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EFFECT OF ETHANOL IMMERSION AND ULTRASOUND PRETREATMENTS ON THE KINETICS OF CONVECTIVE DRYING OF QUINCE

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ABSTRACT
This work studied the impact of ethanol immersion (E), ultrasound (U), and ultrasound-ethanol immersion (UE) for 10, and 20 min on the drying characteristics of quince. After pretreatments, the samples were dried at a hot dryer at 90°C and air velocity of 2 m/s. Drying time was reduced by 50% for samples pretreated in Ultrasonic-Ethanol (UE20) for 20 min. Moisture diffusion coefficient varied from 1.880 to 2.933×10^{-9} m²/s. The friction drag force, convective heat transfer coefficient, and convective mass transfer coefficient were 6.110×10^{-6} N, 24.077 W/m²K, and 0.020 m/s, respectively. The thermal conductivity, the specific heat, and the density of quince samples ranged from 0.5278 to 0.5876 W/m. K, 3554.00 to 3908.00 J/kg. K, and 814.95 to 904.60 kg/m³, respectively. Among all pretreatments, UE20 could prefer for significant decreases in the drying time and improve drying characteristics of quince at the industrial extent.
Keywords: Ethanol-immersion, ultrasound, pretreatment, drying kinetics, diffusion coefficient, quince

ETANOLE DALDIRMA VE ULTRASON ÖN İŞLEMLERİNİN AYVANIN KONVEKTİF KURUTMA KİNETİĞİNE ETKİSİ

ÖZ
Bu çalışmada 10 ve 20 dak etanole daldırma (E), ultrason (U) ve ultrason-etanole daldırma (UE) ön işlemlerinin ayvanın kuruma özellikleri üzerindeki etkileri incelenmiştir. Ön işlemler sonrası, numuneler sıcak hava kurutucusunda 2 m/s hızda 90 °C'de kurutulmuştur. Ultrason-etanole daldırma ile 20 dak ön işlem görmüş numunelerde (UE20) kuruma süresinin %50 oranında azaldığı görülmüştür Numunelerin nem difüzyon katsayıları 1.880 ile 2.933×10^{-9} m²/s arasında değişmiştir. Sürtünme kuvveti, konvektif ısı transfer katsayısı ve konvektif kütle transfer katsayısı sırasıyla 6.110×10^{-6} N; 24.077 W/m²K ve 0.020 m/s olarak elde edilmiştir. Ayvaların ısı iletkenliğinin 0.5278-0.5876 W/m K, özgül ısısının 3554-3908 J/kg. K ve yoğunluğunun 814.95-904.60 kg/m³ aralıklarında değiştiği belirlenmiştir. Tüm ön işlemler karşılaştırıldığında ayva üzerinde UE20 işleminin kurutma süresini önemli ölçüde azalttığı belirlenmiş ve endüstriyel boyutta bu işlemin kullanılabilir olduğu sonucuna varılmıştır.
Anahtar kelimeler: Etanole daldırma, ultrason, ön işlem, kurutma kinetiği, difüzyon katsayısı, ayva

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INTRODUCTION

Quince (*Cydonia oblonga* Miller) is a valuable fruit, which belongs to the Rosaceae family. Quince shows health-promoting potential due to its valuable bioactive compounds, vitamins, and fibers (Najman et al., 2023; Salehi et al., 2023). Quince can be consumed as both fresh and processed. However, due to its unique characteristic of astringent flavor, distinct aroma, and hardness quince has been processed into different products (Berktas et al., 2023). It is consumed as jam, juice, jellies, syrups, alcoholic beverages, cakes, desserts, confectionery, tea, etc. (Najman et al., 2023). According to the high moisture content of quince, it exposed microbial and chemical deterioration. Drying can be used to decrease its moisture content, extend the shelf life and decrease the transportation and storage costs (Salehi et al., 2023). Hot air dying is one of the oldest methods universally used to dry foodstuff at the industrial extent (Kian-Pour N. , 2023a). However, the most disadvantages of long drying time are losses of nutrition and undesirable changes in the quality attributes of dried food. Long drying time with the use of more energy has a negative effect in terms of economic, global warming, and environmental pollution (Kian-Pour et al., 2022). Recently, there is a significant effort to improve drying operation and decrease the drying time, energy consumption, and process cost (Miano et al., 2021).

Using different pretreatment techniques before drying can improve the drying behavior of food products via different mechanisms such as increases in the rate of mass transfer and water migration (da Cunha et al., 2020). The ultrasound and ethanol immersion pretreatment can be used as a promising alternative to non-thermal pretreatments for improving the drying kinetics of food (de Freitas et al., 2021; Santos et al., 2021; Bassey et al., 2021). Recently, the usage of ethanol immersion pretreatment rises due to its effect in drying without any residues in the dried products (Santos et al., 2021). The Marangoni effect of ethanol produces a surface tension gradient in the surface of the sample, also acts as a solvent to dissolve some cell wall components, and increases the permeability of the cell wall. All of these effects lead to an increase in the moisture transfer in products, which boosts drying process (Rojas and Augusto, 2018). Different authors studied the effect of ethanol pretreatments on the drying characteristics of food products such as celery (Miano et al., 2021), melon (da Cunha et al., 2020), pineapple (de Freitas et al., 2021), and apple (Rojas et al., 2020).

Ultrasonic waves is an acoustic wave that when passed through a food matrix caused compression and expansions in tissue known as the sponge effect, which improves the transfer of water within the food (de Freitas et al., 2021). These mechanical tension produce facilitate to drawn out of the water from food. Also, due to the sponge effect some microchannels formed in the food matrix resulting to improve the transfer of intracellular water from the interior of the food to its surface (Pandiselvam et al., 2023). Also, the cavitation phenomenon takes place during ultrasonic pretreatment due to the formation and collapse of air bubbles. The explosion of microbubbles produces strong shock wave energy, high pressure, shear force, and liquid jets that can help separation of water, which is strongly bound to the cell and can destroy the cell membrane (Pandiselvam et al., 2023; Zang et al., 2023). All of these phenomena lead to improvement in the mass transfer and movement of water from the interior to the surface of food and consequently improve the drying characteristics. Water is the main medium to transmit sound waves to the food. The use of ethanol as the liquid medium can improve the drying kinetics, energy consumption, rehydration, and retention of bioactive compounds in different foods such as carrot (Santos et al., 2021), pineapple (de Freitas et al., 2021), and celery slice (Miano et al., 2021). However, the impact of emerging ultrasound/ethanol immersion technology for various fruits and vegetables still needs to study to serve as a foundation for industrial application.

To the best of our knowledge, there is no study in the literature about the impact of non-thermal ultrasound/ethanol immersion on the drying characteristics of quince. Consequently, the current study investigated the effect of ethanol immersion, ultrasound, and ultrasound/ethanol immersion on the kinetics of drying, heat and mass transfer, mathematical modeling, and thermophysical properties of quince.

MATERIALS AND METHODS

Materials

Fresh quince (*Cydonia oblonga* Miller) was obtained from a local market in Istanbul/Turkey. The quince was washed, peeled, and diced into cubes with a dimension of 5×5×2 mm. Ethanol 99.90% (V/V) (ISOLAB GmbH) was used in this study. The initial moisture content was calculated according to the standard method of AOAC no.934.06 (AOAC, 1990) via a vacuum dryer (EV018, Nuve, Turkey) which was found to be 5.124 kg water/kg dry solid.

Ultrasound pretreatment (U)

Fresh quince samples were exposed to the ultrasound pretreatments by immersion of samples in distilled water (with the quince/water ratio of 0.08:1 (w/v)) in a beaker at an ultrasonic bath (Protech Ultrasonic Bath PMYU4-Istanbul, Turkey; frequency of 40 kHz, ultrasonic power of 125 W) at 25°C for 10, and 20 min (Santos et al., 2021).

Ethanol immersion pretreatment (E)

Ethanol immersion pretreatment was carried out by immersion of quince in ethanol 99.90% (V/V) for 10, and 20 min at the quince/ethanol ratio of 0.08:1 (w/v) (Rojas and Augusto, 2018).

Combined ultrasound and ethanol immersion pretreatment (UE)

For the pretreatment, first, the quince samples were immersed in ethanol 99.90% (V/V) with the quince/ethanol ratio of 0.08:1 (w/v) in a baker. Then they were exposed to the ultrasound waves bath at 25°C for 10, and 20 min according to the pre-tests. The unpretreated samples were considered as a control sample (CO).

Convective drying

A laboratory-scale convective dryer was used in this study. Samples were dried air at a temperature of 90°C and 2 m/s. The weight reduction of quince during hot air drying was monitored every 1 min via a precious balance (Fz-500i/AND, JAPAN, ± 0.001 g) and software Rs weight-Ver. 5.10. (Kian-Pour and Karatas, 2019). All experiments were performed in duplicate. The schematic of process was shown in Figure 1.

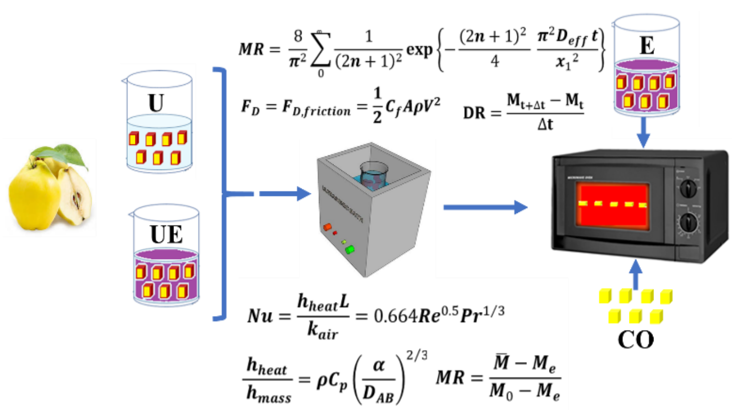

Figure 1: Schematic view of pretreatment and drying process of quince.

Kinetics of drying

The drying rate of quince samples were computed by Eq. (1):

$$DR = \frac{M_{t2}-M_{t1}}{t_2-t_1} \tag{1}$$

where *DR* shows the drying rate (kg water/kg dry solid min); M_{t2} and M_{t1} represent the moisture contents (kg water/kg dry solid) of quince at the drying time of t_2 and t_1 (min), respectively.

The moisture ratio (*MR*) of the sample was determined according to Eq. (2):

$$MR = \frac{\bar{M}-M_e}{M_0-M_e} \quad (2)$$

where, $\bar{M}$, M_e, and M_0 are average, equilibrium, and initial moisture contents of quince (kg water/kg dry solid), respectively.

Mathematical modeling

The experimental data was used for mathematical modeling using a nonlinear regression analysis with the Levenberg-Marquardt algorithm (SPSS statistics 23, IBM. 2015). The *MR* curve was modeled according to the Midilli & Kucuk (semi-theoretical model) (Eq. 3) and Wang & Singh (empirical model) (Eq. 4) equations.

$$MR = a\exp(-kt^n) + bt \quad (3)$$

$$MR = 1 + at + bt^2 \quad (4)$$

The goodness of fit was evaluated according to the statistical criteria of the R^2 (coefficient of determination) (Eq 5), *RMSE* (root mean square error) (Eq. 6), and χ^2 (reduced chi-square) (Eq. 7).

$$R^2 = 1 - \left[\frac{\left(\sum_{i=1}^{N} MR_{pre,i}-MR_{exp,i}\right)^2}{\left(\sum_{i=1}^{N} \overline{MR}_{pre,i}-MR_{exp,i}\right)^2}\right] \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2}{N}} \quad (6)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i}-MR_{pre,i})^2}{N-n} \quad (7)$$

where $MR_{exp,i}$ and $MR_{pre,i}$, represent the experimental and predicted moisture ratios, respectively. Besides, *N* is the number of observations at each drying test and *n* is the number of mathematical model constants (Kian-Pour N. 2023a).

Moisture diffusion coefficient (D_{eff})

The D_{eff} of cube quince samples with plate geometry was determined according to the analytical solution of Fick's second law using linear regression analyses (SPSS statistics 23, IBM. 2015) (Eq. 8).

$$MR = \frac{8}{\pi^2}\sum_0^\infty \frac{1}{(2n+1)^2}\exp\left\{-\frac{(2n+1)^2}{4}\frac{\pi^2 D_{eff}t}{x_1^2}\right\} \quad (8)$$

where D_{eff} , *n*, *t*, and x_1 represent the diffusion coefficient (m/s²), a positive integer, time (s), and the half-thickness of the quince samples (m), respectively.

Transport phenomena

Momentum transfer

As dry air flows on the surface of the quince sample, it produces a friction drag force (N) which is calculated according to Eq. 9 (Çengel and Cimbala, 2006).

$$F_D = F_{D,friction} = \frac{1}{2}C_f A\rho V^2 \quad (9)$$

where C_f , A , ρ , and V represent the friction drag coefficient, the total surface area of quince cubes (m), density of drying air (kg/m³), and air velocity (m/s), respectively. For the Reynolds number Re_L (Eq. 10) less than 5×10^5, C_f in the laminar boundary layer determined by Eq. (11)

$$Re_L = \frac{L\,V\,\rho}{\mu} \quad (10)$$

$$C_f = \frac{1.33}{Re_L^{1/2}}\ , \quad Re_L < 5 \times 10^5 \quad (11)$$

where L and μ are the characteristic length of the quince samples in the flow direction (m), and viscosity of drying air (kg/m.s), respectively (Kian-Pour N. , 2023b).

Heat transfer coefficient (h_{heat})

Eq. 12 was used for the determination of the average heat transfer coefficient (W/m² K) at the laminar boundary layer.

$$Nu = \frac{h_{heat}L}{k_{air}} = 0.664Re^{0.5}Pr^{1/3}\ , \quad Re_L < 5 \times 10^5 \quad (12)$$

where *Nu, L,* k_{air}, and *Pr* represent the Nusselt number, characteristic lengths of quince samples (m), the thermal conductivity of hot air (W/m K), and Prandtl number, respectively (Kian-Pour and Karatas, 2019).

Mass transfer coefficient (h_{mass})

The convective average mass transfer coefficient h_{mass} (m/s) was determined according to (Eq. 13) (Geankoplis, 1993).

$$Sh = \frac{h_{mass}L}{D_{AB}} = 0.664Re^{0.5}Sc^{1/3}\,, \qquad Re_L < 5 \times 10^5 \tag{13}$$

where Sh, D_{AB}, and S_C represent the Sherwood number, the mass diffusivity of air-water vapor mixture (2.2×10^{-5} m²/s), and Shmidt number, respectively. Besides, a Chilton-Colburn analogy was used for the calculation of h_{mass} (Eq. 14) (Çengel, 2007).

$$\frac{h_{heat}}{h_{mass}} = \rho C_p (\frac{\alpha}{D_{AB}})^{2/3} = \rho C_p Le^{2/3} \; 0.6 < Pr < 60, \; 0.6 < Sc < 3000 \tag{14}$$

where C_p shows specific heat (J/kg K), α represents the thermal diffusivity of drying air (m²/s), and Le denotes Lewis number.

Thermophysical properties of quince

The thermal conductivity, specific heat, and density (kg/m³) of quince samples were determined according to their moisture content using the Eq. 15, Eq. 16, and Eq. 17, respectively (Pasban et al., 2017).

$$k = 0.148 + 0.493M_{wb} \tag{15}$$

$$C_p = (1.26 + 2.97M_{wb}) \times 1000 \tag{16}$$

$$\rho = 770 + 16.18\,M_{db} - 295.1 \times \exp(-M_{db}) \tag{17}$$

where k, C_p, M_{wb}, M_{db} and ρ represent the thermal conductivity (W/m K), specific heat (J/kg K), wet basis moisture content (%), dry basis moisture content (kg water/kg dry solid), and the density (kg/m³) of quince.

Statistical analysis

The obtained data from experimental test were submitted to the analysis of variance (ANOVA) with Tukey's tests at the 95% confidence level ($p<0.05$) using the SPSS statistics 23, IBM. 2015 software.

RESULTS AND DISCUSSION

Kinetics of drying

The moisture content *(MR)* and drying rate (*DR)* of quince are shown in Figure 2. As drying progressed, the moisture ratio of all quince samples exponentially decreased. All pretreatments reduced the drying time of quince at different levels (from 8.33% to 50.00%). Also, as the immersion time of quince in ethanol increased from 10.00 to 20.00 min, the drying time decreased (Figure 2a) (Table 1). The drying kinetics of quince samples immersed in ethanol changed due to the Marangoni effect. This is a mass transfer in the interface of water and ethanol with different surface tension (Santos et al., 2021). During the drying of the quince, ethanol vaporized faster than water thus more water remain on the quince surface than ethanol. Therefore, a region with higher surface tension forms on the surface, and this surface tension gradient act as a driving force to pull up the moisture from inside of the quince to its surface. The water flow is maintained as a result of this effect until the surface tension equilibrium is reached (de Freitas et al., 2021). Also, as an organic solvent, ethanol initially dissolves some components of the cell wall, which create new pathways for moisture movement. It leads an increase in the permeability of the cell wall, which boosts the removal of water from quince tissue resulting in decreases in the drying time (Miano et al., 2021). Consequently, the quince samples immersed in the ethanol dried faster than CO samples. Our results are in good agreement with another study (da Cunha et al., 2020) in which was pretreated melon in ethanol and the author observed that drying time of melon pretreated in ethanol 56.90% reduced in comparison with control samples. Guedes et al. (2021) reported that ethanol pretreatment reduced the drying time of potato by 56%. Rojas et al. (2020) demonstrated a 53% reduction in the drying time of apple slices pretreated with ethanol immersion for 30 min.

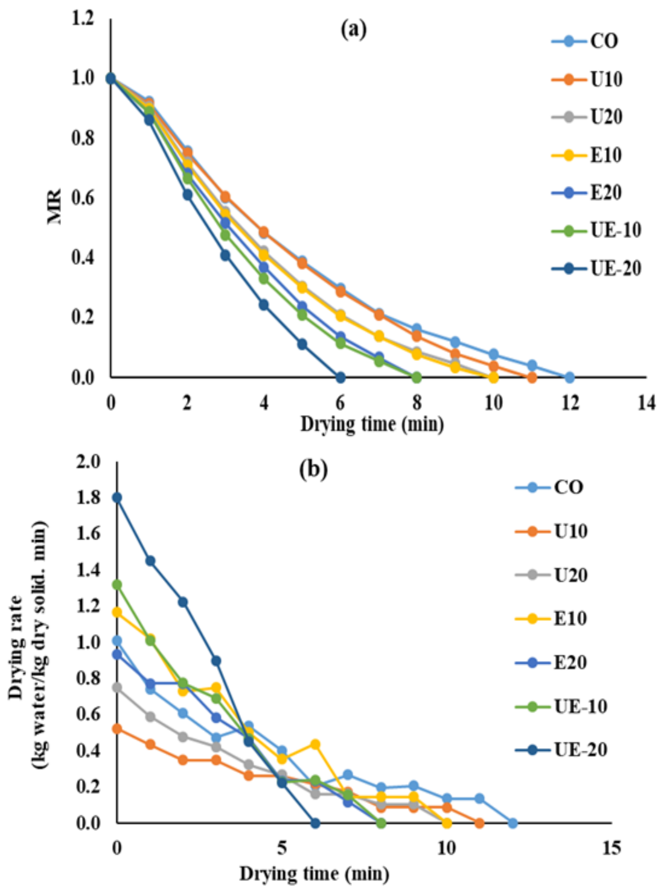

Figure 2. (a) moisture ratio, (b) drying rate of quince samples.

Table 1. Kinetics drying of quince samples.

Samples	Pretreatment time (min)	Code	Difussion coefficient D_{eff} * 10^{-9} m^2/s	Change in D_{eff} (%)	Change in the drying time (%)
Control	0	CO	1.880 ± 0.007[a]	0	0
Ultrasonic	10	U10	2.069 ± 0.014[b]	+10.05	-8.33
	20	U20	2.271 ± 0.006[c]	+20.80	-16.66
Ethanol	10	E10	2.425 ± 0.028[d]	+28.99	-16.66
	20	E20	2.547± 0.046[e]	+35.48	-33.33
Ultrasonic-Ethanol	10	UE10	2.752 ± 0.003[f]	+46.38	-33.33
	20	UE20	2.933 ± 0.012[g]	+56.01	-50.00

*Mean ± standard deviation is computed from duplicate samples. Different letters in the same column indicate differences significant at $p < 0.05$. (-): decreases, (+): increases.

Also, ultrasound pretreatment decreased the drying time of quince samples compared with CO. A sponge effect is created when an ultrasonic wave passes through a product because of acoustic cavitation, which can result in the formation of microchannel inside the food sample. These microchannels make it easier for water to move and enhance mass transfer. As a result, the improvement in the water migration is responsible for the quicker decrease in moisture ratio that was seen in the U10, and U20 samples compared with CO (Santos et al., 2021). At UE samples, decreases in the drying time were higher than CO samples, and a maximum reduction in drying time (50.00%) was observed in UE20 sample (Figure 2a). It can be related to the synergetic effect of ultrasound and ethanol immersion on the quince tissue. As was shown in Figure 2b, the drying rate of quince samples started from the falling rate period, and a constant rate period was not observed which demonstrated that diffusion was the main mechanism that controled the drying rate of the sample. The highest starting rate was observed in the U20 samples, which can be related to the increases in the formation of microchannels during 20 min, which helped the transfer of water in products. The faster drying was observed at UE samples compared with E and U samples (Figure 2b). It can be related to the synergic effects of E and U pretreatments which caused both ruptures of quince cell walls (due to the Marangoni effect) and the formation of porous structure and microchannel (due to the sponge effect) which improved water flow during drying (de Freitas et al., 2021). Our results are in good agreement with other studies. Fotiou et al., (2023) reported the 37.50% reduction in the drying time of peach peel pretreated with UE method. It was stated that drying time of pineapple pretreated with UE technique 70.00% decreased compared with CO sample (de Freitas et al., 2021). It was stated that ultrasound-ethanol pretreatment decreased the drying time of apple by 70% (Rojas, Augusto, & Cárcel, 2020).

The D_{eff} varied from 1.880 to 2.933 × 10^{-9} m^2/s (Table 1) which was within the expected range for most foodstuffs (10^{-12} to 10^{-8} m^2/s) (Fotiou et al., 2023). All pretreatment significantly ($p<0.05$) increased the *Deff* of quince samples. The lowest and highest D_{eff} values belonged to the CO and UE20 samples, respectively. It can be related to the destruction of the cell wall of quince by ethanol and the formation of new pathways for water transfer due to the ultrasound pretreatment (Miano et al., 2021). Also, as pretreatment time increased, the D_{eff} values increased. Zang et al., (2023) reported that increases in the ultrasonic pretreatment time of *Angelica sinensis* herbs caused an increase in the D_{eff} values. During the UE pretreatment, cavitation was produced by ultrasonic waves, and the quince tissue was exposed to compression and expansion. Also, ethanol with the dissolve of some cell wall components caused a reduction in the internal resistance against water transfer due to the damage to the internal diffusion boundary. Thus, it reduced mass transfer resistance, speed up moisture diffusion and evaporation, produce microspores in quince, forming the turbulence water flow, improving the moisture movement all of them improved the moisture diffusivity. Similar results were reported by different authors (Zang et al., 2023; Fotiou et al., 2023).

Mathematical modeling

Mathematical models are useful tools for simulating the drying process and predicting the behavior of food during drying. The Lamped parameter models are used for modeling the material with uniform thickness such as thin layers and they can be divided into theoretical, semi-theoretical, and empirical models. In this study, the results of mathematical modeling are detailed in Table 2. The R^2 values ranged from 0.95243 to 0.99907, the *RMSE* values changed from 0.010541 to 0.075277 and the χ^2 values varied from 0.000200 to 0.007286. The Midilli & Kucuk model showed the highest R^2 and lowest values of RMSE and χ^2 which represent the suitability of this model for predicting the drying characteristics of quince samples. Various authors demonstrated that Midilli & Kucuk model is a suitable model for predicting the drying behavior of many food products such as apples (Kian-Pour and Karatas, 2019), bananas (Macedo et al., 2020), and papaya (Islam et al., 2019).

Transport and thermophysical properties

Simulation and modeling are useful methods for explaining operational processes and transfer phenomena. Hot air drying consider a complex unit operation due to simultaneous heat and mass transfer (Kian-Pour and Karatas, 2019). The drying operation is affected from both external and internal conditions. Convection heat and mass transfer coefficients as well as friction drag force are the important external parameters. However, as external drying conditions were equal for all quince samples (such as drying air, characteristics length of samples, etc.) the transport parameters were valid for all samples. The friction drag force, convective heat, and mass transfer coefficients were evaluated according to Newton's law of viscosity, Fourier's law, and Fick's law, respectively, which were 6.110×10^{-6} N, 24.077 W/m^2 K, and 0.020 m/s, respectively (Table 3). Our results are in good agreement with the results reported about the drying of green almonds (Kian-Pour N. , 2023b) and celery root (Kian-Pour et al., 2022). The thermal conductivity, the specific heat, and the density of quince samples varied from 0.5278 to 0.5876 W/m K, 3554.00 to 3908.00 (J/kg K), and 814.95 to 904.60 (kg/m^3), respectively with the maximum values in UE20 samples. The effect of ethanol pretreatment for 10 min in the increasing of these parameters was more pronounced than ultrasound. The results revealed that the pretreatment of quince with a combination of ultrasound and ethanol immersion caused an increase in the moisture content of the sample after pretreatments which caused an increase in the thermophysical properties of quince. The faster drying also was observed in UE20 samples which were related to the availability of moisture movement and change in its microstructure. During hot air drying, both external and internal conditions affect the drying kinetics of the sample. The results were consistent with other studies about celery root (Kian-Pour, et al., 2022), green almond (Kian-Pour N. , 2023b), and Santa Maria pear (Kian-Pour N. 2023a). The experimental data about external and internal parameters that affect the drying can be useful for simulating the drying of quince and useful in understanding the drying mechanisms.

Table 2. Model parameters obtained by nonlinear regression analysis and statistical criteria for selecting ideal model

Models	Code					R^2	RMSE	X^2
Wang &Singh	CO	a= -0.112	b= 0.003			0.96816	0.058177	0.004000
	U10	a= -0.107	b= 0.002			0.97090	0.056273	0.003800
	U20	a= -0.121	b= 0.002			0.96042	0.066742	0.005444
	E10	a= -0.124	b= 0.003			0.96132	0.066058	0.005333
	E20	a= -0.115	b= 0.000			0.96176	0.066667	0.005714
	UE10	a= -0.126	b= 0.001			0.95243	0.075277	0.007286
	UE20	a= -0.106	b= -0.006			0.95921	0.070711	0.007000
Midilli &Kucuk	CO	a= 0.000	b= -0.050	k=-9.127	n=-0.027	0.98046	0.045573	0.003000
	U10	a= 0.001	b= -0.062	k=-7.692	n=-0.026	0.98698	0.037639	0.002125
	U20	a= 0.000	b= -0.064	k=-8.751	n=-0.027	0.98061	0.046710	0.003429
	E10	a= 0.000	b= -0.062	k=-8.672	n=-0.029	0.98066	0.046710	0.003429
	E20	a= 1.082	b= -0.007	k=0.063	n=1.706	0.99904	0.010541	0.000200
	UE10	a= 1.082	b= -0.004	k=0.064	n=1.790	0.99907	0.010541	0.000200

Table 3. Thermophysical properties of quince

Sample	Thermal conductivity k (W/m K)	Specific heat Cp (J/kg K)	Density ρ (kg/m^3)
CO	0.5671 ± 0.014^a	3785 ± 85.56^a	862.45 ± 22.42^a
U10	0.5287 ± 0.005^a	3554 ± 32.53^a	814.95 ± 5.44^a
U20	0.5406 ± 0.028^a	3625 ± 168.29^a	828.90 ± 31.11^a
E10	0.5761 ± 0.011^a	3839 ± 68.59^a	878.00 ± 22.49^a
E20	0.5592 ± 0.024^a	3737 ± 142.84^a	852.60 ± 32.95^a
UE10	0.5725 ± 0.012^a	3817 ± 69.30^a	871.15 ± 20.58^a
UE20	0.5876 ± 0.007^a	3908 ± 45.26^a	904.60 ± 21.21^a

*Mean ± standard deviation is computed from duplicate samples. Different letters in the same column indicate differences significant at $p < 0.05$.

CONCLUSION

The use of different non-thermal pretreatments of ethanol immersion (E), ultrasound (U), and ultrasound-ethanol immersion (UE) before hot air drying of quince was investigated. Overall the pretreatments improved the drying kinetics of quince samples. The maximum decrease in drying time was observed at the sample pretreated by UE for 20 min. The synergetic effect of the ethanol immersion and ultrasound in terms of Marangoni, sponge effect, and cavitation phenomenon improved the mass transfer in the sample and decreased the drying time. Also, as pretreatment time increased, the moisture diffusion coefficient increased. Mathematical modeling showed the suitability of the Midilli & Kucuk model for predicting the drying behavior of quince. The UE pretreatment can decrease the drying time by 50%, which is very valuable in terms of the reduction of energy consumption of dryers at both large and small-scale food factories.

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