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ORIGINAL ARTICLE

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Dehydration of green beans using ultrasound-assisted vacuum drying as a novel technique: drying kinetics and quality parameters

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Abstract

The ultrasound-assisted vacuum (USV) drying technique is a novel method and ultrasonic treatment under vacuum causes to accelerate the dehydration rate of food materials. This study compared the drying kinetics and some quality parameters for green beans subjected to USV, oven, and vacuum drying at 55, 65, and 75°C. The drying time was shortened by around 1 hr using USV at each temperature. Effective moisture diffusivity values was found between $2.00 \times 10^{-10} - 4.81 \times 10^{-10}$ m^2 s^{-1} and it was increased compared with control treatment between 8.9% and 24.5%. USV treatment resulted phenolic compounds compared with unsonicated control. However, USV caused more color change than the control, oven and vacuum. Lower the total color difference values were obtained for samples dehydrated by vacuum dryer. USV had greater advantages compared with the control and it can potentially be applied to green beans and other vegetables for faster drying processing.

Practical applications

This study exhibit the usability of ultrasound-assisted vacuum dehydration to increase the drying rate, to improve the energy efficiency of the drying process and to develop quality of the final products. The results indicated that ultrasound treatment could be used as an assistant technique to accelerate drying rate and improve product quality. Besides mathematical models and drying kinetic, this study presents useful information about the different dehydration process for green bean. It was expected that this study will great contribution to literature, food science and technology.

KEYWORDS

color, drying kinetics, green beans, phenolic compounds, ultrasound-assisted vacuum drying

1 | INTRODUCTION

Fruits and vegetables are easily deteriorated by microorganisms due to their high sugar and water contents; consequently, some type of preservation method must be applied to increase the shelf life of these food products. Drying has been widely used as a food preservation method since ancient times because of its ease of operation and low cost. However, food producers and consumers have continued to demand higher quality of food, greater economy, and more usefulness technique as a result of rapid advancements in technology. Therefore, drying techniques have improved for enhancing food quality, introducing new products, and saving energy (Doymaz, 2012). Ultrasound, high electric field, electro hydrodynamic force, and radio frequency are some novel techniques to improve drying operation of food product (Muthukumaran, Orsat, Bajgai, & Raghavan, 2010).

The ultrasonic drying method is very popular among these novel alternatives. It has a potential use in the drying industry since it reduces the processing time and increases the mass transfer and effective diffusivity rates compared with traditional methods (He, Yang, Peng, & Yi, 2013). The ultrasound waves can affect both internal and external resistance to mass transfer in a medium (Mulet, Cárcel, Sanjuán, & Bon, 2003). In addition, the ultrasonic waves result in the formation of a sponge-like micro channel structure because of its continuous compression and release (Fernandes & Rodrigues, 2008). These two processes result in easy removal of both free and strongly bound water (He, Yang, et al., 2013). In other words, the ultrasonic treatment facilitates heat transfer and accelerates the water transfer from material by inducing mechanical waves. Therefore, ultrasonic waves have been combined some dehydration techniques such as convective (Gamboa-Santos, Montilla, Carcel, Villamiel, & Garcia-Perez, 2014), osmotic (Fernandes, Gallao, & Rodrigues, 2008), vacuum (Başlar, Kilicli, Toker, Sagdic, & Arici, 2014), and freeze drying (Santacatalina, Fissore, Carcel, Mulet, & Garcia-Perez, 2015; Schössler, Jäger, & Knorr, 2012).

Ultrasound-assisted vacuum (USV) drying was introduced to decrease drying time and cost, and reduce quality loss during processing by combining ultrasonic and vacuum dryers. Vacuum drying involves rapid surface evaporation by lowering the boiling temperature of water under vacuum. At the surface of a food, the resistance to mass transfer is lower and drying rate is higher. However, the drying rate decreases for the long drying period because of the reduction of mass transfer from the interior to the surface of the food. Increases in the drying rate require a method that will increase the mass transfer. One strategy is to use ultrasound to speed up mass and heat transfer, thereby increasing evaporation under negative pressure. Thus, USV provides the advantages of both of drying processes.

USV drying was first used by He, Zhao, Yang, and Yi (2013) to dry wood. They reported that energy expenditure and quality loss could be decreased by USV. The drying time was also reduced by vacuum drying and the resulting large scale timbers suffered no discoloration. Nevertheless, vacuum drying of wood has some disadvantages. If the timber has a high moisture content, drying of inner part will be difficult and high temperatures will be required to access the moisture in the inner parts of wood. However, when ultrasonic drying is combined with vacuum, water removal from the center of the timber is easier due to the sponge effect and cavitations (He, Yang, et al., 2013; He, Zhao, et al., 2013).

Başlar, Kilicli, et al. (2014) used the USV technique in food technology to dry beef and chicken meat. They found a nearly 2.5 times faster drying time compared with the other techniques for beef and chicken samples. Wood, meat, fish, and chicken have been subjected to USV to date; however, no study has yet been conducted on the use of USV for drying of vegetables and fruits.

In this study, green beans were dried with three different techniques: oven drying, vacuum oven drying, and USV at 55, 65, and 75°C. The drying rates, activation energy, total energy consumption values, phenolic compound contents, and color were determined. Drying kinetics models were fitted to the obtained data to compare the drying properties of these methods.

2 | MATERIALS AND METHODS

2.1 | Materials

Green bean (*Phaseolus vulgaris*) samples were purchased from marketplace in Istanbul, Turkey. The samples were selected to be approximately the same color, size, etc. They were transported to the laboratory and stored at 4°C and 98% relative humidity until analysis. The thickness of the green beans was approximately 0.7 cm. The samples were cut into 4.5 ± 0.1cm lengths with a knife and weighed (nearly 40 g per study). The average moisture content of the beans, determined according to the method described by AOAC (1990), was 92.36 ± 0.65% as wet base (wb).

2.2 | Methods

2.2.1 | Drying of green beans

Green bean samples were dried using different methods: oven, vacuum, and USV drying and control at 55, 65, and 75°C. A vacuum drier (DaihanWOV-30, Gangwondo, South Korea) and an air circulation oven drier (Memmert UF110, Munich, Germany) were used for vacuum and oven drying of the green bean samples, respectively. The vacuum was regulated by a vacuum pump (EVP 2XZ-2C, Zhejiang, China) with 60 mbar ultimate pressure and 2 L/s pump speed. Oven drying was conducted with 1.3 m/s constant air velocity.

The USV system is a combination of an ultrasound water bath (Daihan, WUC-D10H, South Korea) (amplitude: 100%, power intensity: ~1 W/cm^2, volume: 10 L) and a vacuum pump (KNF N838.3KT.45.18, Germany) (pressure: 15 mbar speed: 22 L/min). This system was detailed in our previous published studies (Başlar, Kilicli, et al., 2014; Başlar, Kiliçli, & Yalinkiliç, 2015). The green beans samples were put into a conical flask attached to the vacuum pump and sonicated at 40 kHz by using the ultrasonic water bath. The USV technique differed from the other vacuum drier, therefore these samples were compared with control samples that were dried using the same USV pump system and a standard water bath (Daihan, WSB-30, Gangwondo, South Korea) with no ultrasonic application. The bath temperatures were measured with a thermocouple (k-type, Omega Engineering, Inc., USA) and controlled by manual circulation of the bath water (Başlar, Kilicli, et al., 2014).

For all drying methods, the samples (about 40 g) were weighed every 30 min during the drying process until water content decreased to 11.75% (w/w). The time spent while weighing is about 15 s. Minimizing this time was important for obtaining reproducible drying curves (Jamradloedluk, Nathakaranakule, Soponronnarit, & Prachayawarakorn, 2005). Drying process was ended when the moisture content of the sample reached to 0.2 kg water/kg dry matter.

2.2.2 | Fitting of drying curves

Seven thin layer models (Table 1) (a, b, c, n, k, k_0, and k_1, which were fit the parameters for these models) were used to express dehydration kinetics of the green beans and were calculated by nonlinear regression using SPSS 15.0 software (SPSS, Inc., Chicago, IL, USA). The coefficient (R^2), reduced chi-square (χ^2), and root mean square error (RMSE) were calculated to determine the most suitable model by selecting the highest R^2 and lowest χ^2 values and the RMSE (Doymaz, 2013):

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(Y_{\text{exp},i} - Y_{\text{pre},i}\right)^2}{N - z} \tag{1}$$

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TABLE 1 Drying models used for dehydration kinetics of the green beans

Model names	Equation	References
Lewis	$MR = \exp(-kt)$	Lewis (1921)
Page	$MR = \exp(-kt^n)$	Page (1949)
Modified Page	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Overhults, White, Hamilton, and Ross (1973)
Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis (1961)
Logarithmic	$MR = a\exp(-kt) + c$	Yagcioglu, Degirmencioglu, and Cagatay (1999)
Two-term	$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$	Lee and Hsieh (2008)
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)

MR, moisture ratio.

$$\mathrm{RMSE}=\left[\frac{1}{N}\sum_{i=1}^{N}(Y_{\mathrm{pre},i}-Y_{\exp,i})^2\right]^{0.5} \quad (2)$$

where $Y_{\exp,i}$ is the experimental moisture ratio, $Y_{\mathrm{pre},i}$ is the predicted moisture ratio, N is the number of observations, and z is the number of constants (Doymaz, 2013).

Fick's law was used to express mass transportation by diffusion. Generally, Fick's second law is used to define moisture transportation of agricultural products by diffusion in drying process (Ghazanfari, Emami, Tabil, & Panigrahi, 2006):

$$\frac{\partial\chi}{\partial t}=D\left[\frac{\partial^2\chi}{\partial x^2}+\frac{\partial^2\chi}{\partial y^2}+\frac{\partial^2\chi}{\partial z^2}\right] \quad (3)$$

where X is the moisture, at location of x, y, z, at the time of t (s), and D is the diffusion coefficient (m^2/s). However, the diffusion equation is modified to fit drying foods, as these have longer falling rate periods rather than a constant rate period, as indicated in *Equation* 4 (Ratti, 2009):

$$\frac{\partial\chi}{\partial t}=\nabla_z(D_{\mathrm{eff}}\nabla_z\chi) \quad (4)$$

where D_{eff} is the effective moisture diffusivity coefficient (m^2/s) at location z (a spatial coordinate).

Moisture ratio equations are expressed by *Equation* 5 by adapting for a slab shape and moisture loss taking place from both sides (Ratti, 2009). D_{eff} were calculated according to *Equation* 5 by using nonlinear regression modeling.

$$\mathrm{MR}=\frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{\mathrm{eff}}t}{4L^2}\right) \quad (5)$$

where D_{eff} is the effective diffusion coefficients (m^2/s), t is drying time, and L is the thickness of green bean.

Temperature dependency of D_{eff} was calculated using Arrhenius equation in *Equation* 6 (Ratti, 2009):

$$D_{\mathrm{eff}}=D_0(\chi)\exp\left(-\frac{E_a(\chi)}{RT}\right) \quad (6)$$

where D_0 is a pre-exponential factor of Arrhenius equation (m^2/s), E_a is activation energy (kJ/mol), R is the ideal gas constant (kJ/mol K), and T is the temperature of drying in degrees Kelvin.

2.3 | Extraction procedure

The fresh green bean samples were directly extracted whereas dried samples were extracted after rehydration with pure water to provide the same extraction conditions as the fresh ones. The samples were mixed with aqueous methanol (80%) and the mixture was homogenized with a digital homogenizer (Daihan HG15A, Gangwondo, South Korea) at about 10,000 rpm for 2 min. The mixture was ultrasonicated for 10 min for further homogenization and incubated by shaking for 2 hr at room temperature. The mixture was filtered through filter paper, centrifuged at 2,665.31*g* (Hettich 320R, Tuttlingen, Germany) for 10 min, and the supernatants were filtered again.

2.4 | Total phenolic content (TPC)

Total phenolic content (TPC) was determined according to methods described by Singleton and Rossi (1965). Folin Ciocelteau's phenol reagent (2N) was diluted 10-fold with pure water to give a 0.2 N reagent solution. Reagent (2.5 ml) was added to green bean extract (0.5 ml) in test tubes, followed by 7.5% Na_2CO_3 (2 ml), and the tubes were incubated at room temperature in a dark place. After a 30 min incubation period, absorbance was measured at 760 nm in a UV/VIS spectrophotometer (Shimadzu UV-1800, Japan). The TPC results were expressed as gallic acid equivalents per kg of fresh matter (mg GAE/kg) (Lie, Specht, Marshall, & Fink, 2006).

2.5 | Color measurement

A chroma meter (CR-400 Konica, Minolta, Tokyo, Japan) was used to determine L* (whiteness/darkness), a* (redness/greenness), and b* (yellowness/blueness) values. The total color change in the green beans was determined by calculating ΔE values using *Equation* 7.

$$\Delta E=\left[(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^{*2})\right]^{0.5} \quad (7)$$

2.6 | Total energy consumption

A digital energy meter (PeakTech 9035, Germany) was plugged into a socket during drying experiments. Total energy consumption of the systems was recorded after dehydration (Başlar & Ertugay, 2013).

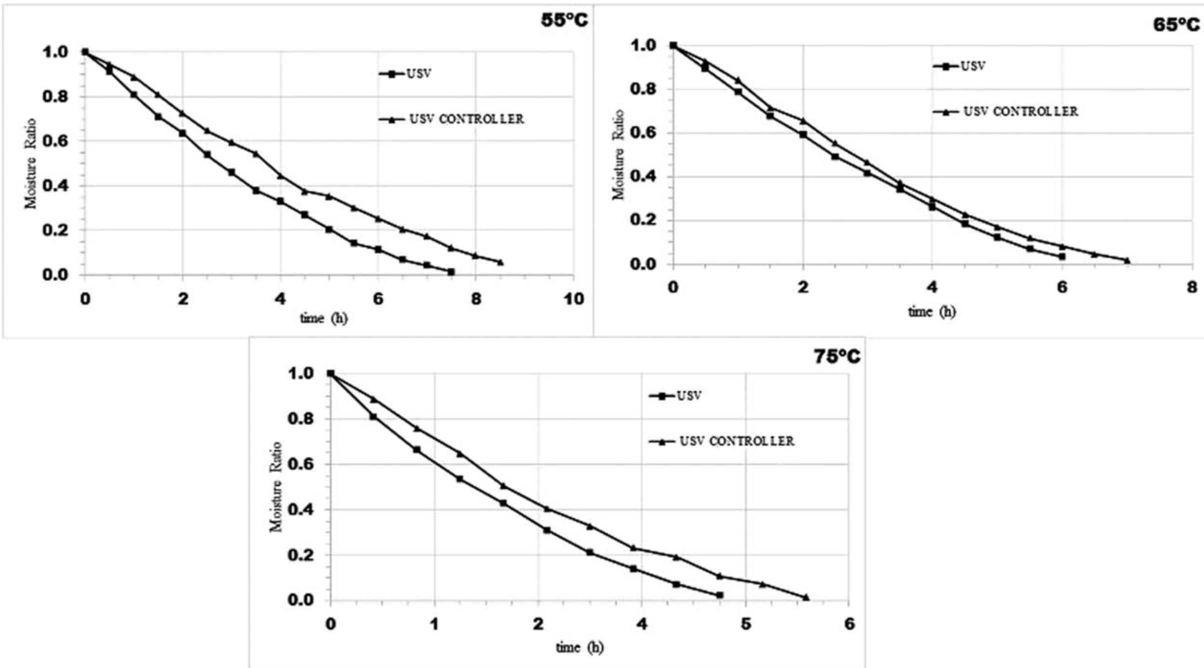

FIGURE 1 Dehydration curves of the green beans dried by USV

3 | RESULTS AND DISCUSSION

3.1 | Drying kinetics

The plots of moisture ratio versus time at 55, 65, and 75°C for the different techniques are shown in Figure 1. The slopes of the drying curves decreased during drying period, indicating that the drying rate of the green beans was not constant during the drying period. Instead, the curves showed two main parts: a constant rate and then a falling rate period. At the beginning stage, the drying rate was rapid and then it continuously decreased toward the end of the drying period (Figure 2). The constant rate period was shorter than falling rate period, indicating that a diffusion mechanism dominated the moisture transfer in the green bean samples. Doymaz (2005) and Ertekin and Yaldiz (2004) reported similar

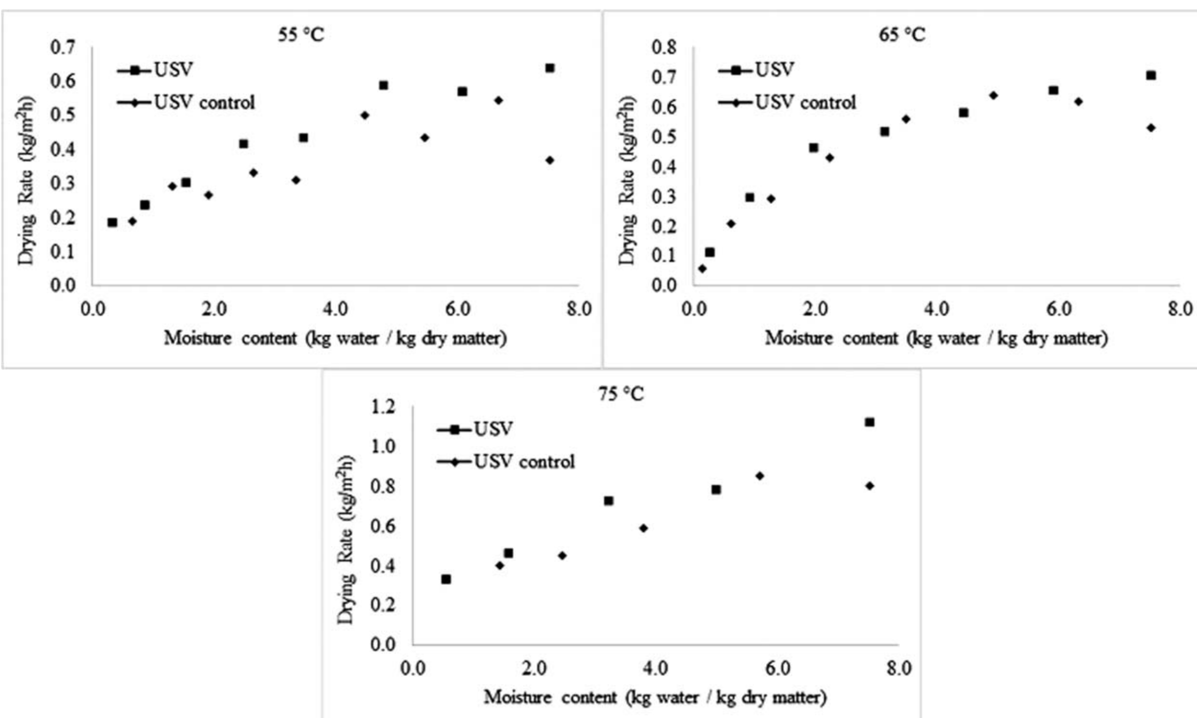

FIGURE 2 Dehydration rate of the green beans dried by USV

TABLE 2 Drying times, total energy consumption and effective moisture diffusivity of the green beans

Green bean	Drying technique	Temp. (°C)	Drying time (min)	Total energy consumption (kW·hr)	D_{eff} (m²/s)
	Drying oven	55	480	1.300	2.79×10^{-10}
		65	390	1.357	3.30×10^{-10}
		75	270	1.197	4.48×10^{-10}
	Vacuum oven	55	300	1.491	3.70×10^{-10}
		65	270	1.500	4.54×10^{-10}
		75	180	1.107	4.81×10^{-10}
	USV	55	450	1.731	2.65×10^{-10}
		65	360	1.961	2.92×10^{-10}
		75	270	1.832	4.13×10^{-10}
	USV control	55	510	1.665	2.00×10^{-10}
		65	420	1.647	2.66×10^{-10}
		75	330	1.571	3.23×10^{-10}

D_{eff}, effective moisture diffusivity.

results for short constant rate periods of drying in green bean and eggplant samples.

The drying times for the different drying methods are presented in Table 2. The drying times were determined as 270–480 min for oven drying and 180–300 min for vacuum drying. The drying time of the USV compared with the control was shorter 60 min at all drying temperatures. The drying rate of the USV was 60 min shorter compared with the control at all drying temperatures. The drying times were significantly reduced by increases in drying temperature, most likely due to increased water vapor pressure because of the increased heat transfer rate (Kingsly & Singh, 2007).

In addition to comparing with drying times of the samples dried by different methods, the drying rate is shown in Figure 2. The drying rate is expressed as the quantity of moisture removed from the dried sample per unit time per unit of drying sample surface (Wankhade, Sapkal, & Sapkal, 2012). In other words, when the drying rate increases, the amount of moisture removed from the sample rises. The amounts of moisture removed from the green bean samples per unit time per unit of drying sample surface were higher for the USV samples than for the control at all tested temperatures, indicating that USV gave a higher drying rate compared with vacuum drying alone under the same processing conditions. Therefore, green beans can be dried at a higher drying rate by applying a USV process, making USV an attractive alternative drying method to vacuum and oven drying. This result confirmed the findings in our previous study, where USV gave a higher drying rate compared with oven and vacuum drying (Başlar, Kilicli, et al., 2014).

The higher moisture transfer rate of the ultrasonic and vacuum drying can be explained from different aspects. Ultrasonic waves can cause a sponge effect, which means the occurrence of continuous contractions and expansions (Gallego-Juarez, Rodriguez-Corral, Ga Lvez-Moraleda, & Yang, 2007) so that moisture can be removed easily by the microscopic channels that are created. Cavitation is a basic phenomenon explained acoustic effect at ultrasonic dehydration. Cavitation was separated stabile and transient depending ultrasonic intensity. Lower ultrasonic intensity (<1 to 3 W/cm²) causes stabile cavitation and generally used for degassing, microstreaming, and mass transfer; whilst higher ultrasonic intensity (>10 W/cm²) causes transient cavitation and generally used for homogenization, microbial and enzymatic decontamination, and depolymerization processing (Feng & Yang, 2010; Kiani, Zhang, & Sun, 2014). It was expected the low ultrasonic intensity (~1W/cm²) used in the study causes mass (water) transfer through the samples. It accelerate strongly attached moisture to be removed from the product (Mulet et al., 2003). In addition to these advantages of ultrasound, vacuum drying achieves some preferred quality characteristics such as higher drying rate, lower drying temperature, lower drying time, lower enzymatic browning (by providing oxygen-deficient processing), and high quality and nutritional dried food (Zhang, Jiang, & Lim, 2010). The combination of ultrasound and vacuum is preferred because of lower drying time and higher drying rate values.

3.2 | Total energy consumption

The total energy consumption values were calculated as 1.197–1.357 kWh for oven drying, 1.107–1.500 kWh for vacuum drying, 1.731–1.961 kWh for USV, and 1.571–1.665 kWh for the control. Although the total energy consumption was highest for USV, the

TABLE 3 Arrhenius equation parameters calculated for D_{eff} values of the green bean

Drying technique	Arrhenius parameters		
	D_0 (m²/s)	E_a (kJ/mol)	R^2
Oven	1.52×10^{-6}	23.568	0.971
Vacuum	3.04×10^{-8}	11.941	0.908
USV	1.08×10^{-6}	22.839	0.913
USV control	6.99×10^{-7}	22.196	0.991

TABLE 4 Estimated model parameters obtained from fitting the drying models under oven and vacuum oven drying methods

Model	Parameters	Oven drying			Vacuum oven		
		55°C	65°C	75°C	55°C	65°C	75°C
Lewis	$k \times 10^3$	4.220	4.946	6.748	5.612	6.852	7.448
	R^2	0.900	0.951	0.925	0.888	0.881	0.860
	χ^2	0.10151	0.06141	0.08027	0.10797	0.13951	0.11684
	RMSE	0.01104	0.00404	0.00716	0.01282	0.02271	0.01593
Page	$k \times 10^3$	0.058	0.576	0.568	0.087	0.107	0.107
	n	1.784	1.401	1.492	1.809	1.837	1.882
	R^2	0.999	0.993	0.985	0.995	0.996	0.990
	χ^2	0.00013	0.00074	0.00174	0.00069	0.00863	0.00136
	RMSE	0.01075	0.0253	0.03734	0.02385	0.0785	0.03119
Henderson and Pabis	$k \times 10^3$	5.506	6.144	8.843	7.697	9.693	10.982
	a	1.296	1.237	1.304	1.362	1.412	1.439
	R^2	0.969	0.995	0.998	0.977	0.982	0.981
	χ^2	0.00368	0.00031	0.00013	0.00289	0.00881	0.00249
	RMSE	0.05649	0.01648	0.03236	0.04864	0.07933	0.04221
Logarithmic	$k \times 10^3$	2.739	5.158	6.439	4.839	5.959	6.024
	a	1.649	1.268	1.368	1.529	1.562	1.685
	c	−0.479	−0.077	−0.155	−0.277	−0.287	−0.405
	R^2	0.995	0.998	0.995	0.992	0.998	0.997
	χ^2	0.00067	0.00017	0.00065	0.00114	0.01142	0.00053
	RMSE	0.02323	0.01163	0.02137	0.02879	0.08078	0.01742
Two-term	$k_1 \times 10^3$	1.623	4.166	6.096	3.006	3.664	3.634
	$k_2 \times 10^3$	1.570	2.903	0.980	2.947	3.587	3.493
	a	49.477	2.310	1.466	60.002	58.200	38.545
	b	−48.312	−1.126	−0.256	−58.758	−56.931	−37.270
	R^2	0.996	0.998	0.995	0.992	0.998	0.997
	χ^2	0.00069	0.00018	0.00087	0.00115	0.01522	0.00090
	RMSE	0.02257	0.01163	0.02282	0.02711	0.08078	0.01968
Wang and Singh	a	−0.003	−0.004	−0.005	−0.004	−0.004	−0.004
	$b \times 10^3$	1.132	3.571	5.194	2.339	2.840	−8.437
	R^2	0.977	0.982	0.975	0.959	0.962	0.959
	χ^2	0.00279	0.00177	0.00273	0.00505	0.01837	0.00551
	RMSE	0.04919	0.03912	0.04672	0.06425	0.11455	0.06274
Approximation of diffusion	a	−51.106	−0.364	−0.305	−34.116	−37.280	−45.376
	b	0.977	0.190	0.045	0.963	0.966	0.971
	k	10.277	34.839	195.548	14.349	17.592	19.877
	R^2	0.996	0.997	0.988	0.999	0.999	0.994
	χ^2	0.00054	0.00013	0.00150	0.00024	0.009	0.00108
	RMSE	0.02078	0.01024	0.03236	0.01311	0.07171	0.02488

a, b, c, n, k , k_0, and k_1 are fit parameters.

drying time was shorter and the drying rate was more rapid for USV than for the control. A short time drying can be preferred over lower energy consumption because when the drying rate is increased, the costs for storage and personnel can be decreased, so that USV can be more economical for drying of green beans.

3.3 | Effective moisture diffusivity (D_{eff})

The D_{eff} values obtained for the different drying methods are shown in Table 2. The D_{eff} values of green beans dried with USV were measured as 2.65×10^{-10}–4.13×10^{-10} m^2/s and calculated as 2.00×10^{-10}–3.23×10^{-10} m^2/s. These D_{eff} values were in agreement with

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TABLE 5 Estimated model parameters obtained from fitting the drying models under USV drying and USV control drying

Model	Parameters	USV drying			USV control drying		
		55°C	65°C	75°C	55°C	65°C	75°C
Lewis	$k \times 10^3$	4.056	4.486	6.253	3.108	4.191	5.176
	R^2	0.919	0.902	0.899	0.917	0.893	0.897
	χ^2	0.08660	0.09613	0.09936	0.08624	0.10523	0.10162
	RMSE	0.00865	0.01092	0.01234	0.00837	0.01278	0.01239
Page	$k \times 10^3$	0.124	0.094	0.162	0.077	0.050	0.107
	n	1.635	1.720	1.719	1.648	1.810	1.736
	R^2	0.997	0.995	0.994	0.997	0.998	0.997
	χ^2	0.0003	0.00056	0.0007	0.00031	0.00022	0.01888
	RMSE	0.0160	0.02186	0.0236	0.01664	0.01389	0.00043
Henderson and Pabis	$k \times 10^3$	5.156	5.817	8.437	3.913	5.359	6.706
	a	1.252	1.275	1.342	1.228	1.286	1.305
	R^2	0.976	0.968	0.978	0.972	0.965	0.978
	χ^2	0.00247	0.00354	0.00273	0.00284	0.00453	0.00333
	RMSE	0.04629	0.05475	0.04671	0.05022	0.06268	0.05265
Logarithmic	$k \times 10^3$	2.535	2.248	4.487	1.628	2.081	6.024
	a	1.628	1.906	1.596	1.827	1.937	1.685
	c	−0.493	−0.775	−0.400	−0.712	−0.790	−0.405
	R^2	0.999	0.999	0.999	0.998	0.997	0.997
	χ^2	0.00012	0.00008	0.00010	0.00029	0.00055	0.06333
	RMSE	0.00961	0.00782	0.00822	0.01556	0.02099	0.21795
Two-term	$k_1 \times 10^3$	0.929	1.289	2.675	0.946	10.320	2.005
	$k_2 \times 10^3$	0.938	1.216	2.571	0.895	10.386	1.936
	a	110.299	39.079	37.568	38.400	209.963	47.563
	b	−109.303	−37.950	−36.377	−37.286	−209.036	−46.384
	R^2	0.995	0.999	0.999	0.998	0.994	0.998
	χ^2	0.00057	0.00009	0.00013	0.00031	0.00097	0.00036
	RMSE	0.02046	0.00782	0.00881	0.01543	0.02663	0.01540
Wang and Singh	a	−0.0003	−0.003	−0.004	−0.002	−0.003	−0.003
	$b \times 10^3$	1.142	0.635	2.394	0.422	0.338	0.876
	R^2	0.986	0.987	0.979	0.986	0.981	0.975
	χ^2	0.00152	0.00146	0.00263	0.00142	0.00291	0.00295
	RMSE	0.03624	0.03509	0.04587	0.03549	0.05021	0.04958
Approximation of diffusion	a	−40.851	−58.713	−43.215	−34.272	−57.877	−47.782
	b	0.974	0.981	0.973	0.969	0.980	0.976
	k	9.437	10.685	15.044	7.385	10.095	12.448
	R^2	0.995	0.991	0.992	0.995	0.994	0.997
	χ^2	0.00055	0.00108	0.00098	0.00048	0.00099	0.00077
	RMSE	0.02099	0.02887	0.02619	0.01993	0.02813	0.02406

a, b, c, n, k, k_0, and k_1 are fit parameters.

previously published data on the drying kinetics of agricultural products (Başlar, Karasu, Kilicli, Us, & Sagdiç, 2014; Karasu et al., 2015). The D_{eff} (m^2/s) values of green beans were higher with USV than for the USV control, indicating that moisture in the samples was transferred rapidly by the ultrasound. These results can be explained as the sponge effect resulting from pressure changes due to compression and expansion during the ultrasound process. Expanded micro channels formed, allowing increased mass and heat transfer rates. In addition, cavitations were produced and the diffusion boundary layer was decreased, thereby increasing convective mass transfer (Fernandes & Rodrigues, 2008).

TABLE 6 The total phenolic compound analysis of green beans

Drying methods	Initial	55°C	65°C	75°C
Oven	228.033 ± 7.432[a]	249.279 ± 87.859[ab]	284.414 ± 37.525[b]	336.685 ± 43.450[b]
Vacuum	228.033 ± 7.432[a]	212.117 ± 57.652[a]	255.811 ± 71.028[ab]	276.532 ± 32.967[b]
USV	228.033 ± 7.432[a]	244.775 ± 5.415[b]	338.656 ± 6.889[c]	332.162 ± 10.511[c]
USV control	228.033 ± 7.432[b]	200.180 ± 10.511[a]	304.009 ± 4.459[c]	333.288 ± 7.644[d]

Same letters at each row are not statistically different according to Duncan's test ($p = 5\%$).

The temperature dependency parameters of the D_{eff} values were calculated by the Arrhenius equation 6. The R^2 values (>0.90) in Table 3 indicated that the relation between temperature and D_{eff} values was well described by the Arrhenius equation. The parameters of the Arrhenius equation shown in Table 3 indicated that E_a values varied from 11.941–23.568 kJ/mol. The lowest activation energy values were obtained from vacuum drying. Activation energy is a parameter showing the effectiveness of the dehydration temperature to D_{eff}. The activation energy for vacuum dehydration was determined lower because D_{eff} difference between 55°C and 75°C is lower. In other words, lower activation energy at vacuum drying indicated that the increase in drying temperature affects D_{eff} value less. It was determined USV slightly has higher activation energy according to control treatment. Similarly, the results indicated that USV affected more dehydration temperature. Similar results were obtained by Başlar, Kilicli, et al. (2014).

3.4 | Evaluation of the models

The acceptability of the models was evaluated based on the R^2, χ^2, and RMSE values calculated using *Equations* 1 and 2. The estimated model parameters obtained from fitting the drying models under oven and vacuum drying methods are shown in Table 4. The parameters of USV and control drying methods are shown in Table 5. The R^2 value of the of Page model was the highest and χ^2 and RMSE values lowest, this model was the most suitable for describing the drying characteristics of green beans, as also concluded by Doymaz (2005). Analysis of the RMSE values indicated that the Henderson and Pabis (1961) model was the worst based on moisture ratio versus drying time values.

3.5 | Phenolic compounds

Phenolic compounds are phytochemicals found many fruits and vegetables. These compounds have antioxidant effects on humans and show health benefits such as preventing some cancers by suppressing various oxidative stresses. In addition to their beneficial health effects, phenolic compounds directly affect sensorial qualities such as flavor, color, bitterness, and sweetness (Khoddami, Wilkes, & Roberts, 2013; Tomas Barberan & Espin, 2001; Wojdylo, Oszmianski, & Czemerys, 2007).

The TPCs are shown in Table 6; for fresh green beans, this value was 228.033 mg GAE kg^{-1} for fresh green beans, which was similar to the value reported previously (Baardseth, Bjerke, Martinsen, & Skrede, 2010). TPC varied from 249.279 to 338.656 mg GAE kg^{-1} for the drying methods at 55, 65, and 75°C. In this study, the highest phenolic content was obtained for USV at 65°C ($p < .05$). The increasing may be due an increase at extractability of the phenolic compounds by ultrasonic treatment at the drying temperature. The higher TPC value for the samples dehydrated by using USV can be explained by cavitations, which increases the extraction rate by accelerating the destruction of plant cells. Besides, ultrasound can be causes that solvent penetrates more to material and chemical compounds are easily released from the cell (Metherel, Taha, Izadi, & Stark, 2009). A lot of research, it was reported that ultrasonic treatment increased some bioactive component such as total phenolic (Abid et al., 2013; Başlar & Ertugay, 2013; Bhat, Kamaruddin, Min-Tze, & Karim, 2011; Zafra-Rojas et al., 2013), total flavanols (Abid et al., 2013; Bhat et al., 2011), and ascorbic acid (Zafra-Rojas et al., 2013); flavonoid (Abid et al. 2013; Bhat et al., 2011) at food materials. It can be believed that this increase in results based on extractability but not dependent reproduction.

3.6 | Color value

Color is one of the most important sensorial quality attributes affecting consumer preferences for both fresh and processed fruits and vegetables. Therefore, limiting the pigment losses and browning reactions during food processing should be taken into consideration. In this study, the total color change (ΔE) value was measured to determine color differences between fresh and dried green beans for all methods. L*, a*, and b*, and corresponding ΔE values are shown in Table 7. The highest and lowest ΔE values were obtained for USV and vacuum drying, respectively (6.41–18.09). The color alteration was higher for USV than for the control, indicating that ultrasound application altered the color ($p < .05$). In addition to changes in ΔE, changes in the L*, a*, and b* values were higher for USV samples than for control samples. The L* and b* values decreased while a* values increased during drying. Color changes observed in fruits and vegetables during drying processes are highly related to enzymatic and non-enzymatic browning reactions and pigment losses due to heat treatment. Increases in a* values and decreases in L* values can be explained by browning reactions, while decreases in b* values might be due to degradation of the heat-stable green and yellowish pigments. The current study indicated that ultrasound application stimulated pigment degradation. The lower color change during vacuum

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TABLE 7 The effect of different drying methods on the color

Methods	Temp. (°C)	Fresh	Drying oven	Vacuum oven	USV	USV control
L*	55	58.444 ± 3.173^{b}	48.094 ± 4.095^{a}	53.753 ± 4.504^{ab}	46.095 ± 1.470^{a}	46.187 ± 3.362^{a}
	65	55.047 ± 2.807^{b}	47.373 ± 4.543^{a}	48.136 ± 4.463^{ab}	41.457 ± 3.648^{a}	43.452 ± 7.402^{a}
	75	57.335 ± 3.587^{b}	51.150 ± 4.752^{ab}	49.97 ± 4.542^{ab}	51.010 ± 4.975^{ab}	46.187 ± 3.362^{a}
a*	55	−7.440 ± 1.346^{a}	−4.949 ± 1.384^{ab}	−5.805 ± 1.940^{ab}	−3.640 ± 0.901^{b}	−3.205 ± 2.011^{b}
	65	−9.904 ± 1.538^{a}	−2.653 ± 1.092^{b}	−6.655 ± 2.236^{a}	−1.483 ± 1.776^{b}	−6.652 ± 2.492^{a}
	75	−9.096 ± 2.662^{a}	−2.835 ± 6.244^{ab}	−3.821 ± 2.398^{b}	0.987 ± 1.207^{bc}	−3.205 ± 2.011^{b}
b*	55	14.333 ± 2.144^{b}	10.848 ± 1.662^{ab}	10.313 ± 3.969^{a}	7.065 ± 1.652^{a}	6.637 ± 3.069^{a}
	65	16.557 ± 3.686^{b}	10.058 ± 3.258^{a}	12.528 ± 4.357^{a}	12.865 ± 4.191^{a}	12.452 ± 3.628^{a}
	75	17.522 ± 3.210^{b}	12.627 ± 4.105^{b}	11.038 ± 3.449^{ab}	9.76 ± 5.037^{a}	6.637 ± 3.069^{a}

Same letters at each row are not statistically different according to Duncan's test ($p = 5\%$).

drying might be due to limitation of oxygen in the drying environment.

Another result inferred from Table 7 is that drying temperature significantly affected the ΔE value. The color change was lower for samples dried at 65°C for all drying methods. Therefore, 65°C should be selected to meet the desired color quality of green bean samples.

4 | CONCLUSION

The USV drying technique was applied to determine its effectiveness for drying green beans. USV dehydration dramatically shortened dehydration time around 1 hr. The USV method had a higher drying rate compared with vacuum drying under the same processing conditions. Besides extractability of total phenolic components was dramatically increased. A lower color change and higher phenolic content was determined in samples dried at 65°C.As a result, it was suggested that the temperature can be used for the drying of green beans by the USV technique. Therefore, USV can be used successfully for drying of green beans and it has potential uses in drying of other fruits and vegetables due to its higher drying rate and preservation of bioactive compounds.

REFERENCES

Abid, M., Jabbar, S., Wu, T., Hashim, M. M., Hu, B., & Lei, S. (2013). Effect of ultrasound on different quality parameters of apple juice. *Ultrasonic Sonochemistry*, *20*, 1182–1187.

AOAC. (1990). *Official methods of analysis* (15th ed.). Arlington, VA: Author.

Baardseth, P., Bjerke, F., Martinsen, B., & Skrede, G. (2010). Vitamin C, total phenolics and antioxidative activity in tip-cut green beans (*Phaseolus vulgaris*) and swede rods (*Brassica napus* var. *napobrassica*) processed by methods used in catering. *Journal of the Science of Food and Agriculture*, *90*, 1245–1255.

Başlar, M., & Ertugay, M. (2013). The effect of ultrasound and photosonication treatment on polyphenoloxidase (PPO) activity, total phenolic component and colour of apple juice. *International Journal of Food Science and Technology*, *48*, 886–892.

Başlar, M., Karasu, S., Kilicli, M., Us, A. A., & Sagdiç, O. (2014). Degradation kinetics of bioactive compounds and antioxidant activity of pomegranate arils during the drying process. *International Journal of Food Engineering*, *10*, 839–848.

Başlar, M., Kilicli, M., Toker, O., Sagdic, O., & Arici, M. (2014). Ultrasonic vacuum drying technique as a novel process for shortening the drying period for beef and chicken meats. *Innovative Food Science and Emerging Technologies*, *26*, 182–190.

Başlar, M., Kiliçli, M., & Yalinkiliç, B. (2015). Dehydration of salmon and trout fillets using ultrasonic vacuum drying in enhancing drying rates and moisture diffusivity. *Ultrasonics Sonochemistry*, *27*, 495–502.

Bhat, R., Kamaruddin, N. S. B. C., Min-Tze, L., & Karim, A. A. (2011). Sonication improves kasturi lime (*Citrus microcarpa*) juice quality. *Ultrasonic Sonochemistry*, *18*, 1295–1300.

Doymaz, I. (2005). Drying behaviour of green beans. *Journal of Food Engineering*, *69*, 161–165.

Doymaz, I. (2012). Evaluation of some thin-layer drying models of persimmon slices (*Diospyros kaki* L.). *Energy Conservation and Management*, *56*, 199–205.

Doymaz, I. (2013). Experimental study on drying of pear slices in a convective dryer. *International Journal of Food Science and Technology*, *48*, 1909–1915.

Ertekin, C., & Yaldiz, O. (2004). Drying of eggplant and selection of a suitable thin layer drying model. *Journal of Food Engineering*, *63*, 349–359.

Feng, H., & Yang, W. (2010). Ultrasonic processing. In H. Q. Zhang, G. V. Barbosa-Cánovas, V. M. B. Balasubramaniam, C. P. Dunne, D. F. Farkas, & J. T. C. Yuan (Eds.), *Nonthermal processing technologies for food* (pp. 135–154). Wiley-Blackwell.

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

Fernandes, F. A. N., & Rodrigues, S. (2008). Application of ultrasound and ultrasound-assisted osmotic dehydration in drying of fruits. *Drying Technology*, *26*, 1509–1516.

Gallego-Juarez, J. A., Rodriguez-Corral, G., Ga Lvez-Moraleda, J. C., & Yang, T. S. (2007). A new high intensity ultrasonic technology for food dehydration. *Drying Technology*, *17*, 597–608.

Gamboa-Santos, J., Montilla, A., Carcel, J. A., Villamiel, M., & Garcia-Perez, J. V. (2014). Air-borne ultrasound application in the convective drying of strawberry. *Journal of Food Engineering*, *128*, 132–139.

Ghazanfari, A., Emami, S., Tabil, L. G., & Panigrahi, S. (2006). Thin-layer drying of flax fiber: I. Analysis of modeling using Fick's second law of diffusion. *Drying Technology*, *24*, 1631–1635.

He, Z., Yang, F., Peng, Y., & Yi, S. (2013). Ultrasound assisted vacuum drying of wood: Effects on drying time and product quality. *BioResources*, *8*, 855–863.

He, Z., Zhao, Z., Yang, F., & Yi, S. (2013). Effects of ultrasound on wood vacuum drying characteristics. *Pro Ligno: Scientific Journal in the Field of Wood Engineering*, *9*, 693–699.

Henderson, S., & Pabis, S. (1961). Grain drying theory I. Temperature effect on drying coefficient. *Journal of Agricultural Engineering Research*, *6*, 169–174.

Jamradloedluk, J., Nathakaranakule, A., Soponronnarit, S., & Prachayawarakorn, S. (2005, 11–13 January). *Modeling of dehydration and rehydration kinetics of durian*. The Second International Conference on Innovations in Food Processings Technology and Engineering (pp. 267–277). Thailand: Asian Institute of Technology.

Karasu, S., Başlar, M., Kilicli, M., Arici, M., Sagdic, O., & Karaagcli, M. (2015). Dehydration kinetics and changes of bioactive compounds of tulip and poppy petals as a natural colorant under vacuum and oven conditions. *Journal of Food Processing and Preservation*, *39*, 2096–2106.

Khoddami, A., Wilkes, M., & Roberts, T. (2013). Techniques for analysis of plant phenolic compounds. *Molecules*, *18*, 2328–2375.

Kiani, H., Zhang, L., & Sun, D. (2014). Ultrasonic assistance for food freezing. İn D.-W. Sun (Ed.), *Emerging technologies for food processing* (pp. 498–500). Oxford: Page.

Kingsly, A. R. P., & Singh, D. B. (2007). Drying kinetics of pomegranate arils. *Journal of Food Engineering*, *79*, 741–744.

Lee, G., & Hsieh, H. (2008). Thin-layer drying kinetics of strawberry fruit leather. *Transactions of the ASABE*, *51*, 1699–1705.

Lewis, W. K. (1921). The rate of drying of solid materials. *Journal of Industrial Engineering Chemistry*, *13*, 427–432.

Lie, C. H., Specht, K., Marshall, J. C., & Fink, G. R. (2006). Using MRI to decompose the neural processes underlying the Wisconsin Card Sorting Test. *Neuroimage*, *30*, 1038–1049.

Metherel, A., Taha, A., Izadi, H., & Stark, K. (2009). The application of ultrasound energy to increase lipid extraction through put of solid matrix samples (flaxseed). *Prostaglandins Leukotrienes and Essential Fatty Acids*, *8*, 417–423.

Mulet, A., Cárcel, J., Sanjuán, N., & Bon, J. (2003). New food drying technologies—Use of ultrasound. *Food Science and Technology International*, *9*, 215–221.

Muthukumaran, A., Orsat, V., Bajgai, T. R., & Raghavan, G. S. V. (2010). Effect of high electric field on food processing. In J. Ahmed, H. Ramaswamy, S. Kasapis, & J. Boye (Eds.), *Novel food processing: Effects on rheological and functional properties* (pp. 35–45). Boca Raton, FL: CRC Press.

Overhults, D. D., White, G. M., Hamilton, M. E., & Ross, I. J. (1973). Drying soybeans with heated air. *Transactions of the ASAE*, *16*, 195–200.

Page, G. (1949). *Factors influencing the maximum rates of air-drying shelled corn in thin layer* (Unpublished MS thesis). Department of Mechanical Engineering, Purdue University, West Lafayette, IN.

Ratti, C. (2009). Convective drying of foods. In C. Ratti (Ed.), *Advances in food dehydration* (pp. 133–134). Boca Raton, FL: CRC Press.

Santacatalina, J. V., Fissore, D., Carcel, J. A., Mulet, A., & Garcia-Perez, J. V. (2015). Model-based investigation into atmospheric freeze drying assisted by power ultrasound. *Journal of Food Engineering*, *151*, 7–15.

Schössler, K., Jäger, H., & Knorr, D. (2012). Novel contact ultrasound system for the accelerated freeze-drying of vegetables. *Innovative Food Science and Emerging Technologies*, *16*, 113–120.

Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture*, *16*, 144–158.

Tomas Barberan, F., & Espin, J. (2001). Phenolic compounds and related enzymes as determinants of quality in fruits and vegetables. *Journal of the Science of Food and Agriculture*, *81*, 853–876.

Wang, C. Y., & Singh, R. P. (1978). *A single layer drying equation for rough rice*. ASAE Paper, No, 78-3001, ASAE, St. Joseph, MI.

Wankhade, P., Sapkal, R., & Sapkal, V. (2012). *Drying characteristics of okra slices using different drying methods by comparative evaluation*. Proceedings of the World Congress on Engineering and Computer Science, San Francisco.

Wojdylo, A., Oszmianski, J., & Czemerys, R. (2007). Antioxidant activity and phenolic compounds in 32 selected herbs. *Food Chemistry*, *105*, 940–949.

Yagcioglu, A., Degirmencioglu, A., & Cagatay, F. (1999). Drying characteristic of laurel leaves under different conditions. In *Proceedings of the 7th International Congress on Agricultural Mechanization and Energy* (A. Bascetincelik, ed.) pp. 565–569. Adana: Turkey.

Zafra-Rojas, Q. Y., Cruz-Cansino, N., Ramirez-Moreno, E., Delgado-Olivares, L., Villanueva-Sanchez, J., & Alanis-Garcia, E. (2013). Effects of ultrasound treatment in purple cactus pear (*Opuntia ficus-indica*) juice. *Ultrasonics Sonochemistry*, *20*, 1283–1288.

Zhang, M., Jiang, H., & Lim, R. (2010). Recent developments in microwave-assisted drying of vegetables, fruits, and aquatic products-drying kinetics and quality considerations. *Drying Technology*, *28*, 1307–1316.

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