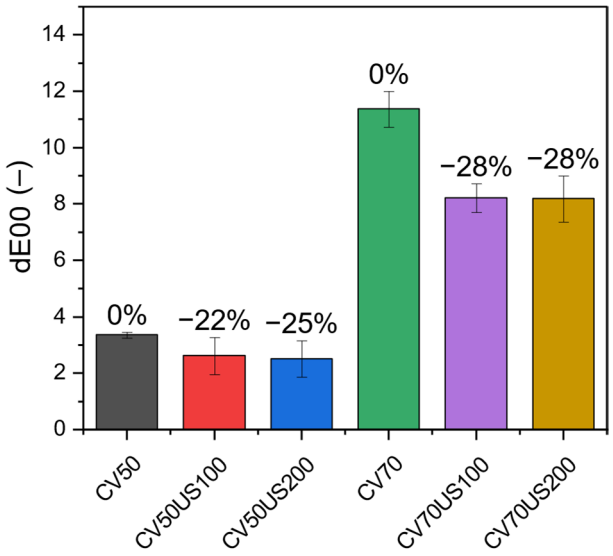


Figure 8. Color change. The value above the columns indicates the relative change (%change) determined in relation to the reference process (CV50 or CV70).

The observed reduction in the color change (*dE00*) in nettle leaves subjected to ultrasound-assisted drying aligns well with previous studies on plant materials. In a study on strawberry slices, the application of ultrasound-assisted convective drying shortened the overall drying time and resulted in smaller total color changes compared to conventional drying, indicating better pigment retention and less browning [51].

Similarly, Bo Chinh Ginseng samples dried by ultrasound-assisted heat pump drying showed that increasing the ultrasonic power from 80 to 120 W led to a gradual decrease in ΔE values. However, when the power exceeded 120 W, the color deviation increased markedly, suggesting that excessive ultrasound intensity may cause tissue damage and pigment degradation rather than protection [52].

These findings are further supported by the review of ultrasound applications in fruit drying, which reported that ultrasonic treatment can effectively reduce non-enzymatic browning and improve color stability through partial or complete enzyme inactivation. The proposed mechanisms involve the generation of free radicals during ultrasonic cavitation, which react with disulfide bonds within enzyme structures, destabilizing their conformation and leading to loss of catalytic activity. In addition, the oxidation of amino acids such as tryptophan, histidine, cysteine, and tyrosine contributes to enzyme inactivation. Microstreaming and microturbulence caused by ultrasonic waves can disrupt van der Waals forces and hydrogen bonds in polypeptide chains, resulting in the denaturation of browning-related enzymes [53]. Tao et al. [54] reported that ultrasound treatment preserved chlorophyll in mulberry leaves, resulting in a higher chlorophyll content compared to the control. This improvement was likely due to the shorter drying time, which reduced pigment degradation and contributed to better retention of green color.

Overall, data from the literature confirm that ultrasound-assisted drying can mitigate pigment degradation and color changes by accelerating moisture removal, reducing drying time, and inactivating enzymes responsible for oxidative and non-enzymatic browning. However, the efficiency of this protective effect depends strongly on the power of ultrasound and the drying temperature, as excessive energy input may intensify pigment oxidation and adversely affect the color of the product.

Figure 9 illustrates the influence of drying temperature and ultrasound power on *PR* retention of polyphenol in nettle leaves.

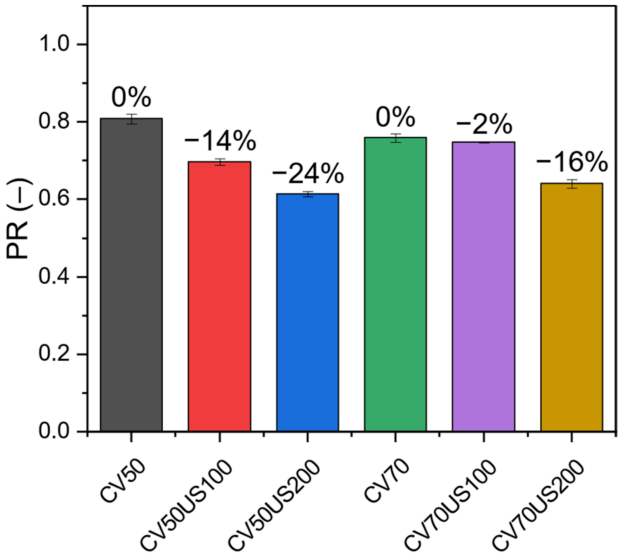


Figure 9. Polyphenol retention. The value above the columns indicates the relative change (%change) determined in relation to the reference process (CV50 or CV70).

Convective drying resulted in a reduction in polyphenols, with a higher loss observed at 70 °C (≈24%) compared to 50 °C (≈19%). The application of ultrasound at moderate power (100 W) did not prevent the decrease in polyphenol content at 50 °C, although the *PR* obtained for 70 °C was similar (≈75%). In contrast, the high ultrasound power (200 W) markedly accelerated the degradation, leading to the lowest levels of polyphenol retention (≈61–64%). These results indicate that polyphenol retention is strongly dependent on drying temperature and ultrasound intensity, with high-power ultrasound exerting a detrimental effect. The retention of polyphenols showed some of the most dramatic results in the study, with effect sizes reaching extreme levels (d = 19.56 for CV50US200). The magnitudes of such an enormous effect ($d \geq 2.0$) demonstrate that the protective effect of shortened drying cycles on bioactive compounds is of extreme practical importance, overshadowing any potential degradative impact of acoustic energy (Table A1).

Vallespir et al. [55] investigated the influence of ultrasound application (20.5 kW/m^3, 22 kHz) on total polyphenol content (*TPC*) in mushroom slices dried at low temperatures (5, 10, and 15 °C). Ultrasound-assisted drying resulted in a more effective retention of bioactive compounds, with an increase of 15–41% in *TPC* compared to samples dried without ultrasound exposure. Similarly, Baeghbali et al. [56] reported that apple slices subjected to hydrodynamic drying assisted by ultrasound (67.9 kW/m^3, 85.0 ± 0.5 °C) exhibited significantly higher *TPC* values (6.51 ± 0.31 mg GAE/g) than those obtained under conventional hot air drying (5.27 ± 0.31 mg GAE/g). Tao et al. [57] also confirmed that ultrasound treatment (902.7 W/m^2) improved *TPC* retention during hot air drying at 60 °C; however, a further increase in ultrasound intensity (1513.5 W/m^2) led to a marked reduction in *TPC* (3.7 ± 0.1 mg/g), indicating that excessive ultrasonic energy can promote degradation of the polyphenolic compound. Likewise, Cárcel et al. [58] found that ultrasound application (20.5 kW/m^3) at lower drying temperatures (30 °C) did not have a significant effect on *TPC* and vitamin C content in red pepper, while a positive influence was observed at moderate temperatures (50 °C) and a negative one at higher temperatures (70 °C). The shortened drying time induced by ultrasound contributed to the protection of *TPC* under intermediate conditions, whereas elevated temperature combined with ultrasonic treatment caused increased cell damage and the thermal degradation of phenolic

compounds. In general, these studies indicate that the beneficial effect of ultrasound on the retention of *TPC* strongly depends on the drying temperature and the acoustic energy level, with moderate ultrasonic intensities being the most favorable for preserving thermolabile bioactive compounds.

Similar findings were observed for perilla leaves subjected to ultrasound blanching. Ultrasonic pretreatment at 50 °C for 1 min resulted in higher flavonoid retention and better preservation of aroma. However, prolonged ultrasound treatment or increased drying temperature led to substantial nutrient degradation [59]. Dadan et al. [60] tested ultrasound treatment using the immersive method at a frequency of 35 kHz and a power outlet of 160 W for basil and parsley leaves. Treatments with US revealed a slight effect on the contents of the bioactive compound.

The relationship between water activity and the preservation of color and bioactive compounds is well-documented in the literature. Lower a_w values are associated with reduced rates of oxidation, enzymatic browning, and degradation of thermolabile compounds such as polyphenols and chlorophylls. In the present study, samples that showed lower water activity also maintained a smaller color change and a higher total polyphenol content, particularly in the ultrasound-assisted treatments. This suggests that faster removal of moisture limits the exposure of sensitive compounds to oxygen and heat, thus minimizing oxidative losses.

4. Conclusions

The results of investigations carried out on the drying of wild nettle confirm that the use of ultrasound intensifies convective drying, providing more effective moisture removal through mechanical effects, such as acoustic vibrations within the material, while reducing the resistance to internal mass transfer. The shape of all drying curves indicates the absence of a constant drying rate period, which further suggests the reason for the improvement of the process by ultrasound. At both temperatures, ultrasound-assisted variants exhibited higher drying rates, effective diffusion, and mass transfer coefficients than convective variants, highlighting the synergistic effect of hot air and ultrasonic waves on moisture transport. However, drying with ultrasound is more efficient at lower temperatures, compared to the relative change in drying time and drying rate.

Despite a slight increase in specific energy consumption, ultrasound-assisted drying improved the overall process efficiency due to reduced drying time and enhanced mass transfer. Better drying effectiveness at lower temperature and ultrasound power were also confirmed by a smaller color change and greater polyphenol retention in dry nettle.

Furthermore, while the current study used two independent drying replicates due to the seasonal availability of the raw material, the clear trends observed across all variants tested confirm the effect of ultrasound process intensification. Taking into consideration all of the parameters analyzed, one can conclude that airborne ultrasound offers a substantial reduction in drying time, and by providing a similar energy intensity, can be successfully applied in the drying of sensitive leafy herbs or vegetables characterized by natural color and high polyphenol content.

This study identified certain limitations of the use of ultrasound to dry stinging nettle, such as the potential increase in specific energy consumption and degradation of natural pigments and polyphenols at higher levels of ultrasound power. Certainly, further investigation of a broader range of parameters and other bioactive compounds (e.g., chlorophyll content) would provide a more comprehensive understanding of ultrasound-assisted drying of such leafy herbs.

From a practical standpoint, these findings provide a basis for the design of energy-efficient, low-temperature industrial dryers for heat-sensitive materials. By integrating

airborne ultrasound, producers can improve antioxidant retention and color quality while significantly increasing throughput during peak harvest seasons.

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Appendix A

Table A1. Cohen's effect size *d* for the comparison of control processes (CV50 and CV70) with ultrasound-assisted variants.

Comparison	DR_{av}	DT_{av}	SEC_{av}	a_w	*dE00*	*PR*
CV50 vs. CV50US100	16.39 ***	14.31 ***	0.70 *	1.87 **	1.59 **	10.28 ***
CV50 vs. CV50US200	5.03 ***	9.08 ***	1.22 **	0.49	1.83 **	19.56 ***
CV70 vs. CV70US100	2.12 ***	2.50 ***	0.39	1.94 **	5.47 ***	1.50 **
CV70 vs. CV70US200	6.50 ***	7.03 ***	1.40 **	1.03 *	4.33 ***	10.84 ***

DR_{av}—average drying rate; DT_{av}—average drying time; SEC_{av}—average specific energy consumption; a_w—water activity; *dE00*—color change; *PR*—polyphenol retention. Interpretation of Cohen's effect size *d* [34]: $d \geq 2.0$ (***)—huge/extreme effect: indicates an overwhelming physical impact of the process modification. $1.2 \leq d < 2.0$ (**)—very large effect: indicates a highly substantial difference between variants. $0.5 \leq d < 1.2$ (*)—medium/large effect: indicates a clearly observable and practical impact. $d < 0.5$ (without asterisk)—indicates a small or negligible effect.

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