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Abolfazl Akhoundzadeh Yamchi

Urmia University

Maziar Feizolahzadeh

m.feizolahzadeh@urmia.ac.ir

Urmia University

Adel Hosainpour

Urmia University

Adel Rezvanivand Fanaei

Urmia University

Ariga Moradians

Urmia University

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Influence of Ultrasound Pretreatment on the Infrared Drying Kinetics and Quality Attributes of Mallow Leaves

**Abolfazl Akhoundzadeh Yamchi¹, Maziar Feizolahzadeh^{1*}, Adel Hosainpour¹, Adel
Rezvanivand Fanaei¹, Ariga Moradians¹**

Department of Mechanical Engineering of Biosystems, Faculty of Agriculture, Urmia
University, Urmia, Iran

* Corresponding author: **Maziar Feizolahzadeh** m.feizolahzadeh@urmia.ac.ir

Abstract

The growing demand for high-quality dried foods has driven the integration of conventional drying techniques with non-thermal energy sources. Furthermore, ultrasonic pretreatment has gained considerable attention because it can operate at ambient temperatures while preserving the physicochemical and sensory characteristics of the product. This study aims to investigate the combined effects of ultrasound and infrared drying on the drying kinetics of mallow (*Malva sylvestris*) leaves, along with their quality attributes (particularly color characteristics and rehydration ratio), thermodynamic parameters, and specific energy consumption.

Fresh mallow leaves were pretreated with ultrasound (0, 5, 10 min) and subsequently dried in an infrared dryer at 40, 45, and 50 °C until a final moisture content of 10% (wet basis). The results showed that color difference (ΔE : 8.15–97.74) and browning index (80.37–144.40) increased with increasing drying temperature and decreasing ultrasound pretreatment time, while chroma values (23.40–29.24) decreased. The effective moisture diffusivity of mallow leaves increased with increasing drying temperature and longer ultrasonic pretreatment duration, ranging from 2.39×10^{-7}

to $8.68 \times 10^{-7} \text{ m}^2 \cdot \text{s}^{-1}$. Furthermore, the activation energy decreased from 86.32 to 73.73 kJmol^{-1} as the ultrasonic pretreatment time increased. Thermodynamic analysis revealed that increasing drying temperature and ultrasonic exposure time reduced both enthalpy and entropy, whereas Gibbs free energy showed the opposite trend, increasing under the same conditions. The lowest specific energy consumption ($\text{SEC} = 33.81 \text{ kWhkg}^{-1}$) was observed at the highest drying temperature (50°C) combined with the longest ultrasound pretreatment duration (10 min). This research demonstrates that ultrasound pretreatment improves drying efficiency and quality in infrared-dried medicinal herbs.

Keywords: Infrared drying; Mallow; Rehydration ratio; Thermodynamic properties; Ultrasound.

Practical Applications

This research demonstrates that ultrasound pretreatment prior to infrared drying significantly improves both the efficiency and quality of dried mallow leaves, a nutrient-rich medicinal herb. These benefits stem from ultrasound-induced microstructural changes that accelerate moisture removal without excessive heat exposure, thereby protecting heat-sensitive bioactive compounds. By reducing drying time and energy consumption while better preserving bioactive compounds, the approach offers a scalable, cost-effective solution for food processors. The identified optimal conditions (specific ultrasound durations and drying temperatures) provide practical guidelines for industry to enhance product quality, extend shelf life, and meet consumer demand for minimally processed, healthy foods. These findings are directly transferable to drying operations for other leafy vegetables and herbs.

Nomenclature

M	Moisture content (kg/kg dry matter, d.b.)	R	universal gas constant ($8.314 \text{ J} \cdot (\text{mol} \cdot \text{K})^{-1}$)
M_e	balance humidity	D_{eff}	effective moisture diffusivity ($\text{m}^2 \cdot \text{s}^{-1}$)

M_t	moisture in time	E_a	Activation energy (kJ.mol ⁻¹)
M_0	initial mass of the matter	ΔS	Entropy (kJ.mol ⁻¹)
M_f	mass of the dry matter	M_{db}	Dry Basis Moisture Content
$dt+t$	moisture content	ΔH	Enthalpy (kJ.mol ⁻¹)
T	temperature (K°)	ΔG	Gibbs free energy (kJ.mol ⁻¹)
$M_{t+\Delta t}$	moisture in t + dt	h_p	Planck constant (0.6262×10 ⁻³⁴ J.s ⁻¹)
MR	moisture content	K_b	Boltzmann constant (1.3806×10 ⁻²³ J.K ⁻¹)
DR	drying ratio	SEC_{Inf}	specific energy consumption for the infrared dryer (kW.h.kg ⁻¹)
t	time (s)	SEC_{Ult}	specific energy consumption for the ultrasound device (kW.h.kg ⁻¹)
Δt	difference between two time scale (s)	SEC_{Total}	total specific energy consumption in an infrared dryer with ultrasonic pretreatment (kW.h.kg ⁻¹)
L	thickness (m)	ΔW	power consumption before, and after drying kW.h
k	line slope	π	pi number

1. INTRODUCTION

Mallow (*Malva sylvestris* L.), belonging to the Malvaceae family, is an herbaceous species that may grow as an annual, biennial, or short-lived perennial. This plant is widely distributed throughout Iran, except in the central desert regions, and represents one of the ten native *Malva* species reported in the country. Due to its medicinal importance, mallow has been widely recognized in traditional medicine, and its leaves and flowers are listed in several authoritative pharmacopoeias for their therapeutic applications (Eghbal et al., 2021; Shokufeh & Gholam Ali, 2016). The plant is rich in essential vitamins such as A, B, and C and contains a variety of bioactive compounds that contribute to its diverse pharmacological activities, including anti-inflammatory, antiseptic, antibacterial, antifungal, and antiviral effects. Traditionally, mallow has been used to relieve inflammation of the respiratory, urinary, and gastrointestinal systems and to treat skin irritations, insect bites, and symptoms associated with the common cold. Owing to these nutritional

55 and therapeutic properties, mallow has attracted increasing attention as a valuable medicinal and
56 functional plant (Ahmad et al., 2020; Khalid & Saleem, 2018). Notably, mallow leaves contain the
57 highest concentration of total phenolic compounds among the different plant parts, which is closely
58 associated with their strong antioxidant capacity. However, similar to many green leafy vegetables,
59 freshly harvested mallow leaves are highly perishable due to their high moisture content, which
60 significantly limits their shelf life and marketability. Postharvest losses of such nutrient-rich crops
61 may reach 25–30%, largely as a result of seasonal overproduction, limited storage facilities, and
62 inadequate on-site processing infrastructure (Gutti et al., 2012). Therefore, the development of
63 effective preservation strategies is essential not only to extend product availability beyond the
64 harvest period but also to maintain the phytochemical stability, sensory properties, and nutritional
65 quality of the leaves. Among the various preservation methods, drying remains one of the oldest
66 and most widely used techniques for stabilizing agricultural products and medicinal plant
67 materials. Nevertheless, conventional drying methods often expose plant tissues to prolonged
68 thermal stress, which can degrade heat-sensitive bioactive compounds and adversely affect product
69 quality. Consequently, increasing research attention has been directed toward integrating
70 innovative technologies with drying processes to enhance efficiency while minimizing quality
71 deterioration (Babiker et al., 2018). In this context, ultrasound-assisted pretreatment has emerged
72 as a promising non-thermal strategy for improving drying performance. Ultrasound typically
73 operates at ambient temperatures and relies on acoustic cavitation—the formation, growth, and
74 implosive collapse of microscopic bubbles in a liquid medium—which generates localized
75 mechanical effects within plant tissues. These effects can induce significant microstructural
76 modifications, including the formation of microchannels and partial disruption of cell walls,

thereby facilitating internal moisture migration and accelerating mass transfer during subsequent drying (Fernandes et al., 2008).

The mechanical effects generated by acoustic cavitation produce a sponge-like phenomenon within plant tissues, which enhances internal mass transfer pathways while largely preserving the biochemical composition and structural integrity of the product (Mason, Paniwnyk, & Lorimer, 1996). In recent years, numerous studies have highlighted the effectiveness of ultrasound pretreatment in improving the drying performance of herbal and plant-based materials. For instance, Song et al. reported that a combined ultrasound–blanching pretreatment significantly accelerated the hot-air drying of perilla leaves, enhanced effective moisture diffusivity, and reduced color degradation (ΔE) compared with conventional blanching (Song et al., 2021). Similarly, Oladejo et al. demonstrated that ultrasound-assisted convective drying of sour tea markedly shortened drying time while better preserving the nutritional quality of the product (Oladejo et al., 2023). In another study, Bennaceur et al. observed that ultrasound pretreatment, coupled with elevated drying temperatures, reduced the drying duration of henna leaves and increased the effective moisture diffusivity coefficient (Bennaceur et al., 2021).

Beyond process efficiency, a comprehensive understanding of thermodynamic parameters—particularly enthalpy (ΔH), entropy (ΔS), and Gibbs free energy (ΔG)—is essential for the rational design and optimization of drying systems. These parameters provide valuable insights into the energetic requirements of moisture removal, the nature of water–food interactions, and the physicochemical transformations occurring within the food matrix during drying (Öztekin et al., 2022). Entropy, for instance, reflects the degree of disorder and mobility of water molecules within the product structure, thereby indicating the strength and nature of water–solid interactions. In contrast, Gibbs free energy serves as a thermodynamic indicator for assessing the spontaneity and

feasibility of moisture removal and associated physicochemical reactions during drying. As highlighted by Wanderley et al., variations in Gibbs free energy can be used to determine whether moisture transfer processes occur spontaneously under given drying conditions (Wanderley et al., 2023).

Despite the growing body of research on ultrasound-assisted drying technologies, studies specifically addressing the application of ultrasound pretreatment prior to infrared drying of *Malva sylvestris* leaves remain scarce. In particular, limited attention has been given to the combined effects of ultrasound exposure and infrared temperature on drying kinetics, thermodynamic characteristics, and key quality attributes such as color stability and rehydration capacity. Therefore, the present study aims to systematically investigate the influence of ultrasound pretreatment duration (0, 5, and 10 min) and infrared drying temperature (40, 45, and 50 °C) on the drying kinetics of mallow leaves. Additionally, the study evaluates effective moisture diffusivity, thermodynamic parameters (activation energy, enthalpy, entropy, and Gibbs free energy), and quality attributes including color parameters and rehydration ratio. The findings are expected to provide valuable insights for the development of energy-efficient and quality-preserving drying strategies for medicinal and aromatic plant materials.

In this study, we have expanded the discussion of prior studies on ultrasound-assisted drying, infrared drying, and their combinations in food and medicinal plant processing. For example, recent work on infrared drying of pretreated Ginkgo seed slices demonstrated that ultrasound pretreatment can significantly improve mass transfer, drying rate, moisture diffusivity, and specific energy consumption, while reducing drying time, thereby confirming the feasibility of sequential ultrasound–infrared processing for commercial applications (Boateng & Yang, 2021). In addition, recent review studies have highlighted the growing interest in novel physical-field drying

techniques for medicinal herbs, including infrared and acoustic/ultrasonic approaches, while also noting that process-specific thermodynamic interpretation and energy analysis remain insufficiently addressed in many plant-based systems. Based on this literature, the novelty of the present study has been clarified as follows:

- the simultaneous evaluation of drying kinetics, color quality, rehydration behavior, thermodynamic parameters, and specific energy consumption in mallow leaves.
- the specific focus on a high-moisture medicinal leafy matrix, which is less frequently investigated than fruits or seeds.
- the integration of ultrasound pretreatment with infrared drying under controlled experimental conditions.
- and the use of response surface methodology to identify not only optimum conditions but also a practical operating window.

These additions make clear that the main contribution of the study is not merely the application of ultrasound-assisted infrared drying, but the quantitative linkage of pretreatment intensity, drying behavior, energy demand, and thermodynamic evolution in mallow leaves.

2. MATERIALS AND METHODS

2.1. Drying procedure

Fresh mallow (*Malva sylvestris* L.) plants used in this study were collected from agricultural areas located in the vicinity of Urmia, West Azerbaijan Province, Iran. The plant material was formally identified by Dr. Abolfazl Akhoundzadeh Yamchi, Department of Biosystems, Urmia University. A voucher specimen was deposited in the public herbarium of Urmia University (Herbarium code:

HUK62) under the accession number HUK-2156. The collection permit was obtained from the [relevant authority, e.g., Natural Resources and Watershed Management Organization of West Azerbaijan Province under permit number 1404/382/91. All collection activities complied with national and local regulations. The species *Malva sylvestris* L. is not listed as endangered under the IUCN Red List or CITES appendices.

Immediately after harvesting, the plant material was manually inspected and cleaned to remove soil particles, damaged tissues, and other foreign materials. Subsequently, intact and pest-free leaves were carefully separated and selected for the experiments. To minimize microbial growth and physiological degradation prior to processing, the prepared samples were stored under refrigerated conditions at 4 °C until further use (Akhoundzadeh Yamchi, Yeganeh, & Kouchakzadeh, 2019).

At the beginning of the experimental procedure, the initial moisture content of the mallow leaves was determined using the standard oven-drying method. Representative samples were dried in a forced-convection oven at 105 ± 1 °C until a constant weight was reached (Tagnamas et al., 2020). The moisture content was subsequently calculated and expressed on a dry basis (g water per g dry matter) according to Equation (1) (Khallaf & El-Sebaii, 2022). Based on these measurements, the average initial moisture content of the fresh mallow leaves was determined to be 2.2 ± 0.1 kg water per kg dry matter.

$$M_{db} = \frac{M_o - M_f}{M_f} \quad (1)$$

Drying experiments were performed using a laboratory-scale infrared dryer (Model GC400, Grok Iran Engineering and Design Co., Iran) designed for the dehydration of medicinal and aromatic plant materials. The dryer is equipped with a localized radiant heating system, high thermal

efficiency, and a programmable control unit that allows accurate regulation of temperature and relative humidity. Infrared heating was supplied by four near-infrared (NIR) halogen lamps, each rated at 250 W, arranged to provide relatively uniform irradiation over the sample surface and to ensure controlled effects on drying behavior and final product quality.

Before drying, mallow leaves were subjected to ultrasound pretreatment at three exposure times: 0 min (control), 5 min, and 10 min. An airborne ultrasonic system (Zagros Ultrasound Co., Iran), operating at 20 kHz with a nominal power output of 20 kW, was used to promote moisture migration through acoustic cavitation and microstructural alterations within the leaf tissue. For each experimental run, approximately 50.0 ± 0.1 g of pretreated leaves were spread uniformly in a thin layer on a perforated stainless-steel tray (25×25 cm) and placed 20 cm below the infrared lamps.

The sample mass was monitored throughout drying using a high-precision digital balance with an accuracy of ± 0.001 g, connected to a computer for automatic data acquisition at 20-min intervals. Prior to each run, the dryer was preheated to reach stable operating conditions and minimize thermal fluctuations during the experiment. Drying trials were carried out at three air temperatures (40, 45, and 50 °C), and each treatment combination was performed in triplicate. The drying process was continued until the sample moisture content reached approximately 10% on a wet basis. Moisture content and drying rate were then calculated using Equations (2) and (3), respectively (Rostami Gharkhloo, Sharifian, Rahimi, & Akhoundzadeh Yamchi, 2022; Sharifian, Gharkhloo, Yamchi, & Kaveh, 2023).

$$MR = \frac{m_e - m_t}{m_0 - m_t} \quad (2)$$

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (3)$$

In these equations, M_t represents the moisture content (% w.b.) at drying time t , M_0 denotes the initial moisture content (% w.b.), and M_e corresponds to the equilibrium moisture content (% w.b.). Moreover, M_t and $M_{t+\Delta t}$ indicate the moisture contents measured at times t and $t+\Delta t$, respectively. To evaluate color alterations induced by the drying process, five mallow leaves were randomly selected from each treatment in both fresh and dried states. Color measurements were performed using a portable digital colorimeter (CR-400, Konica Minolta, Japan). The analysis was conducted under all experimental conditions, including infrared drying temperatures of 40, 45, and 50 °C combined with ultrasound pretreatment durations of 0 min (control), 5 min, and 10 min. Color parameters were recorded in the CIELAB color space, expressed as L^* (lightness; 0 = black and 100 = white), a^* (green [–] to red [+]), and b^* (blue [–] to yellow [+]) (Rostami Gharkhloo et al., 2022). Prior to each set of measurements, the colorimeter was calibrated using the manufacturer-supplied black and white standard tiles to ensure measurement accuracy and repeatability. Based on the measured L^* , a^* , and b^* values, chroma (C), total color difference (ΔE), and browning index (BI) were subsequently calculated using Equations (4)–(7), following the procedure described by Qing et al. (2023).

$$C = \sqrt{a^2 + b^2} \quad (4)$$

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (5)$$

$$X = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 0.3012b^*} \quad (6)$$

$$BI = \frac{100 \times (X - 0.31)}{0.17} \quad (7)$$

204

205 **2.2. Rehydration ratio (RR)**

206 The rehydration capacity of dried mallow leaves was determined following the procedure reported
 207 by Doymaz (2017). For each treatment, approximately 2.5 g of dried sample was immersed in
 208 300 mL of distilled water and subjected to rehydration at two temperatures: 25 °C (ambient
 209 conditions) and 65 °C (elevated temperature). The rehydration process was allowed to proceed for
 210 300 min to ensure sufficient water absorption by the dried tissues.

211 At the end of the rehydration period, the samples were carefully removed from the water and gently
 212 blotted with absorbent paper to eliminate excess surface moisture. The rehydrated samples were
 213 then immediately weighed using a digital analytical balance. The rehydration ratio (RR), which
 214 reflects the ability of the dried material to absorb water and recover its structure, was subsequently
 215 calculated according to Equation (8), as described by Chikpah et al. (2022).

$$RR = \frac{W_2}{W_1} \quad (8)$$

216 where W_1 represents the weight of the rehydrated sample (g) and W_2 denotes the weight of the dry
 217 sample (g).

218 **2.3. Effective Moisture Diffusion Coefficient (D_{eff})**

The determination of effective moisture diffusivity is a key component in modeling the drying kinetics of food and other hygroscopic materials, since it is strongly influenced by both the drying temperature and the moisture content (or relative humidity) of the material. Moisture migration during the falling-rate period of drying can be adequately described using Fick's second law of diffusion under unsteady-state conditions. Therefore, Fick's second law, expressed in Equation (9), was applied to model the internal moisture transfer during the drying process (Öztekin et al., 2022).

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left(D_{eff} \frac{\partial M}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_{eff} \frac{\partial M}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_{eff} \frac{\partial M}{\partial z} \right) \quad (9)$$

Fick's second law of diffusion is widely acknowledged as an appropriate mathematical framework for characterizing moisture migration during the falling-rate drying period of agricultural products. To analytically solve the diffusion equation, several standard simplifying assumptions were adopted: the material was modeled as an infinite slab with one-dimensional mass transfer, the initial moisture distribution was assumed to be uniform, and internal moisture diffusion within the solid matrix was designated as the primary resistance to mass transfer, thereby neglecting external convective resistance (Crank, 1979). Consequently, the effective moisture diffusivity (D_{eff}) was determined by applying the diffusion solution for a slab geometry, as delineated in Equations (10)–(12) (Tagnamas et al., 2020).

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \exp \left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2} \right) \quad (10)$$

$$MR = \frac{8}{\pi^2} \exp \left(-\frac{\pi^2 D_{eff} t}{4L^2} \right) \quad (11)$$

$$k = \frac{\pi^2 D_{eff}}{4L^2} \quad (12)$$

236

237 where MR denotes the moisture ratio of Mallow leaves (d.b.), L represents the half-thickness of
 238 the sample (m), and D_{eff} is the effective diffusion coefficient ($m^2.s^{-1}$).

239 **2.4. Activation energy and thermodynamic characteristics**

240 The drying kinetics of hygroscopic plant materials are fundamentally governed by their intrinsic
 241 moisture-binding characteristics. In this context, activation energy (E_a) serves as a critical
 242 parameter for quantifying the energy barrier associated with moisture desorption.
 243 Thermodynamically, it represents the minimum energy input required to initiate the removal of
 244 one mole of water from the material matrix under conditions of constant moisture content and
 245 chemical composition (Fang et al., 2009).

246 The temperature sensitivity of the effective moisture diffusivity (D_{eff}) is traditionally characterized
 247 using the Arrhenius relationship, as expressed in Equation (13) (Okunola et al., 2023). By applying
 248 a logarithmic transformation to this expression (Equation 14), a linear relationship is established.
 249 Consequently, plotting $\ln(D_{eff})$ against the reciprocal of absolute temperature ($1/T$) yields a linear
 250 plot; the slope of this line (K) is subsequently utilized to calculate the activation energy, as detailed
 251 in Equation (15) (Kalantari et al., 2023).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (13)$$

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \quad (14)$$

$$K = \left(\frac{E_a}{R} \right) \quad (15)$$

252 where E_a denotes the activation energy ($\text{kJ}\cdot\text{mol}^{-1}$), D_0 represents the pre-exponential factor or the
 253 effective moisture diffusivity at infinite temperature ($\text{m}^2\cdot\text{s}^{-1}$), T is the absolute drying temperature
 254 (K), and R is the universal gas constant ($8.314 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$). Furthermore, to provide a
 255 comprehensive understanding of the drying energetics, the fundamental thermodynamic
 256 parameters — specifically the changes in entropy (ΔS), Gibbs free energy (ΔG), and enthalpy (ΔH)
 257 — were determined. These parameters were calculated based on the derived activation energy (E_a)
 258 and the absolute temperature using Equations (16)–(18), following the methodology established
 259 by EL-Mesery et al. (2022) and Rashid et al. (2022).

$$\Delta H = E_a - RT \quad (16)$$

$$\Delta G = R \times T \times \ln \left(\frac{k \times h_p}{T \times K_B} \right) \quad (17)$$

$$\Delta S = \frac{\Delta H - \Delta G}{T} \quad (18)$$

260

261 where ΔH represents the enthalpy change ($\text{kJ}\cdot\text{mol}^{-1}$), ΔS denotes the entropy change
 262 ($\text{kJ}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$), and ΔG corresponds to the Gibbs free energy change ($\text{kJ}\cdot\text{mol}^{-1}$). In addition, h_p
 263 represents Planck's constant ($6.626 \times 10^{-34} \text{ J}\cdot\text{s}$), while k_b denotes Boltzmann's constant ($1.381 \times$
 264 $10^{-23} \text{ J}\cdot\text{K}^{-1}$).

265 **2.5. Specific Energy Consumption (SEC)**

266 In ultrasound-assisted infrared drying, the specific energy consumption (SEC) is defined as the
 267 total amount of energy required to remove one kilogram of water from mallow leaves. Therefore,

improving the economic efficiency of the drying process is closely associated with minimizing the SEC. The total energy input during the drying process consists of two main components: (1) the electrical energy consumed by the infrared dryer and (2) the energy supplied by the ultrasound generator during the pretreatment stage. Accordingly, the specific energy consumption associated with infrared drying (SEC_{inf}) was calculated using Equation (19), following the approach reported by Li et al. (2022).

$$SEC_{inf} = \frac{\Delta W}{M_0 - M_e} \quad (19)$$

where ΔW denotes the total electrical energy consumption for drying (k.Wh), and M_0 and M_e represent the initial and final masses of the samples (kg), respectively. The ultrasound power was calculated according to Equation (20). (Jafari & Zare, 2017).

$$UP = UI \cos \Phi \quad (20)$$

where U (V) represents the applied voltage, I (A) the current supplied to the ultrasonic generator, and $\cos \phi$ the power factor, assumed to be 0.8. The energy consumption of the ultrasound device was calculated using Equation (21) (Abdoli, Zare, Jafari, & Chen, 2018).

$$SEC_{Ult} = \frac{UP.t}{M_0 - M_e} \quad (21)$$

where SEC_{Ult} denotes the specific energy consumption of the ultrasonic device ($kWh \cdot kg^{-1}$), M_0 and M_e refer to the initial and final sample masses (kg), respectively, and the overall specific energy consumption is obtained from Equation (22). (Abdoli et al., 2018; Jafari & Zare, 2017)

$$SEC_{Total} = SEC_{Inf} + SEC_{Ult} \quad (22)$$

3. where SEC_{Total} denotes the overall specific energy consumption of a drying system incorporating ultrasound pretreatment ($kWh \cdot kg^{-1}$).

2.6. Statistical Analysis

All experiments were performed in three replicates, and the results were expressed as mean $\pm$ standard deviation. Data were analyzed using one-way analysis of variance (ANOVA). To determine the significance of differences between the means of the treatments, Tukey's post-hoc test was applied at a significance level of $p < 0.05$. All statistical procedures were carried out using SPSS software (version 26.0).

We have clarified the statistical analysis section in greater detail. The experimental data were analyzed using analysis of variance (ANOVA) to determine the significance of the effects of drying temperature and ultrasound pretreatment time, as well as their interaction, on the measured responses. Because the study involved two independent factors—drying temperature and ultrasound pretreatment duration—a **two-way ANOVA** was the appropriate statistical approach for evaluating:

- the main effect of drying temperature,
- the main effect of ultrasound pretreatment time,
- and the interaction effect between the two factors.

When significant differences were detected, a post hoc mean comparison test was used to separate group means. In this Study, we have specified the exact multiple-comparison procedure used in the study and indicated the significance level applied. We also clarified that statistical analysis was employed to assess the reliability of differences among treatment combinations for drying time, SEC, color parameters, rehydration ratio, effective moisture diffusivity, and thermodynamic parameters.

4. Results and Discussion

Figure 1 depicts the drying kinetics of mallow leaves subjected to infrared drying at three temperature levels (40, 45, and 50 °C) in combination with different ultrasound pretreatment durations (0, 5, and 10 min). As illustrated, both increasing the drying temperature and prolonging the ultrasound pretreatment markedly shortened the overall drying time. The reduction in drying duration at elevated temperatures can be explained by several interacting mechanisms. Higher temperatures reduce the latent heat required for water evaporation and simultaneously increase the kinetic energy of water molecules within the plant matrix. These effects enhance the internal–external temperature gradient and intensify heat and mass transfer, thereby accelerating moisture removal during the drying process (Beigi, 2019). In addition, longer ultrasound pretreatment promotes structural modifications within the mallow leaf tissue through the formation of microchannels and microscopic disruptions in cell walls. Such structural changes facilitate the migration of intracellular moisture toward the surface, ultimately enhancing evaporation and further reducing the total drying time.

The influence of ultrasound pretreatment on the drying rate of mallow leaves is presented in Figure 2. Increasing the duration of ultrasound pretreatment led to a noticeable enhancement in the drying rate, primarily due to its facilitative effect on moisture release from the leaf matrix. As shown in the figure, the drying rate reached its maximum during the initial stage of the process. This behavior is attributed to the presence of abundant free moisture on the surface of the fresh leaves, which can evaporate rapidly when exposed to thermal energy. Consequently, the initial portion of the drying curve exhibits a steep slope, reflecting a rapid rate of moisture removal. As the drying process proceeds, however, the rate gradually decreases and moisture removal becomes progressively slower. This pattern indicates that a significant proportion of moisture loss occurs during the early stages of drying, when surface evaporation dominates the process (Öztekin et al., 2022; Tiliwa et al., 2022). In the later stages, the drying mechanism shifts to the falling-rate period. At this point, most of the readily available surface moisture has already evaporated, and further moisture removal becomes governed primarily by internal diffusion. The increasing resistance to moisture migration from the interior of the tissue to the surface consequently results in a pronounced decline in the drying rate (EL-Mesery et al., 2022).

Figure 3 presents the total drying time of mallow leaves under different infrared drying temperatures (40, 45, and 50 °C) combined with varying ultrasound pretreatment durations. The longest drying time was observed for samples dried at 40 °C without ultrasound pretreatment (control), whereas the shortest drying duration occurred at 50 °C with a 10 min ultrasound pretreatment. This outcome clearly demonstrates the synergistic effect of higher infrared temperature and ultrasound pretreatment in accelerating moisture removal and improving the overall efficiency of the drying process.

FIGURE 1 Drying kinetic curves of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

FIGURE 2 Drying rate curves of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

FIGURE 3 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the drying time of mallow leaves.

The results of the analysis of variance (ANOVA) revealed that both drying temperature and ultrasonic pretreatment duration exerted statistically significant effects on drying time at the 1% probability level ($p < 0.01$). Moreover, the interaction between these two factors was also significant, indicating that their combined influence on drying behavior was not merely additive.

An increase in drying temperature or extension of ultrasonic pretreatment duration individually resulted in a pronounced reduction in total drying time. From a mechanistic perspective, higher infrared temperatures intensify the thermal driving force for moisture evaporation, while ultrasound pretreatment induces microstructural alterations—such as cell wall disruption and the formation of microscopic channels—that reduce internal mass transfer resistance. The concurrent action of enhanced thermal gradients and improved moisture diffusivity within the plant matrix appears to generate a synergistic effect, thereby accelerating water removal and significantly shortening the drying process (Table 1).

Table 1 Analysis of variance for the drying time of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

Color is widely recognized as one of the most important quality attributes influencing consumer perception and acceptance of food products. As a primary visual indicator of freshness and quality, the preservation of natural color during processing is essential, since any noticeable discoloration may negatively affect product appeal. In this context, the total color difference (ΔE) is commonly used to quantify the extent of color change relative to the fresh material. In the present study, the average values of chroma, browning index (BI), and total color difference ranged from 23.40 to 29.24, 80.37 to 144.40, and 8.15 to 97.74, respectively, depending on the applied drying conditions.

As illustrated in Figure 4, chroma values gradually decreased with increasing drying temperature and shorter ultrasound pretreatment durations. In contrast, both ΔE and the browning index increased under these conditions, indicating more pronounced color degradation at higher temperatures and in the absence of sufficient ultrasound pretreatment. The lowest levels of color change and browning were recorded at 40 °C with 10 min of ultrasound pretreatment, suggesting that this combination of parameters provides more favorable conditions for preserving the natural color of mallow leaves.

The development of browning during drying can largely be attributed to enzymatic oxidation and non-enzymatic reactions such as the Maillard reaction, both of which contribute to the formation

of brown pigments. These reactions are strongly temperature dependent, and elevated temperatures accelerate the formation of darker compounds during thermal processing (Macedo et al., 2020). In contrast, the highest chroma value was observed at 40 °C with 10 min of ultrasound pretreatment, indicating a better retention of color saturation and visual intensity under relatively mild drying conditions. Chroma reflects the purity and vividness of color; therefore, higher chroma values generally correspond to less pigment degradation and improved preservation of natural plant pigments (Zzaman et al., 2021). The decline in chroma at higher drying temperatures is likely associated with the thermal degradation of heat-sensitive pigments, particularly carotenoids and chlorophyll derivatives present in mallow leaves (Figure 5).

FIGURE 4 Effect of ultrasound pretreatment prior to infrared drying on the color change of mallow leaves.

FIGURE 5 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the color change of mallow leaves.

The rehydration ratio (RR) is considered one of the most important quality indicators of dried foods, as it reflects the ability of the dehydrated material to absorb water and partially recover its original structural and physicochemical properties after drying. Moreover, RR provides valuable insight into the extent of cellular disruption and tissue damage induced during the dehydration process (Ayala-Aponte et al., 2021).

Figure 6 illustrates the mean rehydration ratio values of dried mallow leaves as affected by drying temperature, rehydration water temperature, and ultrasound pretreatment duration. The highest RR was obtained for samples dried at 50 °C, rehydrated in distilled water at 65 °C, and pretreated with

ultrasound for 10 min. This finding indicates that the combined application of relatively higher drying temperatures and prolonged ultrasound pretreatment improved the rehydration behavior of the dried tissue. Ultrasound treatment likely enhanced the formation of microscopic channels and porous structures within the leaf matrix, thereby facilitating subsequent water penetration during rehydration. In addition, drying at higher temperatures may have promoted the development of a more open internal structure with lower resistance to moisture absorption, as previously reported for similar plant materials (Lin et al., 2023).

In contrast, the lowest rehydration ratio was observed in samples dried at 40 °C, rehydrated at 25 °C, and subjected to no ultrasound pretreatment (control treatment). The inferior rehydration performance under these conditions may be attributed to restricted water diffusion at lower rehydration temperatures together with reduced tissue porosity and partial structural collapse caused by the absence of ultrasound-induced microstructural modification (Izli & Polat, 2019).

As shown in Figure 7, the rehydration capacity of mallow leaves at 65 °C was substantially higher than that obtained at 25 °C. Elevated rehydration temperatures enhance molecular mobility and improve water diffusion into the dried matrix by increasing cell wall permeability and softening plant tissues. These effects collectively facilitate faster and more extensive moisture absorption, resulting in improved rehydration performance (Doymaz, 2017).

FIGURE 6 Effect of ultrasound pretreatment prior to infrared drying on the rehydration ratio of mallow leaves.

FIGURE 7 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the rehydration ratio of mallow leaves.

Figure 8 illustrates the effect of drying temperature and ultrasound pretreatment duration on the average effective moisture diffusivity (D_{eff}) of mallow leaves during infrared drying. The results clearly demonstrate that both increasing the drying temperature and prolonging the ultrasound pretreatment significantly enhanced the effective moisture diffusivity. This behavior can be explained by the intensified internal moisture migration resulting from higher thermal energy and the structural alterations induced by ultrasound treatment. Elevated temperatures increase molecular mobility and reduce the viscosity of liquid water within the plant matrix, thereby facilitating moisture movement toward the product surface. Simultaneously, ultrasound pretreatment promotes the formation of microscopic channels and capillary pathways within the leaf tissue, which reduce internal resistance to mass transfer and accelerate moisture diffusion (Beigi, 2019).

Consistent with this mechanism, samples subjected to ultrasound pretreatment exhibited higher D_{eff} values compared with the untreated control samples. As presented in Figure 9, the highest effective moisture diffusivity was obtained at a drying temperature of 50 °C combined with a 10 min ultrasound pretreatment. Under these conditions, D_{eff} values ranged from 2.39×10^{-7} to $8.68 \times 10^{-7} \text{ m}^2 \cdot \text{s}^{-1}$. These results fall within the typical range reported for agricultural and plant-based materials, where effective moisture diffusivity generally varies between 10^{-12} and $10^{-7} \text{ m}^2 \cdot \text{s}^{-1}$ depending on the product type, structure, and drying conditions (Jha & Sit, 2020).

FIGURE 8 Effect of ultrasound pretreatment prior to infrared drying on the effective moisture diffusivity (D_{eff}) of mallow leaves.

FIGURE 9 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the effective moisture diffusivity (D_{eff}) of mallow leaves.

The activation energy (E_a) associated with moisture diffusion was determined using the Arrhenius relationship by plotting $\ln(D_{\text{eff}})$ against the reciprocal of absolute temperature ($1/T$). The value of E_a was subsequently calculated from the slope of the resulting linear regression. Activation energy represents the minimum energy required to initiate moisture migration from the internal structure of a material during the drying process and is therefore an important indicator of the resistance to moisture transport within the product matrix. For most food materials, reported activation energy values typically range between 12.7 and 110 $\text{kJ}\cdot\text{mol}^{-1}$ (Chikpah et al., 2022).

In the present study, mallow leaves dried by infrared radiation at temperatures between 40 and 50 °C, combined with ultrasound pretreatment durations ranging from 0 to 10 min, exhibited activation energy values between 86.32 and 73.73 $\text{kJ}\cdot\text{mol}^{-1}$ (Figure 10). Notably, a gradual decrease in E_a was observed with increasing ultrasound pretreatment duration. This trend indicates that ultrasonic pretreatment facilitates moisture diffusion by inducing microstructural modifications within the leaf tissue, such as the formation of microscopic channels and partial disruption of cell walls. These structural changes reduce internal mass transfer resistance, allowing moisture to migrate more readily toward the surface during drying. Consequently, the energy

barrier associated with moisture movement is lowered, leading to a reduction in the activation energy required for water removal.

FIGURE 10 Activation energy plot for the infrared drying of mallow leaves under different ultrasound pretreatment conditions.

Table 2 summarizes the thermodynamic parameters, including enthalpy change (ΔH), entropy change (ΔS), and Gibbs free energy change (ΔG), determined for mallow leaves subjected to different infrared drying temperatures and ultrasound pretreatment durations. The results revealed that both ΔH and ΔS decreased progressively with increasing drying temperature (40–50 °C) and longer ultrasound exposure times, whereas ΔG exhibited an increasing trend under the same conditions.

From a thermodynamic perspective, the enthalpy change (ΔH) reflects the energy required to remove bound water molecules from the food matrix and is therefore associated with the strength of water–solid interactions. Higher ΔH values indicate stronger moisture binding within the cellular structure, requiring greater energy input for moisture evaporation during drying (da Silva et al., 2020). In agreement with this interpretation, samples dried at lower temperatures exhibited comparatively higher ΔH values, suggesting that more energy was needed to disrupt the stronger interactions between water molecules and the plant matrix at reduced thermal conditions (Figure 11). As drying progressed and moisture content decreased, the remaining water became

increasingly bound to the solid structure, thereby increasing the energetic requirement for its removal.

Entropy change (ΔS) provides insight into the degree of molecular disorder and the mobility of water molecules within the product matrix, thereby reflecting the nature of water–solid interactions during drying (de Oliveira et al., 2013; Yogendrarajah et al., 2015). In the present study, the decline in ΔS with increasing drying temperature and prolonged ultrasound pretreatment closely paralleled the trend observed for ΔH . This behavior suggests a reduction in molecular randomness and lower mobility of residual moisture as the drying process advanced. Furthermore, the negative entropy values obtained in this study may indicate reduced translational and rotational freedom associated with the formation of activated complexes during moisture diffusion. Such behavior has also been linked to structural rearrangements and physicochemical changes occurring within biological materials during dehydration (Alves et al., 2021; Öztekin et al., 2022).

The Gibbs free energy change (ΔG) is commonly used to evaluate the thermodynamic spontaneity of the drying process, which fundamentally involves water evaporation as a physicochemical transformation. A negative ΔG value indicates that the process proceeds spontaneously, whereas positive values imply that continuous external energy is required to sustain moisture removal (Sarpong et al., 2022). In the current study, ΔG values ranged from 60.15 to 62.89 kJ·mol⁻¹ across all experimental conditions involving drying temperatures of 40–50 °C and ultrasound pretreatment durations of 0–10 min. The consistently positive ΔG values confirm that infrared drying of mallow leaves is a non-spontaneous process and therefore depends on a continuous supply of external thermal energy to maintain moisture evaporation.

Table 2 Thermodynamic properties of mallow leaves during infrared drying with ultrasound pretreatment.

FIGURE 11 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the thermodynamic properties of mallow leaves.

The specific energy consumption (SEC) associated with the infrared drying of mallow leaves under different experimental conditions is presented in Figure 12. The results indicate a clear influence of both drying temperature and ultrasound pretreatment duration on the overall energy requirement of the process. As anticipated, the lowest SEC value was recorded at the highest drying temperature (50 °C) combined with the longest ultrasound pretreatment duration (10 min), highlighting the beneficial role of these parameters in improving the energy efficiency of the drying operation.

An increase in drying temperature resulted in a noticeable reduction in SEC. This behavior can be attributed to the effective mode of heat transfer associated with infrared radiation, which penetrates directly into the product matrix and promotes rapid internal heating. Such direct energy transfer enhances moisture migration from the interior of the leaf tissue toward the surface, thereby accelerating evaporation and substantially reducing the total drying time. As a consequence, the overall energy consumption required to remove a unit mass of water decreases under higher temperature conditions (Lin et al., 2023).

In addition, samples subjected to ultrasound pretreatment consistently exhibited lower SEC values compared with untreated control samples. This improvement can be linked to the structural modifications induced by ultrasonic waves. Acoustic cavitation generates microscopic bubbles that collapse violently within the liquid medium, producing localized mechanical forces and pressure fluctuations. These phenomena lead to the formation of microchannels and increased porosity within the plant tissue. The resulting structural alterations reduce internal mass transfer resistance and facilitate more efficient moisture transport during drying. Consequently, moisture removal occurs more rapidly, leading to a measurable reduction in the overall energy demand of the drying process.

FIGURE 12 Specific energy consumption during infrared drying of mallow leaves with ultrasound pretreatment.

Figure 13 presents the optimization of the independent variables, namely drying temperature and ultrasound pretreatment time, based on their combined effects on key response variables including drying time, specific energy consumption (SEC), effective moisture diffusivity (D_{eff}), color attributes, rehydration ratio (RR), and the thermodynamic parameters (enthalpy, Gibbs free energy, and entropy) of dried mallow leaves. During the optimization procedure, all response variables were assigned equal importance and weight in order to identify a balanced set of processing conditions that simultaneously improve product quality and process efficiency.

Based on the defined optimization criteria, Figure 14 illustrates the predicted solutions corresponding to the highest desirability values. In desirability-based optimization, values

approaching 1 indicate more favorable and optimal operating conditions. The results show that applying the optimized processing parameters leads to a product characterized by reduced drying time, lower specific energy consumption, minimized color deterioration, and lower enthalpy and entropy values, while simultaneously maximizing effective moisture diffusivity (D_{eff}), rehydration capacity (RR), and Gibbs free energy.

According to the model predictions, the optimal conditions for drying mallow leaves were identified as infrared drying at a temperature of 49.27 °C combined with an ultrasound pretreatment duration of 10 min. Under these optimized conditions, the predicted values for drying time, SEC, D_{eff} , color parameters (ΔE , BI, and chroma), rehydration ratio at 65 °C and 25 °C, enthalpy, Gibbs free energy, and entropy were 61.88 min, 33.81 kWh·kg⁻¹, 7.7×10^{-7} m²·s⁻¹, (13.46, 106.1, and 4.54), (4.6 and 4.50), 37.77 kJ·mol⁻¹, 62.74 kJ·mol⁻¹, and -77.39 kJ·mol⁻¹, respectively.

FIGURE 13 Numerical optimization of drying time, specific energy consumption, color change, rehydration ratio, enthalpy, Gibbs free energy, and entropy for mallow leaves dried by infrared drying with ultrasound pretreatment.

The overall desirability value obtained for the selected optimal conditions was 0.713. Although the specific combination of a drying temperature of 49.27 °C and an ultrasound pretreatment time of 10 min was identified as the optimum point based on the highest desirability score, the desirability surface presented in Figure 13 indicates the existence of a broader optimal region around this point. Within this region, different combinations of drying temperature and sonication time are predicted to yield comparatively high and practically acceptable response values.

This behavior is consistent with the fundamental principles of response surface methodology (RSM), in which the optimization outcome is generally interpreted not only as a single numerical point, but also as a feasible operating window. The presence of such an optimal region is expected because the fitted response functions are continuous and are influenced by experimental variability, model uncertainty, and approximation errors. Therefore, from a practical processing perspective, the identified optimum should be regarded as a robust operating condition rather than an isolated point. This interpretation agrees with RSM theory, which emphasizes the identification of reliable and applicable process ranges for industrial or laboratory implementation (Keramat et al., 2025; Myers et al., 2016).

FIGURE 14 Optimized desirability values for input variables, response variables, and overall desirability of mallow leaves dried by infrared drying with ultrasound pretreatment.

Our results showed that increasing drying temperature and ultrasound pretreatment duration significantly reduced SEC. This trend is consistent with the fundamental principle that ultrasound pretreatment can alter tissue microstructure, create microchannels, and reduce internal resistance to moisture migration, thereby shortening drying time and lowering the energy required per unit mass of removed water. Similar behavior has been reported in infrared drying of pretreated agricultural products, where ultrasound-assisted pretreatment improved drying performance and reduced energy demand (Boateng & Yang, 2021).

From a practical standpoint, the significance of these findings is twofold. First, reducing SEC is economically important because drying is one of the most energy-intensive unit operations in food and medicinal herb processing. Second, lowering SEC while preserving quality attributes is especially valuable for heat-sensitive medicinal plants such as mallow, where excessive thermal exposure may compromise pigments, bioactive compounds, and rehydration behavior.

A more detailed discussion emphasizing that the observed SEC reduction is not only a process advantage but also a sustainability-relevant outcome. The revised discussion now situates the present results within the broader context of energy-efficient dehydration technologies and the ongoing transition toward low-energy postharvest processing systems.

5. Conclusions

Increasing the drying temperature (40–50 °C) and ultrasound pretreatment duration (0–10 min) significantly reduced drying time and specific energy consumption (SEC), while simultaneously enhancing effective moisture diffusivity (D_{eff}) and rehydration capacity. In contrast, color quality parameters (chroma, ΔE , and browning index) were better preserved at lower drying temperatures combined with longer ultrasound exposure, suggesting that ultrasonic pretreatment mitigates thermal degradation of pigments during infrared drying.

The results further indicate that ultrasound pretreatment duration and infrared drying temperature jointly influence the thermodynamic characteristics of the dehydration process. Increasing sonication time and drying temperature reduced the activation energy of moisture diffusion ($E_a=73.70\text{--}86.31\text{ kJ}\cdot\text{mol}^{-1}$), reflecting a lower energetic barrier for water removal. Thermodynamic analysis also showed decreasing trends in enthalpy and entropy with increasing

temperature and ultrasound exposure, whereas Gibbs free energy exhibited an increasing trend, confirming the non-spontaneous nature of the drying process while indicating improved energy efficiency under intensified processing conditions.

Overall, the findings demonstrate that ultrasound-assisted infrared drying enhances mass transfer, improves process efficiency, and helps maintain the quality attributes of dried mallow leaves. The integration of ultrasound pretreatment with infrared drying therefore represents a promising and energy-efficient strategy for processing heat-sensitive medicinal herbs such as mallow.

Future studies should investigate the applicability of this approach to other leafy medicinal plants and evaluate its performance under pilot- or industrial-scale infrared drying systems. Such investigations would further clarify the scalability and robustness of ultrasound-assisted drying technologies in sustainable food and herbal processing applications.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

COMPLIANCE WITH ETHICS REQUIREMENTS

Humans or animals are not the subject matter of the present study.

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AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study. Material preparation and data collection were carried out by A. Akhoundzadeh Yamchi, M. Feizolahzadeh, and A. Moradians. Data analysis was performed by A. Akhoundzadeh Yamchi, M. Feizolahzadeh A. Rezvanivand

654 Fanaei and A. Hosainpour. The first draft of the manuscript was prepared by M. Feizolahzadeh.
655 All authors reviewed, provided feedback on, and approved both the preliminary and final versions
656 of the manuscript.

657 **DATA AVAILABILITY STATEMENT**

658 All data generated or analyzed during this study are included in this article.

659 **ORCID**

660 Abolfazl Akhoundzadeh Yamchi <https://orcid.org/0000-0002-4602-6260>

661 Maziar Feizolahzadeh <https://orcid.org/0000-0003-2134-3830>

662 Adel Rezvanivand Fanaei <https://orcid.org/0000-0002-4260-0296>

663 Adel Hosainpour <https://orcid.org/0000-0001-7004-3987>

664 Ariga Moradians

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References

- Abdoli, B., Zare, D., Jafari, A., & Chen, G. (2018). Evaluation of the air-borne ultrasound on fluidized bed drying of shelled corn: Effectiveness, grain quality, and energy consumption. *Drying Technology*, 36(14), 1749–1766.
- Ahmad, S., Saeed, K., Shahzad, Q., & Dad, R. (2020). In vivo identification of pharmacological activities of *Malva neglecta* Wallr. *E3S Web of Conferences*, 185, 4067. EDP Sciences.
- Akhoundzadeh Yamchi, A., Yeganeh, R., & Kouchakzadeh, A. (2019). The Effect Of Ultrasound Pretreatment On Qualitative Characteristics Of Peach Thin Slices (Alberta Variety). *Journal of Researches in Mechanics of Agricultural Machinery*, 8(14), 37–47.
- Alves, N., Arruda-Silva, T. A., Santos, S. B. dos, Galle, N. B. C., Silva, I. D. F., & da Silva, M. I. P. (2021). Drying kinetics and thermodynamic properties of ‘baru’ almond flours. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 25, 30–36.
- Ayala-Aponte, A. A., Cárdenas-Nieto, J. D., & Tirado, D. F. (2021). Aloe vera gel drying by Refractance Window®: Drying kinetics and high-quality retention. *Foods*, 10(7), 1445.
- Babiker, E. E., Juhaimi, F. A. L., Ghafoor, K., & Abdoun, K. A. (2018). Effect of drying methods on nutritional quality of young shoots and leaves of two *Moringa* species as non-conventional fodders. *Agroforestry Systems*, 92(3), 717–729.
- Beigi, M. (2019). Drying of mint leaves: Influence of the process temperature on dehydration parameters, quality attributes, and energy consumption. *Journal of Agricultural Science and Technology*, 21(1), 77–88.
- Bennaceur, S., Berreguioua, A., Bennamoun, L., Mulet, A., Draoui, B., Abid, M., & Carcel, J. A. (2021). Effect of ultrasound on henna leaves drying and extraction of lawsone: Experimental and modeling study. *Energies*, 14(5), 1329.
- Chikpah, S. K., Korese, J. K., Sturm, B., & Hensel, O. (2022). Colour change kinetics of pumpkin (*Cucurbita moschata*) slices during convective air drying and bioactive compounds of the dried products. *Journal of Agriculture and Food Research*, 10, 100409.
- Crank, J. (1979). *The mathematics of diffusion*. Oxford university press.

694 da Silva, G. M., Ferreira, A. G., Coutinho, R. M., & Maia, C. B. (2020). Thermodynamic analysis
695 of a sustainable hybrid dryer. *Solar Energy*, 208, 388–398.

696 de Oliveira, D. E. C., Resende, O., Bessa, J. F. V., & Kester, A. N. (2013). Kinetic and
697 thermodynamic properties of soybean grains during the drying process. *Journal of*
698 *Agricultural Engineering*, 44(s2).

699 Doymaz, İ. (2017). Drying kinetics, rehydration and colour characteristics of convective hot-air
700 drying of carrot slices. *Heat and Mass Transfer*, 53(1), 25–35.

701 Eghbal, H., Mohammadi, A., Mohammad Nejad Khiavi, N., Ahmadi Sabegh, M., & Jahani, N.
702 (2021). Comparison of the antibacterial properties of essential oils of *Malva sylvestris* and
703 *Salvia officinalis* on common bacteria of oral infection with chlorhexidine mouthwash.
704 *Journal of Mashhad Dental School*, 45(3), 217–229.

705 EL-Mesery, H. S., Sarpong, F., Xu, W., & Elabd, M. A. (2022). Design of low-energy consumption
706 hybrid dryer: A case study of garlic (*Allium sativum*) drying process. *Case Studies in Thermal*
707 *Engineering*, 33, 101929.

708 Fang, S., Wang, Z., & Hu, X. (2009). Hot air drying of whole fruit Chinese jujube (*Zizyphus jujuba*
709 Miller): thin-layer mathematical modelling. *International Journal of Food Science and*
710 *Technology*, 44(9), 1818–1824.

711 Fernandes, F. A. N., Gallão, M. I., & Rodrigues, S. (2008). Effect of osmotic dehydration and
712 ultrasound pre-treatment on cell structure: Melon dehydration. *LWT-Food Science and*
713 *Technology*, 41(4), 604–610.

714 Gutti, B., Kiman, S., & Murtala, A. M. (2012). Solar dryer-an effective tool for agricultural
715 products preservation. *Journal of Applied Technology in Environmental Sanitation*, 2(1).

716 I.D. Boateng, X. Yang, Do non-thermal pretreatments followed by intermediate- wave infrared
717 drying affect toxicity, allergenicity, bioactives, functional groups, and flavor components of
718 Ginkgo biloba seed ? A case study, *Ind. Crop Prod.* 165 (2021), 113421,
719 <https://doi.org/10.1016/j.indcrop.2021.113421>.

720 Izli, N., & Polat, A. (2019). Freeze and convective drying of quince (*Cydonia oblonga* Miller.):
721 Effects on drying kinetics and quality attributes. *Heat and Mass Transfer*, 55(5), 1317–1326.

722 Jafari, A. & Zare, D. (2017). Ultrasound-assisted fluidized bed drying of paddy: energy
 723 consumption and rice quality aspects, *Drying Technology*, vol. 35, no. 7, pp. 893–902.

724 Jha, A. K., & Sit, N. (2020). Drying characteristics and kinetics of colour change and degradation
 725 of phytocomponents and antioxidant activity during convective drying of deseeded
 726 Terminalia chebula fruit. *Journal of Food Measurement and Characterization*, 14(4), 2067–
 727 2077.

728 Kalantari, D., Naji-Tabasi, S., Kaveh, M., Azadbakht, M., Majnooni, M., Khorshidi, Y., ...
 729 Khalife, E. (2023). Drying kinetics and shrinkage rate of thin-sliced pears in different drying
 730 stages. *Journal of Food Process Engineering*, 46(3), e14264.

731 Keramat, S., Sharifian, F., Hosainpour, A., Kaveh, M., Gondek, M., & Nowacka, M. (2025).
 732 Airborne Ultrasound-Assisted Infrared Drying of Yellow Mealworm (*Tenebrio molitor*)
 733 Larvae: Nutritional Changes and Process Optimization Using Response Surface Method.
 734 *Journal of Food Science*, 90(8), 1–17. <https://doi.org/10.1111/1750-3841.70476>

735 Khalid, S., & Saleem, U. (2018). Phytochemical and pharmacological importance of *Malva*
 736 *neglecta*: An updated review. *PharmacologyOnLine*, 2, 52–62.

737 Khallaf, A. E.-M., & El-Sebaili, A. (2022). Review on drying of the medicinal plants (herbs) using
 738 solar energy applications. *Heat and Mass Transfer*, 58(8), 1411–1428.

739 Li, C., Chen, Y., Zhang, X., Mozafari, G., Fang, Z., Cao, Y., & Li, C. (2022). Exergy analysis and
 740 optimisation of an industrial-scale circulation counter-flow paddy drying process. *Energy*,
 741 251, 123901.

742 Lin, Q., Zong, X., Lin, H., Huang, X., Wang, J., & Nie, S. (2023). Based on quality, energy
 743 consumption selecting optimal drying methods of mango slices and kinetics modelling. *Food*
 744 *Chemistry: X*, 17, 100600.

745 Macedo, L. L., Vimercati, W. C., da Silva Araújo, C., Saraiva, S. H., & Teixeira, L. J. Q. (2020).
 746 Effect of drying air temperature on drying kinetics and physicochemical characteristics of
 747 dried banana. *Journal of Food Process Engineering*, 43(9), e13451.

748 Mason, T. J., Paniwnyk, L., & Lorimer, J. P. (1996). The uses of ultrasound in food technology.
 749 *Ultrasonics Sonochemistry*, 3(3), S253–S260.

750 Myers, R. H., Montgomery, D. C., & Anderson-Cook, C. M. (2016). *Response surface*
751 *methodology: process and product optimization using designed experiments*. John Wiley &
752 Sons.

753 Okunola, A. A., Adekanye, T. A., Okonkwo, C. E., Kaveh, M., Szymanek, M., Idahosa, E. O., ...
754 Wojciechowska, K. (2023). Drying characteristics, kinetic modeling, energy and exergy
755 analyses of water yam (*Dioscorea alata*) in a hot air dryer. *Energies*, 16(4), 1569.

756 Oladejo, A. O., Nkem, O. M., Alonge, A. F., Akpan, M. G., Etti, C. J., Okoko, J. U., & Etuk, N.
757 (2023). Influence of ultrasound-pretreated convective drying of Roselle (*Hibiscus sabdariffa*
758 L) leaves on its drying kinetics and nutritional quality. *Scientific African*, 20, e01704.

759 Öztekin, Y. B., Aktaş, M., Dolgun, E. C., Bilim, H. I. C., & Sacilik, K. (2022). Drying kinetics
760 and thermodynamic properties of Uzun pistachios dried by convective drying. *Journal of*
761 *Food Processing and Preservation*, 46(11), e17035.

762 Qing, S., Long, Y., Wu, Y., Shu, S., Zhang, F., Zhang, Y., & Yue, J. (2023). Hot-air-assisted radio
763 frequency blanching of broccoli: Heating uniformity, physicochemical parameters, bioactive
764 compounds, and microstructure. *Journal of the Science of Food and Agriculture*, 103(5),
765 2664–2674.

766 Rashid, M. T., Liu, K., Jatoi, M. A., Safdar, B., Lv, D., & Wei, D. (2022). Developing ultrasound-
767 assisted hot-air and infrared drying technology for sweet potatoes. *Ultrasonics*
768 *Sonochemistry*, 86, 106047.

769 Rostami Gharkhloo, Z., Sharifian, F., Rahimi, A., & Akhoundzadeh Yamchi, A. (2022). Influence
770 of high wave sound pretreatment on drying quality parameters of echinacea root with infrared
771 drying. *Journal of the Science of Food and Agriculture*, 102(5).
772 <https://doi.org/10.1002/jsfa.11557>

773 Sarpong, F., Dwumfour, F., Rashid, M. T., & Aly, T. (2022). Modelling the kinetics,
774 thermodynamic and physical properties of coconut (*Cocos nucifera* L.) during convective
775 drying. *Ghana Journal of Science*, 63(1), 63–73.

776 Sharifian, F., Gharkhloo, Z. R., Yamchi, A. A., & Kaveh, M. (2023). Infrared and hot drying of
777 saffron petal (*Crocus sativus* L.): Effect on drying, energy, color, and rehydration. *Journal of*

Food Process Engineering, 46(7), e14342.

Shokufeh, S., & Gholam Ali, H. (2016). [*Different aspects of mallow [malva sylvestris] and results of new research findings: a review*].

Song, C. F., Ma, X., Wang, J., Ding, T., & Song, W. (2021). Effects of ultrasound and blanching pretreatments on mass transfer and qualities of hot-air drying of perilla (*Perilla frutescens* L.) leaves. *Journal of Food Processing and Preservation*, 45(12), 0–2. <https://doi.org/10.1111/jfpp.15947>

Tagnamas, Z., Bahammou, Y., Kouhila, M., Hilali, S., Idlimam, A., & Lamharrar, A. (2020). Conservation of Moroccan truffle (*Terfezia boudieri*) using solar drying method. *Renewable Energy*, 146, 16–24.

Tiliwa, E. S., Han, C., Xu, B., Mujumdar, A. S., Zhou, C., & Ma, H. (2022). Comparative study of intermediate-wave and catalytic infrared drying on the kinetics and physicochemical properties of pineapple rings. *Drying Technology*, 40(12), 2568–2580.

Wanderley, R. de O. S., de Figueirêdo, R. M. F., Queiroz, A. J. de M., Dos Santos, F. S., Paiva, Y. F., Ferreira, J. P. de L., ... da Silva, W. P. (2023). The temperature influence on drying kinetics and physico-chemical properties of pomegranate peels and seeds. *Foods*, 12(2), 286.

Yogendrarajah, P., Samapundo, S., Devlieghere, F., De Saeger, S., & De Meulenaer, B. (2015). Moisture sorption isotherms and thermodynamic properties of whole black peppercorns (*Piper nigrum* L.). *LWT-Food Science and Technology*, 64(1), 177–188.

Zzaman, W., Biswas, R., & Hossain, M. A. (2021). Application of immersion pre-treatments and drying temperatures to improve the comprehensive quality of pineapple (*Ananas comosus*) slices. *Heliyon*, 7(1).

Figure caption

FIGURE 1 Drying kinetic curves of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

FIGURE 2 Drying rate curves of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

FIGURE 3 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the drying time of mallow leaves.

FIGURE 4 Effect of ultrasound pretreatment prior to infrared drying on the color change of mallow leaves.

FIGURE 5 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the color change of mallow leaves.

FIGURE 6 Effect of ultrasound pretreatment prior to infrared drying on the rehydration ratio of mallow leaves.

FIGURE 7 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the rehydration ratio of mallow leaves.

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FIGURE 12 Specific energy consumption during infrared drying of mallow leaves with ultrasound pretreatment.

FIGURE 13 Numerical optimization of drying time, specific energy consumption, color change, rehydration ratio, enthalpy, Gibbs free energy, and entropy for mallow leaves dried by infrared drying with ultrasound pretreatment.

FIGURE 14 Optimized desirability values for input variables, response variables, and overall desirability of mallow leaves dried by infrared drying with ultrasound pretreatment.

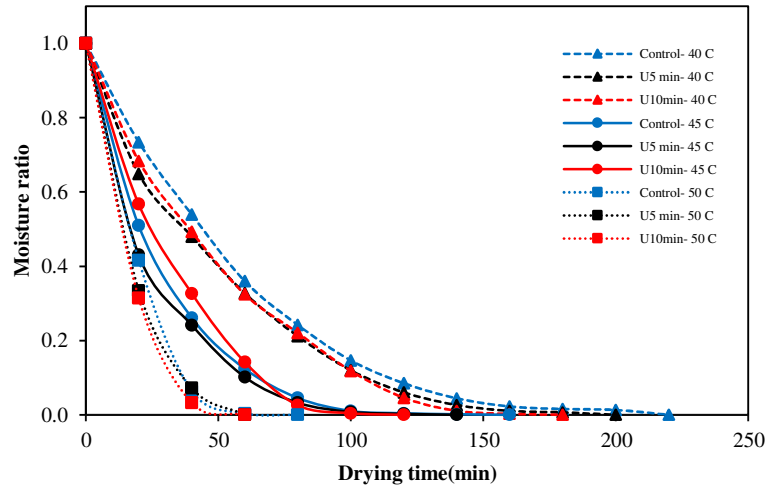


FIGURE 1 Drying kinetic curves of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

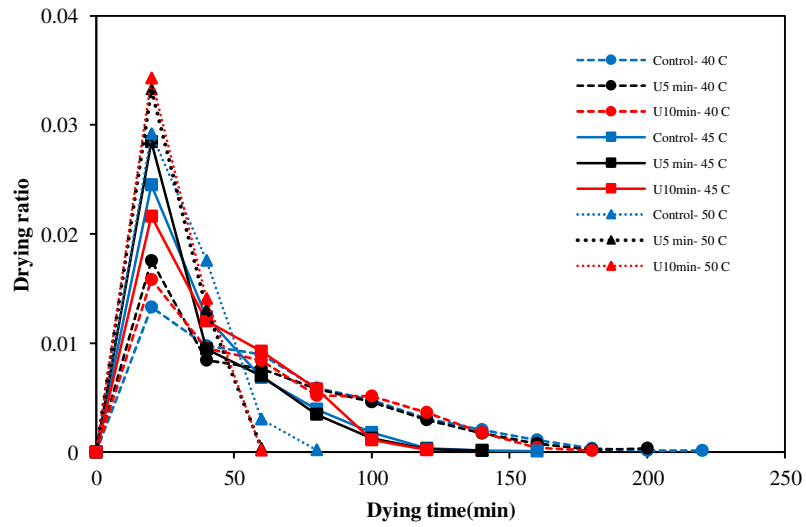


FIGURE 2 Drying rate curves of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

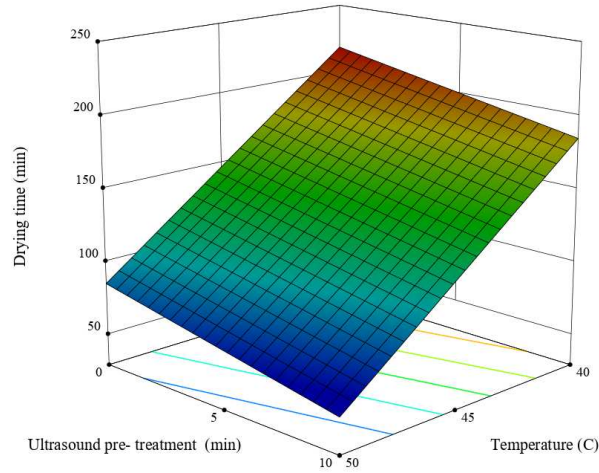


FIGURE 3 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the drying time of mallow leaves.

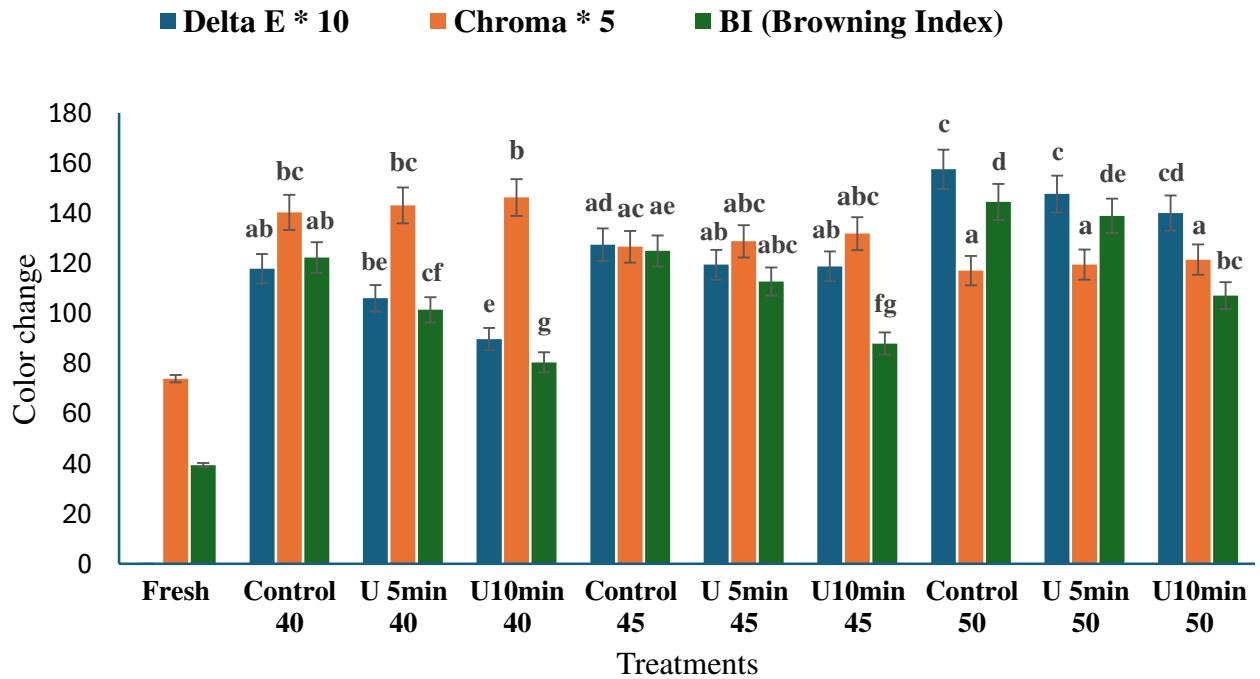


FIGURE 4 Effect of ultrasound pretreatment prior to infrared drying on the color change of mallow leaves.

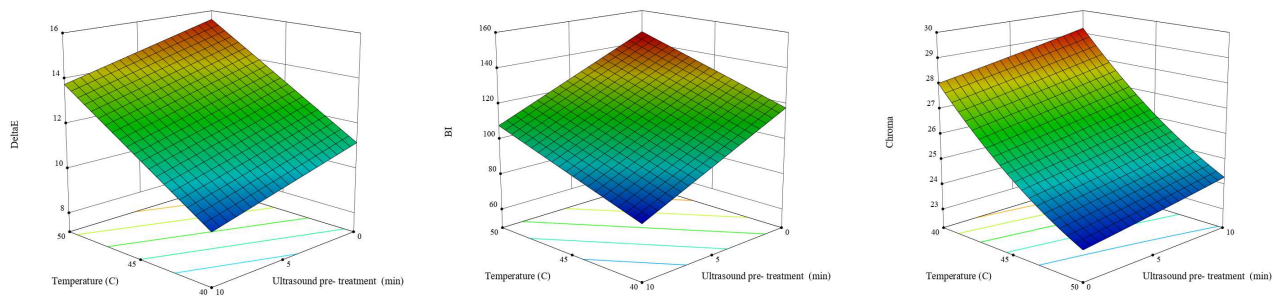


FIGURE 5 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the color change of mallow leaves.

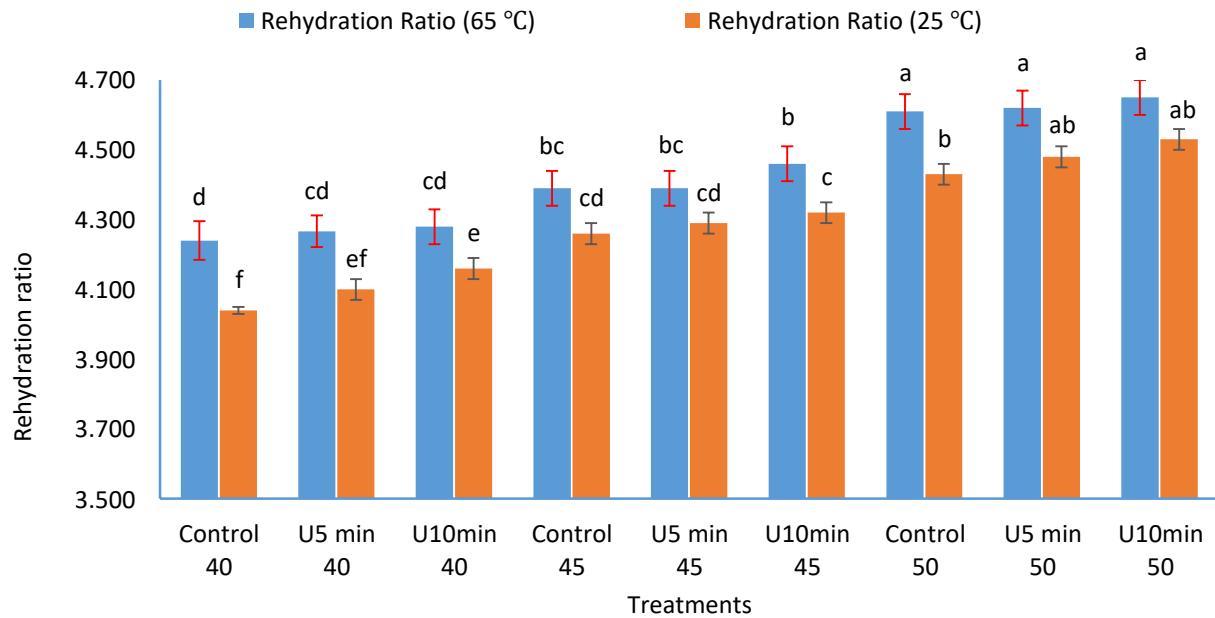


FIGURE 6 Effect of ultrasound pretreatment prior to infrared drying on the rehydration ratio of mallow leaves.

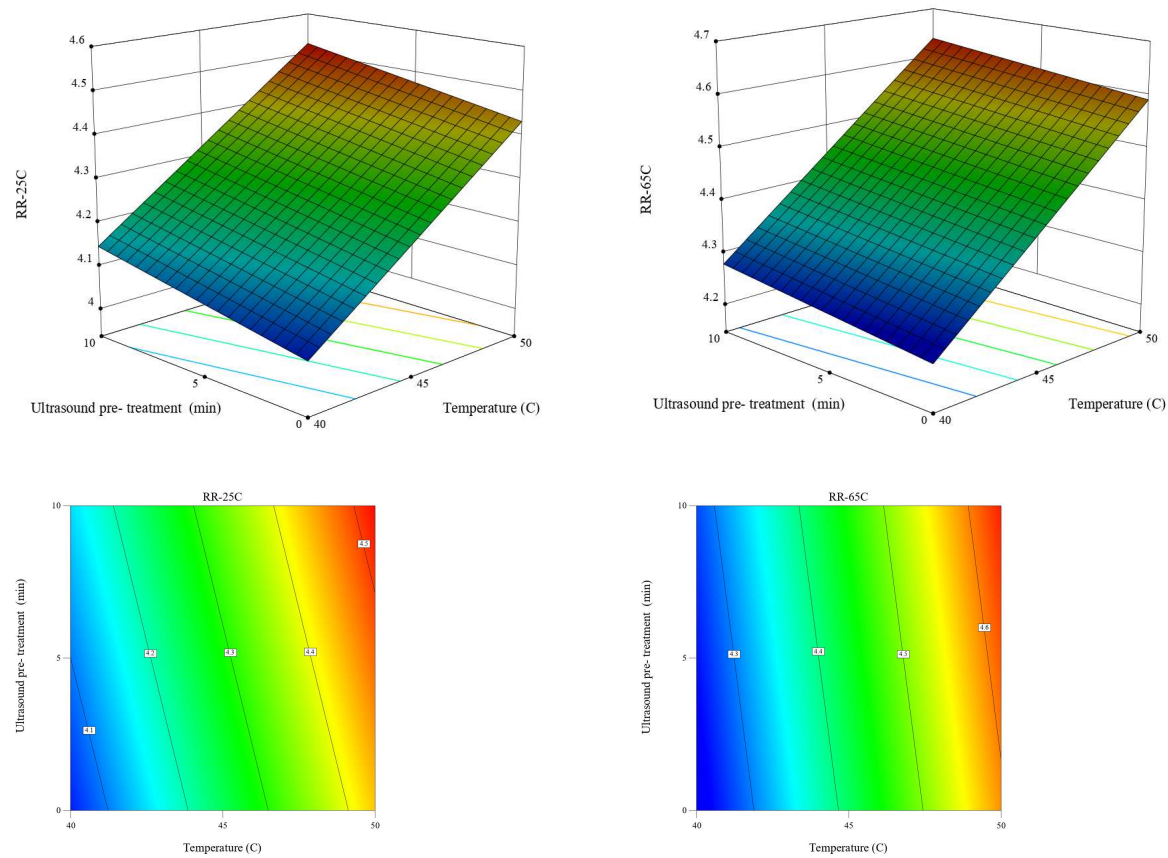


FIGURE 7 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the rehydration ratio of mallow leaves.

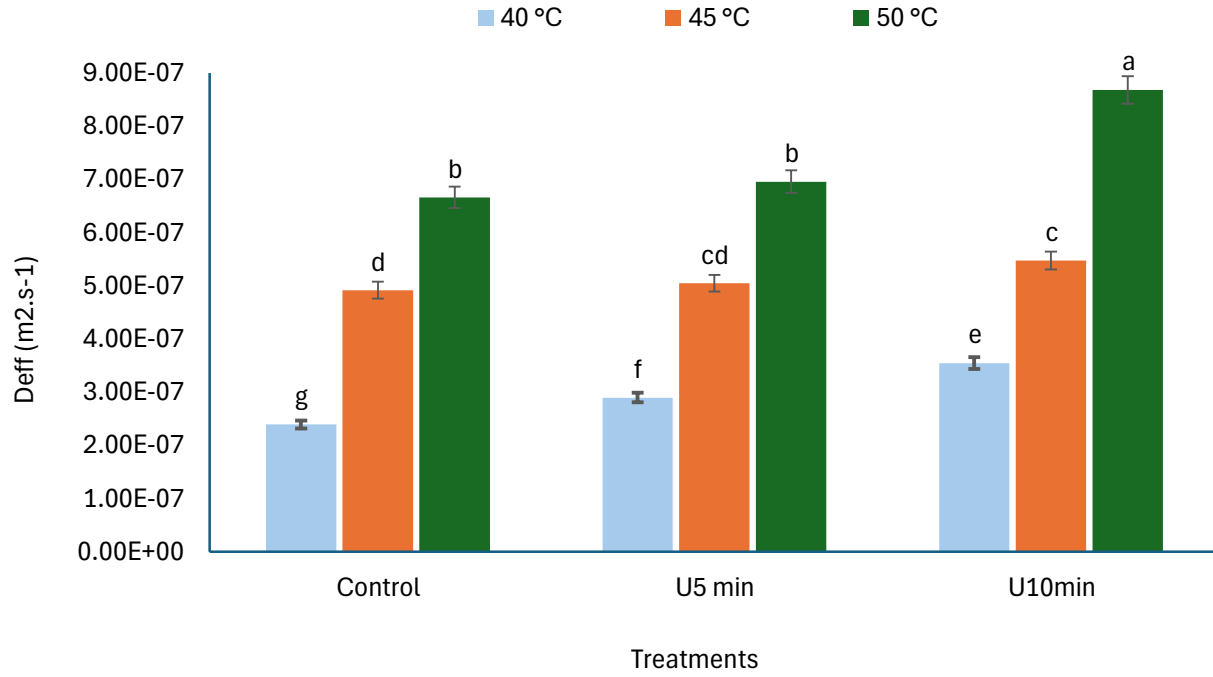


FIGURE 8 Effect of ultrasound pretreatment prior to infrared drying on the effective moisture diffusivity (D_{eff}) of mallow leaves.

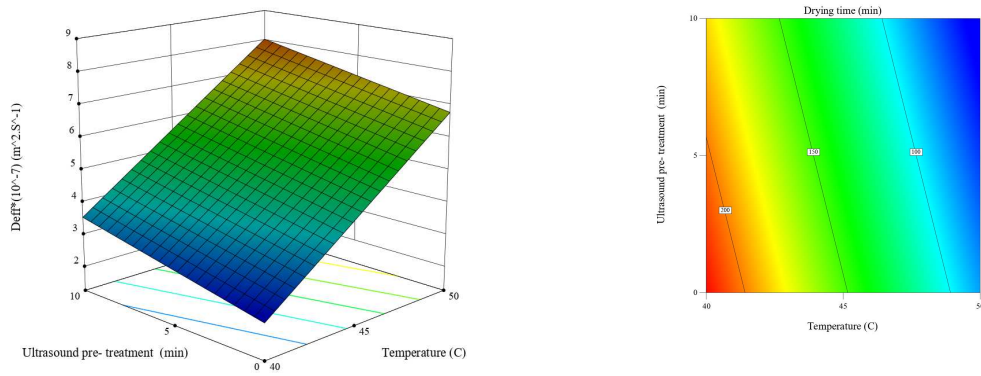


FIGURE 9 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the effective moisture diffusivity (D_{eff}) of mallow leaves.

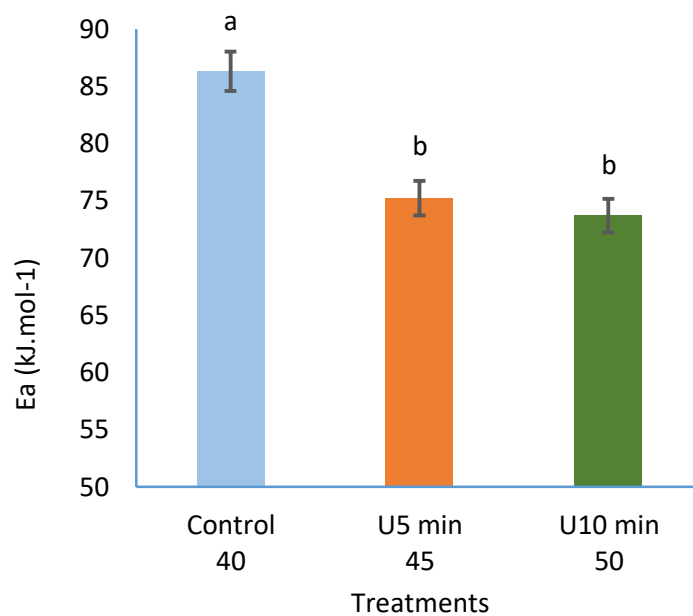
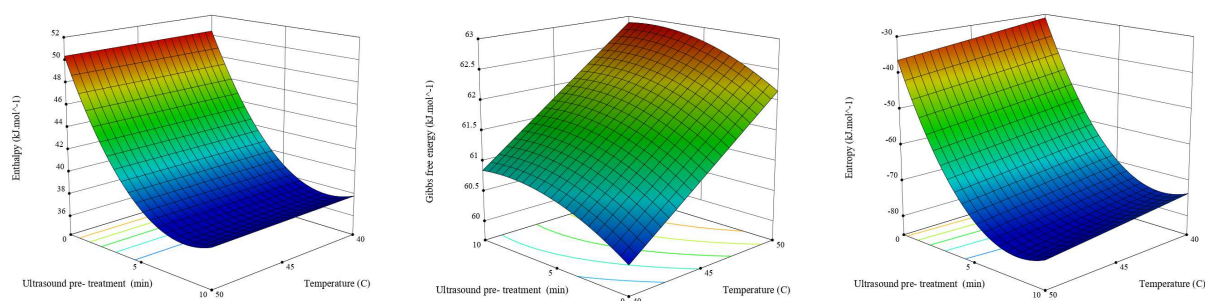


FIGURE 10 Activation energy plot for the infrared drying of mallow leaves under different ultrasound pretreatment conditions.



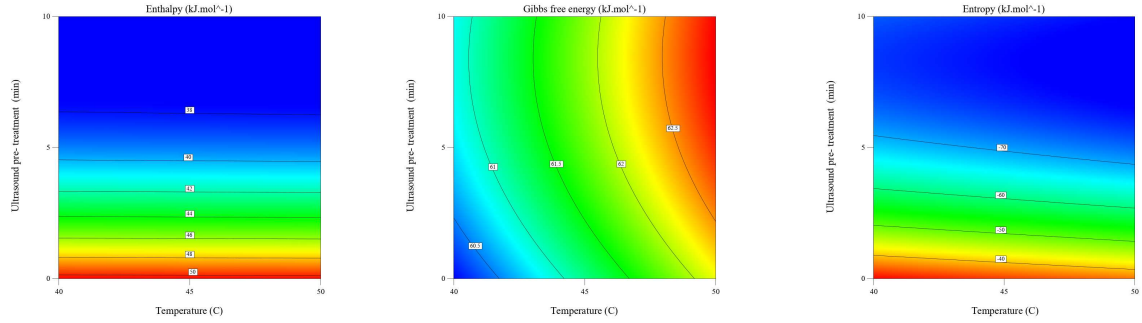


FIGURE 11 Three-dimensional response surface plots showing the effects of drying temperature and ultrasound treatment duration on the thermodynamic properties of mallow leaves.

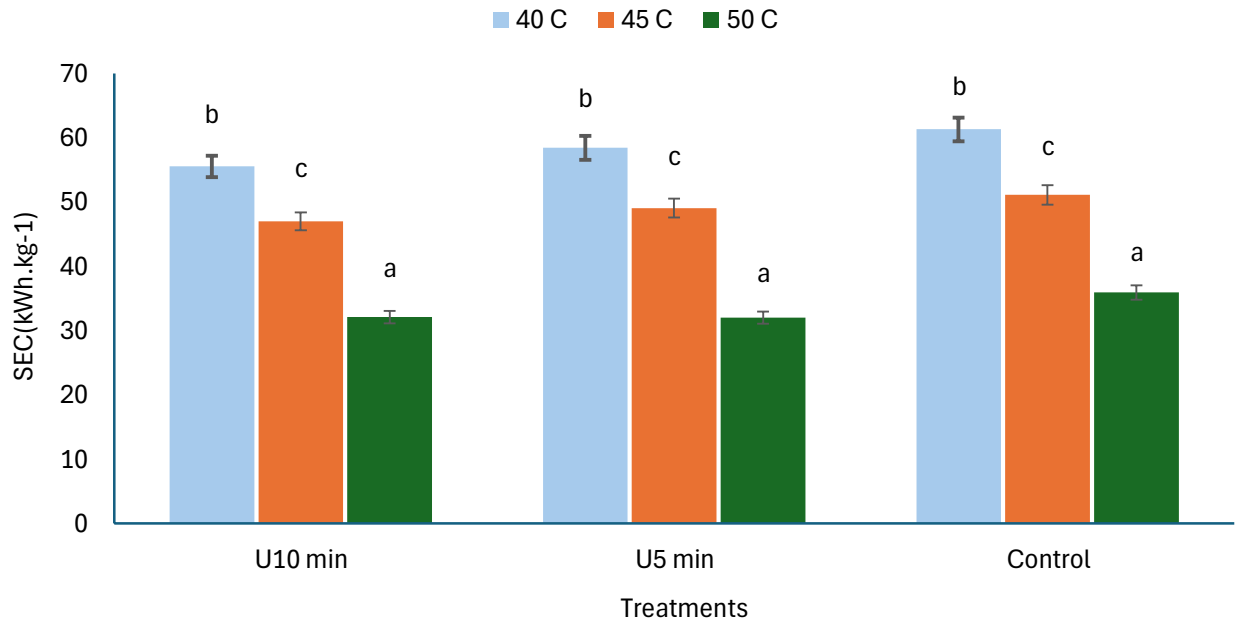


FIGURE 12 Specific energy consumption during infrared drying of mallow leaves with ultrasound pretreatment.

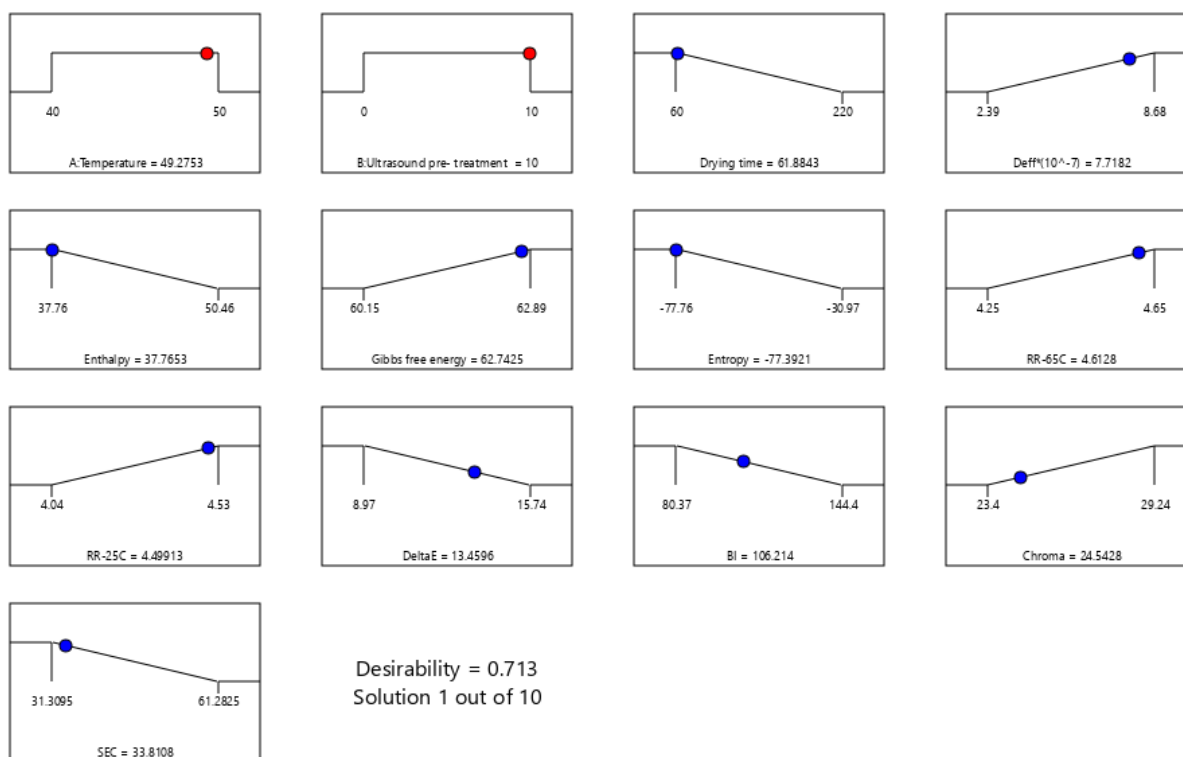


FIGURE 13 Numerical optimization of drying time, specific energy consumption, color change, rehydration ratio, enthalpy, Gibbs free energy, and entropy for mallow leaves dried by infrared drying with ultrasound pretreatment.

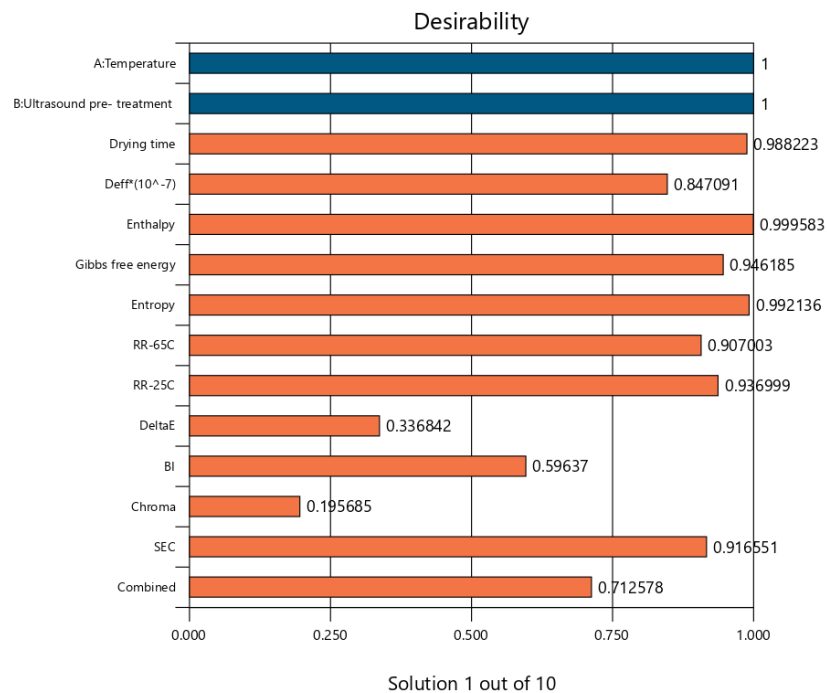


FIGURE 14 Optimized desirability values for input variables, response variables, and overall desirability of mallow leaves dried by infrared drying with ultrasound pretreatment.

Tables caption

Table 1 Analysis of variance for the drying time of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

Table 2 Thermodynamic properties of mallow leaves during infrared drying with ultrasound pretreatment.

Table 1 Analysis of variance for the drying time of mallow leaves at different drying temperatures and ultrasound pretreatment durations.

Source	Sum of Squares	df	Mean Square	F-value
Model	28333.33	2	14166.67	294.23**
Temperature	26666.67	1	26666.67	553.85**
Ultrasound pre- treatment	1666.67	1	1666.67	34.62**
Residual	288.89	6	48.15	
Cor Total	28622.22	8		

Table 2 Thermodynamic properties of mallow leaves during infrared drying with ultrasound pretreatment.

Thermodynamic properties	Temperature(°k)	U10 min	U5min	Control
Enthalpy (kJ.mol ⁻¹)	313.15	37.84±0.46 ^c	39.37±0.47 ^b	50.46±0.61 ^a
	318.15	37.80±0.45 ^c	39.32±0.47 ^b	50.41±0.60 ^a
	323.15	37.76±0.46 ^c	39.28±0.48 ^b	50.37±0.62 ^a
Gibbs free energy (kJ.mol ⁻¹)	313.15	60.86±0.73 ^a	60.76±0.73 ^a	60.15±0.72 ^a
	318.15	61.87±0.74 ^a	61.78±0.74 ^a	61.16±0.73 ^a
	323.15	62.89±0.74 ^a	62.79±0.77 ^a	62.16±0.75 ^a
Entropy(kJ.mol ⁻¹)	313.15	-73.50±0.88 ^c	-68.33±0.82 ^b	-30.97±0.37 ^a
	318.15	-75.66±0.91 ^c	-70.57±0.85 ^b	-33.76±0.41 ^a
	323.15	-77.76±0.93 ^c	-72.74±0.87 ^b	-36.47±0.42 ^a

Values are expressed as mean ± standard deviation (n=5). Different letters in the same row indicate significant differences (p < 0.05) according to Tukey's test.

Supplementary Files

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- [4GraphicalAbstractFinal.jpg](#)