



Original research

# Effect of microwave and ultrasonic pretreatment of carrot slices before infrared drying

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## ABSTRACT

The purpose of this study was to investigate the impacts of microwave pretreatment (MWP) and ultrasonic pretreatment (USP) on drying time, mass transfer rate, and effective water diffusivity ( $D_{eff}$ ) of carrot slices during drying in an infrared (IR) dryer. MWP was applied for 0, 15, 30, 45, and 60 s before the IR drying of carrot slices. Also, USP was applied in an ultrasonic bath for 0, 5, 10, 15, and 20 minutes. The results demonstrated that the MWP and USP decreased the drying time (higher moisture loss) of carrot slices. Also, the drying time of pretreated samples by 30-60 s microwave and 15-20 min ultrasound was significantly lesser than the untreated carrot slices ( $p < 0.05$ ). The calculated  $D_{eff}$  values were varied from  $1.80 \times 10^{-9}$  to  $2.79 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ , and from  $1.53 \times 10^{-9}$  to  $2.24 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ , for samples pretreated by microwave and ultrasound, respectively. The experimental data of the drying process are in agreement with the commonly used thin film models, and the Page model with experimental constants ( $k$  and  $n$ ) is suitable for describing the dehydration rate of carrot slices. In general, the use of MWP for about 30 s or USP for about 15 min is promising pretreatment techniques for IR drying of carrot slices with higher mass transfer and shorter drying time.

**Keywords:** Effective water diffusivity; Moisture loss; Page equation; Thin-layer drying.

Received 27 May 2026; Received in revised form 23 Jul 2026; Accepted 29 Jul 2026

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## 1. Introduction

As a fast and effective heating source with together thermal and non-thermal impacts, microwaves can directly affect the food material, thereby speeding up physicochemical reactions, and dehydration rate, and producing high-quality dried products (Xu, 2015; Kayisoglu, 2020; Tasova and Polatci, 2022; Khodadadi and Masoumi, 2025). Also, MWP accelerates the mass transfer in the dehydration process and can reduce the drying time of fruit and vegetable products (Sharma and Prasad, 2006; Kayisoglu, 2020). For example, Sharma and Prasad (2006) used a laboratory microwave for garlic drying. They confirmed that the microwave drying of garlic cloves decreased dehydration time compared to convective drying, and the quality attributes of the dried product by microwave methods, was found higher. Salehi (2024) reported that MWP improved the drying efficiency of IR drying of mung bean sprouts by reducing drying time and increasing  $D_{eff}$ . The combination of

MWP and IR drying was suggested as an effective method for enhancing mass transfer during dehydration.

Of all the available pretreatment approaches, ultrasound is propounded as one of the most promising processes for the treatment of fruit and vegetable slices before drying. The USP process accelerates mass transfer rates in the dehydration of fruits and vegetables slices, primarily through cell disruption and micro-channel formation (Allahdad et al., 2019; Salehi and Cheraghi, 2023). Wang et al. (2019) used USP to improve the drying rate of kiwifruit slices. Their results confirmed that the USP method can improve the drying process and preserve a high content of phenols. In addition, the results of Liu et al. (2020) confirmed that the USP can improve the color (higher lightness) of dried cranberries. Baratian Ghorghi et al. (2026) reported that USP significantly influenced the quality characteristics of freeze-dried apple cubes, particularly by reducing hardness and improving textural properties. The findings indicated that ultrasound treatment can be an effective

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<https://doi.org/10.22059/jfab.e.2026.415308.1233>

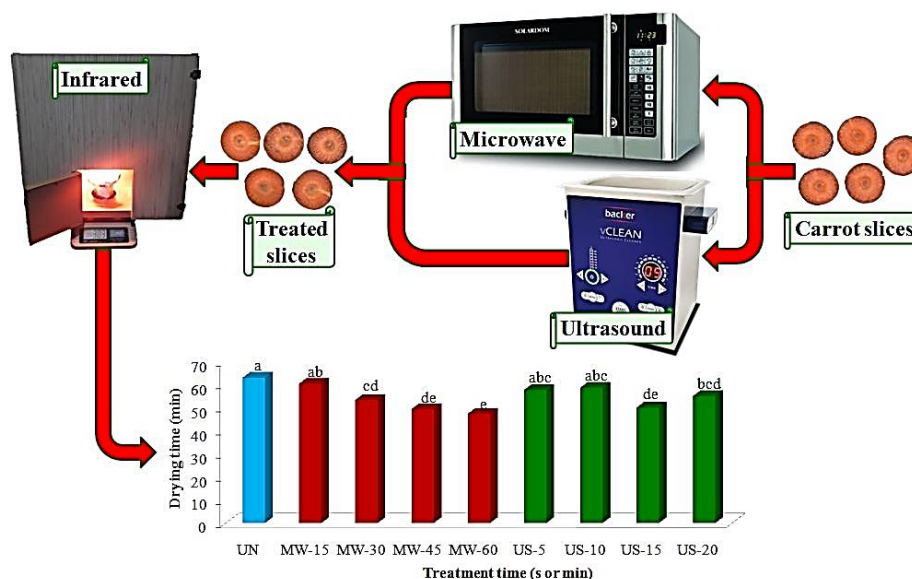


Fig. 1. Schematic of microwave and ultrasound pretreatments, and infrared drying process of carrot slices.

pretreatment method for modifying structural properties and enhancing the quality of dried fruit products.

Among different techniques used for food products dehydration, IR drying is one of the widely used techniques for moisture decrease. Higher heat transfer rate, shorter drying time, a higher quality dried fruit and vegetable product, high performance, and energy savings in the procedure are revealed as the main advantages of the IR drying method over hot-air drying (Salehi, 2020). Recent research has shown that IR drying can effectively preserve the quality attributes of agricultural products. In a comparative study on wild saffron corm (*Crocus haussknechtii*), IR drying resulted in the highest retention of total phenolic compounds compared with other drying methods, indicating its potential for preserving bioactive components during dehydration (Salehi et al., 2025).

Pretreatment and drying conditions can greatly influence the moisture diffusivity of fruit and vegetable slices. Hence, the purpose of this study was to estimate the impacts of MWP and USP approaches on the drying time, mass transfer kinetic, and  $D_{eff}$  of carrot slices. In addition, changes in moisture ratio (MR) of carrot slices during IR drying were modeled.

## 2. Materials and Methods

### 2.1. Raw materials

Fresh carrots (*Daucus carota* L.) were purchased from a local market in Hamedan, Hamedan Province, Iran. In each experiment, fresh carrots were cut with a steel cutter into 5-mm-thick cylindrical slices and placed directly into the microwave and ultrasonic equipment (Fig. 1). In this study, the water content (WC) of fresh carrot slices was measured by an oven at 105°C for 5 hours (Shimadzu, Iran).

### 2.2. Microwave pretreatment

To apply the MWP to carrot slices, a microwave oven (Delmonti, model; DL740, Italy) was used under atmospheric pressure. In this

work, the effect of MWP time at five levels of 0, 15, 30, 45, and 60 s on the carrot slices was examined.

### 2.3. Ultrasound pretreatment

Due to the physicochemical effects, ultrasonic frequencies among 20 kHz and 1 MHz are usually used for fruit and vegetable processing (Salehi, 2023). An ultrasound bath (40 kHz, 100W, vCLEAN1-L2, Backer, Iran) was used to apply sonication to carrot slices. This work examined the effect of USP time on carrot slices at five levels of 0, 5, 10, 15, and 20 minutes. The ultrasonic bath was maintained at 25°C, with a volume of 2 L, which was filled with distilled water during the pretreatment process.

### 2.4. Infrared drying

An IR dryer (length 440 mm, width 200 mm, and height 400 mm) with an IR radiation source (250 W, near-IR (NIR), Noor Lamp Company, Iran) was used for drying carrot slices. In this dryer, the distance of carrot slices from the radiation lamp was 5 cm. The mass changes of samples were recorded using Lutron GM-300p digital balance (Taiwan).

### 2.5. Drying kinetics

The dehydration kinetics of carrot slices have been described using 9 simplified drying equations (Henderson and Pabis, Logarithmic, Midilli, Newton, Page, Quadratic, Two-term, Verma, and Wang and Singh) (Salehi and Satorabi, 2021; Manikantan et al., 2022). In these equations, MR was employed to represent dehydration data, and for every experiment condition, MR values were plotted against drying time and parameters of the models were calculated and compared. Equations 1 and 2 calculate the drying rate (DR) and MR of carrot slices during dehydration, respectively. Eqs. (1) and (2):

$$DR = \frac{M_{t2} - M_{t1}}{t_2 - t_1} \quad (1)$$

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

Where  $M_{t2}$  and  $M_{t1}$  are the WC of the carrot slices at times  $t_2$  and  $t_1$ . Also, where  $M_t$ ,  $M_e$ , and  $M_o$  are the WC of the carrot slices at time  $t$ , equilibrium, and initial WC of the carrot slices on a dry basis (g water/g dry matter) (Amini et al., 2021).

Regression analysis was performed using Matlab software (version R2012a) to estimate models parameters. When the highest coefficient of determination ( $r$  value) is combined with the minimum sum of squared errors (SSE) and root mean squared error (RMSE) values, a satisfactory fit between the actual data and the correlations is established.

## 2.6. Calculation of effective water diffusivity ( $D_{eff}$ )

Fick's second law of diffusion using slab coordinates (equation 3) was used to calculate the moisture diffusivity of carrot slices at various pretreatments and IR drying. Eq. (3):

$$MR = \frac{8}{\pi^2} \exp \left[ \frac{-\pi^2 D_{eff} t}{4L^2} \right] \quad (3)$$

where  $D_{eff}$  is the effective water diffusivity ( $m^2/s$ ),  $L$  is the half thickness of carrot samples which is equal to 0.0025 m, and  $t$  is dehydration time (s). For food drying process modeling, equation 3 can be rewritten as equation 4. Eq. (4):

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

In this study, equation 4 is employed for the calculation of  $D_{eff}$  values from the slope of  $\ln MR$  and  $t$  (experimental drying duration, s) plot, which is calculated by equation 5 (Salehi and Satorabi, 2021). Eq. (5):

$$\text{Slope} = - \frac{\pi^2 D_{eff}}{4L^2} \quad (5)$$

## 2.7. Statistical analysis

The dehydration tests of carrot slices were conducted in a factorial design with three replications in a completely randomized design. Also, the means were compared using Duncan's test at  $p$ -value < 0.05 (using SPSS software version 21).

## 3. Results and Discussion

### 3.1. Drying time

In this study, the average WC of fresh carrot slices was 88% (wet basis). Statistical analysis of empirical results (data) confirmed that the pretreatments time has a significant effect on the drying time of carrot slices ( $p < 0.01$ ) (Table 1); But, the pretreatments type (MWP and USP), and its interactions with pretreatments time, had no significant effect on the drying time of carrot slices ( $p > 0.05$ ). The impacts of pretreatment type (MWP and USP) and time to drying time of carrot slices are revealed in Fig. 2. The drying time of pretreated carrot slices was shorter than that of untreated samples under all conditions. Kouchakzadeh (2013) reported that by applying ultrasonic pretreatment, the drying time of moist pistachios in a film layer can be decreased to 4 hours. The average drying time of untreated, microwave-treated, and ultrasound-treated carrot slices were 63.0, 52.6, and 55.3 min, respectively. The drying time of carrot slices decreased by increasing the MWP and USP time. As MWP time increased from 15 to 60 s, the drying time of samples inside the IR dryer was decreased from 60.3 to 47.3 minutes ( $p < 0.05$ ). Also, by increasing the USP time from 5 to 15 minutes, the drying time of samples was decreased from 57.7 to 50.0 minutes ( $p < 0.05$ ). Results of the Wang et al. (2019) study showed that ultrasonic pre-treatment reduced the drying time of treated samples by 16.7–25.0% compared

Table 1. Results of analysis of variance for infrared drying time of pretreated carrot slices by microwave and ultrasound.

| Sources of changes  | Degrees of freedom | Sum of squares | Mean square | P     |
|---------------------|--------------------|----------------|-------------|-------|
| Pretreatment        | 1                  | 36.30          | 36.30       | 0.067 |
| Time                | 4                  | 727.20         | 181.80      | 0.000 |
| Pretreatment × Time | 4                  | 105.87         | 26.47       | 0.058 |
| Error               | 20                 | 194.00         | 9.70        |       |
| Total               | 29                 | 1063.37        |             |       |

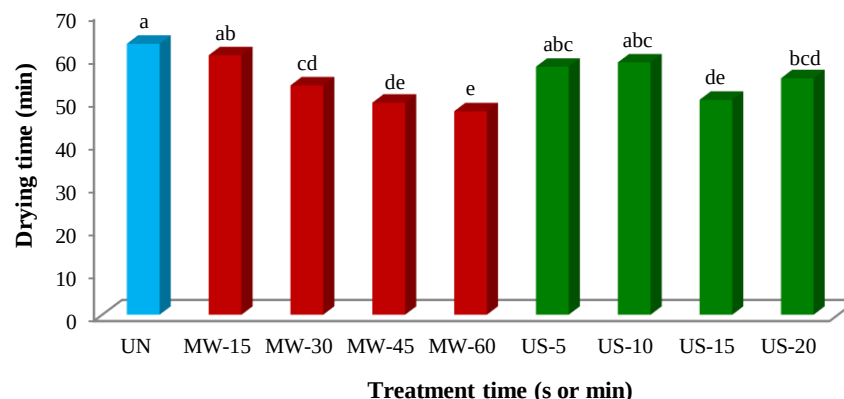


Fig. 2. Effect of microwave and ultrasound pretreatment on drying time of carrot slices (UN= untreated; MW=microwave (second); US=ultrasound (minutes)). Various letters above columns indicate the significant differences among means ( $p < 0.05$ ).

with the untreated kiwifruit slices. Also, Fijalkowska et al. (2016) reported that the USP decreased the dehydration time of apple slices by 13–17% in comparison with the un-treated apples.

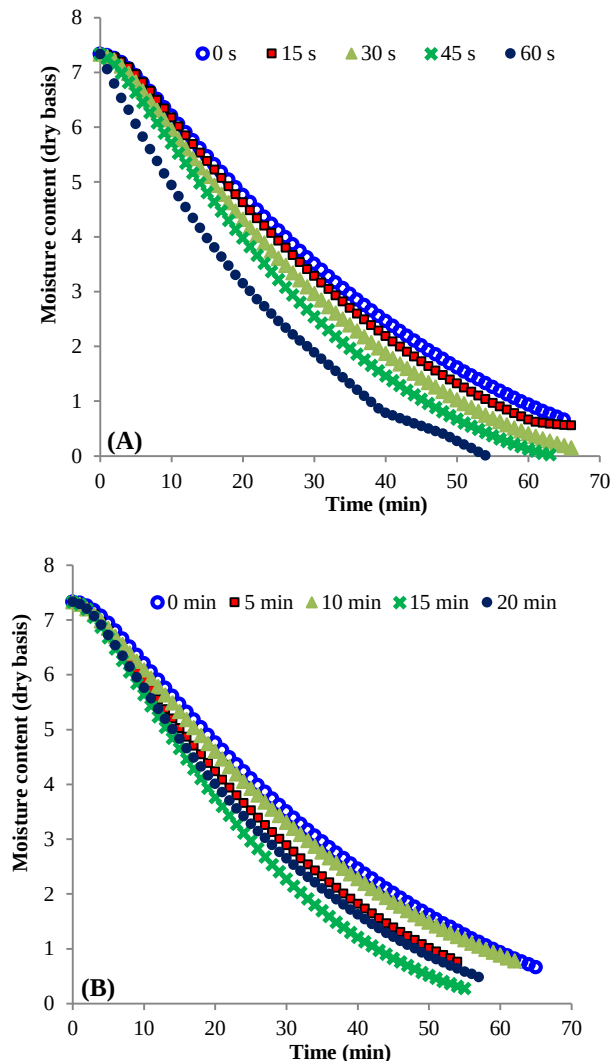


Fig. 3. Effect of microwave (A) and ultrasound (B) pretreatments on the moisture content changes of carrot slices during drying in the infrared dryer.

The effects of MWP and USP time on the WC changes (dry basis) of carrot slices during drying in the IR dryer are shown in Fig. 3. As shown in Fig. 3, the application of MWP and USP have increased the rate of moisture removal from carrot slices and, as a result, increased the drying rate of the samples. Similar results were also reported for papayas (Fernandes et al., 2008), apple (Fijalkowska et al., 2016), carrot (Rostami Baroji et al., 2017), and kiwifruit slices (Wang et al., 2019) after the USP process. In addition, the same trends were also reported for orange slices (Özkan-Karabacak et al., 2020), and myrtus fruit (Karimi et al., 2021) after the MWP process.

### 3.2. Effective water diffusivity coefficient ( $D_{eff}$ )

The impacts of pretreatment type and time on the  $D_{eff}$  values of carrot slices are presented in Fig. 4. The  $D_{eff}$  values of pretreated samples by 30–60 s microwave were significantly higher than the pretreated samples by ultrasound ( $p < 0.05$ ). The average  $D_{eff}$  value of untreated carrot slices during drying in the IR dryer was  $1.38 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ . The  $D_{eff}$  values were varied from  $1.80 \times 10^{-9}$  to  $2.79 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ , and from  $1.53 \times 10^{-9}$  to  $2.24 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ , for samples pretreated by microwave and ultrasound, respectively. These  $D_{eff}$  values are comparable to those reported from  $2.50 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$  to  $8.16 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$  when drying green pea in a microwave (Kayisoglu, 2020), and from  $8.58 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$  to  $3.67 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$  when drying potato chips in microwave (Tasova and Polatci, 2022).

Fernandes et al. (2008) used the ultrasound process to improve the mass (water and sugar) loss of papayas before hot-air drying. The results showed that the  $D_{eff}$  was increased after treatment by ultrasound causing a decrease of about 16% in the dehydration duration of papayas. Results obtained by Karimi et al. (2021) for myrtus fruit and by Rostami Baroji et al. (2017) for carrot showed that MWP applied before drying influenced mass transfer rate and  $D_{eff}$  values in comparison with dehydrated untreated samples. In another study, Özkan-Karabacak et al. (2020) used MWP before vacuum-drying of orange slices. Their results showed that the use of MWP reduced the drying time of samples and increased the dehydration rate,  $D_{eff}$ , and rehydration capacity.

### 3.3. Kinetics modeling

It is important to understand drying kinetics for efficient control of the process (Chokngamvong and Suvanjumrat, 2023). The drying behavior of pretreated carrot slices by microwave and ultrasound in

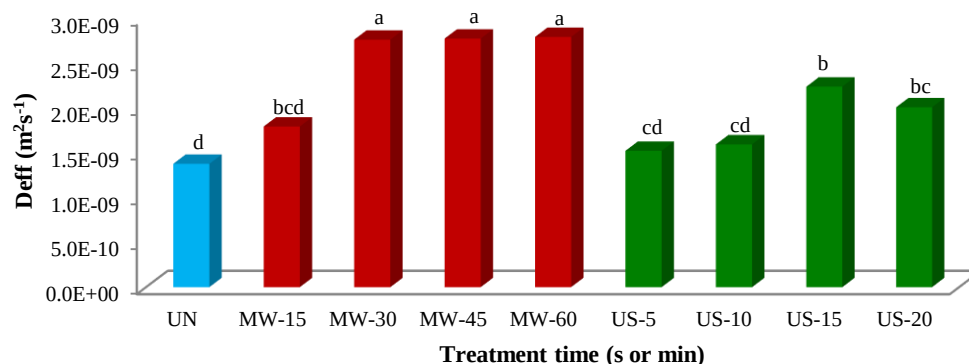


Fig. 4. Effect of microwave and ultrasound pretreatment on effective water diffusivity coefficient ( $D_{eff}$ ) of carrot slices (UN= untreated; MW=microwave (second); US=ultrasound (minutes)).

Table 2. The constants and coefficients of the Page model.

| Pretreatment | Pretreatment time | k      | n      | SSE    | r      | RMSE   |
|--------------|-------------------|--------|--------|--------|--------|--------|
| Untreated    | 0                 | 0.0067 | 1.3737 | 0.0025 | 0.9997 | 0.0061 |
| Microwave    | 15 s              | 0.0077 | 1.3933 | 0.0073 | 0.9994 | 0.0103 |
|              | 30 s              | 0.0058 | 1.5127 | 0.0159 | 0.9989 | 0.0153 |
|              | 45 s              | 0.0094 | 1.4157 | 0.0145 | 0.9988 | 0.0154 |
|              | 60 s              | 0.0128 | 1.3783 | 0.0186 | 0.9982 | 0.0180 |
| Ultrasound   | 5 min             | 0.0077 | 1.3713 | 0.0024 | 0.9997 | 0.0065 |
|              | 10 min            | 0.0084 | 1.3630 | 0.0025 | 0.9997 | 0.0060 |
|              | 15 min            | 0.0097 | 1.4023 | 0.0047 | 0.9996 | 0.0092 |
|              | 20 min            | 0.0080 | 1.4070 | 0.0067 | 0.9994 | 0.0090 |

IR dryer was fitted with the Page model (equation 6). This model showed a good fit with the maximum r-value (higher than 0.9975) and the minimum SSE, and RMSE values (lower than 0.0232 and 0.0209, respectively) for all conditions compared to that of the other models. The calculated constant coefficients of the Page equation include k and n are reported in Table 2 together with matching statistical error values (SSE, RMSE, and r) for all dehydration conditions. The SSE, RMSE, and r values in a range from 0.0008 to 0.0232, 0.0036 to 0.0209, and 0.9975 to 0.9999, respectively, were found for the Page equation used to estimate the drying kinetics of carrot slices in this work. Eq. (6):

$$MR = \exp(-kt^n) \quad (6)$$

Fig. 5 demonstrates the similarity of fitted MR data using the Page equation with experimental results (microwave time=30 s). The results show that the Page equation is appropriate for estimating the IR drying kinetics of carrot slices under all conditions. Wang et al. (2019) reported that the Page model acceptably predicted the rehydration properties of dehydrated kiwifruit slices. Kouchakzadeh (2013) reported that the Page model acceptably predicted the dehydration rate of pistachios.

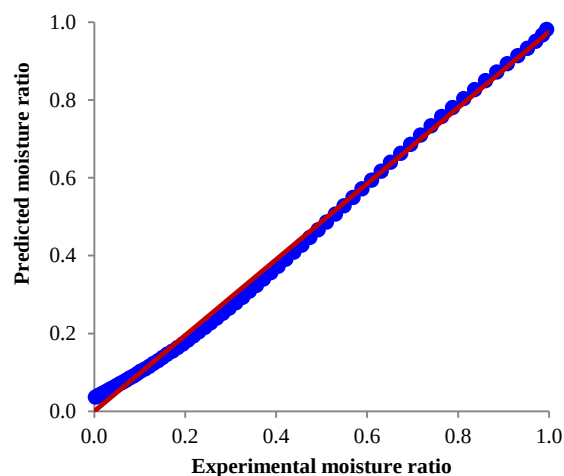


Fig. 5. Compare the Page model fit data with the experimental moisture ratio results (microwave time=30 s).

## 4. Conclusion

This study demonstrated that microwave and ultrasound pretreatments are effective strategies for enhancing the IR drying performance of carrot slices by accelerating moisture removal and improving mass transfer. Among the investigated conditions, MWP for approximately 30-60 s and USP for about 15-20 min showed promising potential for reducing drying time and increasing  $D_{eff}$ . The Page model provided the best prediction of the drying kinetics, indicating its suitability for describing the dehydration behavior of pretreated carrot slices.

From an industrial perspective, the integration of MWP or USP with IR drying can be considered as an efficient approach for shortening drying processes, reducing energy consumption, and improving the productivity of dried carrot products. However, the present study was limited to laboratory-scale experiments, and further investigations are required to evaluate the economic feasibility, energy efficiency, and scale-up performance of these combined technologies in industrial dryers. Future research should also focus on optimizing pretreatment parameters, evaluating the effects on nutritional and sensory quality attributes, and assessing the long-term storage stability of the dried products.

## Acknowledgements and foundation

This work was supported by a grant from the Bu-Ali Sina University, Hamedan, Iran (Grant No. 40346).

## Conflict of interest

The authors declare that there is no conflict of interest.

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