Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 13(1), 305-316, 2023
Journal of the Institute of Science and Technology, 13(1), 305-316, 2023

ISSN: 2146-0574, eISSN: 2536-4618

Food Engineering **DOI: 10.21597/jist.1166340**

Research Article

Received: 24.08.2022 **Accepted: 18.11.2022**

To Cite: Kian-Pour, N. (2023). Impact of Microwave-Starch-Blanching on the Drying Kinetics, Transport and Thermophysical Properties of Green Almond. *Journal of the Institute of Science and Technology*, 13(1), 305-316.

Impact of Microwave-Starch-Blanching on the Drying Kinetics, Transport and Thermophysical Properties of Green Almond

Nasim KIAN-POUR[1]

Highlights:

- Decrease the drying time of green almonds between 7.14% to 55%
- Improving drying characteristics of green almonds via microwave-starch blanching pretreatment
- The fastest drying in the lowest drying temperature was achieved by using microwave (600W)-starch (0.5%w/w) blanching of samples

Keywords:

- Diffusion coefficient
- Drying kinetics
- Green almond
- Microwave blanching
- Starch

ABSTRACT:

This study aimed to investigate the effect of different pretreatment blanching methods on the drying characteristics of green almonds. Microwave blanching at 300, 450, and 600 W power in the water and/or starch solution (0.5% w/w), water blanching (95°C, 5 min), and starch blanching (0.5% w/w) were preferred. Non-blanched samples were considered as the control samples. All samples were dried at a constant air velocity of 1.5 m/s and temperatures of 70, 90, and 110°C. As drying time increased, moisture ratio of all samples exponentially decreased. Nonlinear regression analysis was used to fit the experimental data to drying models. Effective diffusivities, which ranged from 2.238×10^{-9} to 6.434×10^{-9} m^2/s were calculated using Fick's second law of diffusion. Activation energies were determined according to the Arrhenius equation and ranged from 12.32 to 15.39 kJ/kg mol. The highest diffusion coefficient was observed in the microwave starch blanched (600 W-110°C) samples. The highest increases in the diffusion coefficient and decreases in the drying time in comparison with control samples were observed in the microwave-starch (600W- 70°C) samples. Thermal conductivity, density, and specific heat of samples ranged from 0.544-0.586 (W/m K), 3643.85-3900.00 (J/kg K), and 835.80-899.44 (Kg/m^3), respectively. The friction drag force, convective heat, and mass transfer coefficients varied from 3.965 to 3.972×10^{-6} N, 66.29 to 66.44 W/m^2 K, and 0.03410 to 0.03428 m/s, respectively. The using microwave-starch blanching pretreatment can significantly decrease the drying time and improve the drying process of green almond at the industrial scale.

[1]Nasim KIAN-POUR (**Orcid ID:** 0000-0001-9558-4077), Istanbul Aydın University, Faculty of Fine Arts, Department of Gastronomy and Culinary Arts, Istanbul, Türkiye

***Corresponding Author*:** Nasim KIAN-POUR, e-mail: nasimkianpour@aydin.edu.tr

INTRODUCTION

Almond belongs to the family of *Rosaceae* and it is a seasonal valuable fruit with high nutritional value. Almond in the unripe form known as green almond which harvested before maturing and is consumed as a whole (with its hull and shell), fresh (in the salad), cooked (almond stew), etc. It is one of the most common snacks in the Middle East and many countries (Lavasani and Motie, 2022). Different kinds of food products can be produced from green unripe almonds such as hummus, pickle, ice cream, and vegan food. Ascorbic acid, total phenolic, and flavonoid compounds, and antioxidant activity of green almonds have been reported by Murathan et al. (2020). However, to increase the shelf life and protection of green almonds from deterioration, their water content needs to be decrease (Kian-Pour and Karatas, 2019). Drying is one of the most popular food processes which with decreases in the water content can protect fruits and vegetables from unwanted enzymatic, chemical, and microbial decay. Most industrial dryers use hot air drying because it is a cost-effective drying technology (Kian-Pour et al. 2022). However, for decreasing the drying time and production of dried food with high quality, fast drying is necessary (Mujumdar, 2006). Simultaneous momentum, heat, and mass transfer during hot air drying, give complexity to this unit operation. It was stated that pretreatment before drying can improve the drying process (Islam et al. 2019).

Blanching is an essential primary thermal treatment performed before the industrial drying of vegetables and fruits which can inactive enzymes, enhance the drying properties and alter the quality characteristics of the food (Latorre et al. 2013; Kian-Pour et al. 2022). Also, blanching can remove air from the intracellular space and can change food structure, and produce superficial micro-cracks which cause an improvement in the rate of heat and mass transfer during drying (Wang et al. 2017). It can be accomplished using a variety of techniques, including hot water, steam, microwave, ohmic, etc., (Wang et al. 2017; Kian-Pour et al. 2022). Microwave heating has become popular in food industries due to its fast heating rates, a significant reduction in cooking time, simplicity of use, and low maintenance requirements (Chandrasekaran et al. 2013). Microwaves are in the spectrum of electromagnetic radiation with frequencies ranging from 300 MHz to 300 GHz (Guzik et al. 2021). Microwave blanching has been successfully used due to decrease time and energy for inactivation of enzymes and decrease the drying time. It may be used as an alternative for water and steam blanching (Latorre et al. 2013; Guzik et al. 2021). Coating foods before drying in the drying aid material solutions such as starch can improve the drying behavior of food products. Islam et al. (2019) coated papaya slices with starch to protect the color of the sample. It was stated that starch solution at low concentration caused an increase in the drying rate of papaya. Kian-Pour et al. (2022) demonstrated that blanching of celery roots at the native corn starch solution increased the diffusion coefficient by 70.79%. However, there are relatively rare studies conducted on green almonds (Murathan et al. 2020; Lavasani & Motie, 2022).

To the best of our knowledge, no research has been done on the microwave-water, and microwave-starch blanching pretreatments of green unripe almonds before drying. The main aim of this research was to study the effect of different microwave-water and microwave-starch blanching at 300, 450, and 600W on the kinetics of drying, drying time, diffusion coefficient, mathematical modeling, transport and thermophysical properties of green almond dried at 70, 90, and 110° C.

MATERIALS AND METHODS

Sample Preparation

Fresh green unripe almonds (Ak Badem) (*Prunus amygdalus* var. *dulcis*) were purchased from a local market (Istanbul, Turkey). Almond of similar size was chosen and washed with tap water. The samples were blanched in water or starch solution by different methods. Non-blanched green almonds were considered as the control (CON) sample. The initial moisture content of samples was determined according to the standard AOAC (no. 934.06) method (Association of Official Analytical Chemists, 1990) by a vacuum dryer (EV018, Nuve, Turkey) which was 5.626 kg water/ kg dry solid.

Blanching pretreatment

The fresh green unripe samples were blanched in the water or corn starch solution. The blanching solution was prepared by adding native corn starch to the distilled water under continuous stirring (160 rpm) (Wisd, Daihan Scientific. Co., Ltd. Model msh-20A, Korea) to obtain 0.5% (w/w) aqueous starch solution (Kian-Pour et al. 2022). Microwave heating and hot water heating methods were selected for blanching pretreatments.

A microwave system (Samsung, Turkey, 2450 MHz, and 23 L capacity) was used for the blanching of green almonds. For microwave-water blanching, green almonds (35 g) were immersed in 300 ml of deionized water in a backer (Latorre et al. 2013) and blanched in the microwave at 300, 450, and 600 W power for 5 min. After each experiment, blanched green almonds were cooled rapidly for 5 min by immersing in a cooling water bath (ice + water) to stop blanching pretreatment. The same procedure was applied for the microwave-starch blanching of samples except that water is replaced with the native corn starch with a concentration of 0.5% w/w. The experiments were done in triplicate.

Hot water blanching as a conventional heat treatment was performed by immersion of green almond samples into a water bath at 95°C for 5 min followed by immediately cooling in a cooled water bath for 5 min with three replication (Latorre et al. 2013; Kian-Pour et al. 2022). Also, for starch blanching pretreatment, the fresh green almonds were immersed in the starch solution with concentration of 0.5% w/w by using a magnetic stirrer (160 rpm) (Wisd, Daihan Scientific. Co., Ltd. Model MSH-20A, Korea). The samples blanched at 95°C for 5 min and after that, their temperature was decreased by immersing in the cooled water bath for 5 min (Kian-Pour et al. 2022). The experiments were replicated three times.

Hot air dying experiment

The blanched and non-blanched green almond samples were uniformly sliced to 4 mm thickness. Then, the almond slices were cut with the use of specific cutters to a square shape (5×5 mm) for the determination of drying kinetics. The drying processes were conducted at the lab-scale convective dryer (Kian-Pour and Karatas, 2019) with three replicate, using air temperatures of 70, 90, and 110 °C and a velocity of 1.5 m/s. An analytical balance was used to online measuring the weight change of green almonds every 60 s during the drying process.

Kinetics of drying

Experimental data was used for investigation of the drying behavior of green almond sample. The drying rate (DR) was calculated by Equation 1.

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{1}$$

where, DR, Δt, M_t and $M_{t+\Delta t}$ are the drying rate (kg water/ kg dry solid. min), the time difference (min), and moisture content at times t and $t + \Delta t$, respectively. The moisture ratio (MR) were computed according to the Equation 2. (Kian-Pour et al. 2022).

$$MR = \frac{\bar{M} - M_e}{M_0 - M_e} \tag{2}$$

where , M_0, $\bar{M}$ and M_e are moisture ratio (dimensionless), the initial, the average and equilibrium moisture contents (kg water/ kg dry solid), respectively (Tepe and Tepe, 2020).

The experimental data were fitted to the empirical (Wang & Singh) (Equation 3) and semi-theoretical (Midilli & Kucuk) (Equation 4) models using the software package (SPSS statistics 23, IBM. 2015).

$$MR = 1 + at + bt^2 \quad (3)$$

$$MR = a\exp(-kt^n) + bt \quad (4)$$

where *a*, *b*, *n*, are model constant and *k* is drying constant. The goodness of fit was determined by the statistical parameters such as determination coefficient (R^2), root mean square error (*RMSE*), and reduced chi-square (x^2) (Kian-Pour et al. 2022).

Fick's second law of diffusion as a theoretical model was applied in the computation of the effective moisture diffusion (*Deff*) of samples (Equation 5) (SPSS statistics 23, IBM, 2015).

$$MR = \frac{8}{\pi^2}\sum_{0}^{\infty}\frac{1}{(2n+1)^2}\exp\left\{-\frac{(2n+1)^2}{4}\frac{\pi^2 D_{eff}\,t}{{x_1}^2}\right\} \quad (5)$$

where, D_{eff}, is the diffusion coefficient (m^2/s), *n* is a positive integer, and x_1 represent the half thickness of the slab (m), respectively (Souza et al. 2022). A linear regression analysis was used to fit the data of curve $LnMR$ against the drying time (Equation 6) and the slope of the straight line was used to determine the moisture diffusivity (Souza et al. 2022; Kian-Pour et al. 2022).

$$lnMR = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4x_1^2}\right) \quad (6)$$

Activation energy *(Ea)* represents the temperature dependency of *Deff* which is calculated according to the Arrhenius equation (Equation 7) (Kian-Pour and Karatas, 2019).

$$D_{eff} = D_0\exp\left(\frac{-E_a}{RT}\right) \quad (7)$$

where, E_a is the activation energy (kJ/mol), D_0 is the pre-exponential factor (m² /s), *R* shows the universal gas constant (kJ /kmol K) and *T* is the drying temperature (K), respectively.

Transport phenomena

The flowing of drying air over the green almond produces a friction drag force F_D (N), which was determined by Equation 8. Besides, in the laminar boundary layer for Reynolds number Re_L lower than 5×10^5, the friction drag coefficient (C_f) can be determined using Equation 9.

$$F_D = F_{D,friction} = \frac{1}{2}C_f A\rho V^2 \quad (8)$$

$$C_f = \frac{1.33}{Re_L^{1/2}}, \quad Re_L < 5\times10^5 \quad (9)$$

where A is surface area (m), ρ represent the density (Kg/ m^3), V is velocity (m/s), L shows the sample length and μ is viscosity (Kg/ m s), respectively.

The average convective heat transfer coefficient (h_{heat}) was determined using Equation 10.

$$Nu = \frac{h_{heat}L}{k_{air}} = 0.664Re^{0.5}Pr^{1/3}, Re_L < 5\times10^5 \quad (10)$$

where h_{heat} is average heat transfer coefficient (W/m^2 K), *Nu* is Nusselt number, *L* represent the characteristic lengths (m), k_{air} *is* the thermal conductivity of air (W/m K), and *Pr* is the Prandtl number.

The average convective mass transfer coefficient (h_{mass}) at $Re_L < 5\times10^5$ was calculated using a Chilton-Colburn analogy by Equation 11. (Çengel, 2007; Kian-Pour et al. 2022).

$$\frac{h_{heat}}{h_{mass}} = \rho C_p\left(\frac{\alpha}{D_{AB}}\right)^{2/3} = \rho C_p Le^{2/3} \quad (11)$$

where D_{AB}, represents the mass diffusivity (2.2×10^{-5} m² /s), h_{mass} is convective mass transfer coefficient (m/s), C_p is the specific heat of the air (J/kg K), α is thermal diffusivity of air (m² /s), and Le represents the Lewis number.

Thermophysical properties

The thermophysical properties of green almond respect with to its moisture content were determined by Equations 12-14 (Pasban et al. 2017; Kian-Pour et al. 2022):

$$k = 0.148 + 0.493M_{wb} \quad (12)$$

$$C_p = (1.26 + 2.97M_{wb}) \times 1000 \quad (13)$$

$$\rho = 770 + 16.18\ M_{db} - 295.1 \times \exp\ (-M_{db}) \quad (14)$$

where k represent thermal conductivity (W/m K), C_p is specific heat (J/kg K), M_{wb} is wet basis moisture content (%), M_{db} is dry basis moisture content (kg water/ kg dry solid), and ρ is the density (Kg/ m^3) of the green almond.

Statistical analysis

The SPSS program (SPSS statistics 23, IBM, 2015) and analysis of variance (ANOVA) at the significant level of $p < 0.05$ was used for statistical analysis.

RESULTS AND DISCUSSION

Drying Kinetics of Green Almond

The drying curves of moisture ratio (MR) against drying time were shown in Figure 1. The MR of all samples exponentially decreased as drying time decreased at 70°C (Figure 1a), 90 °C (Figure 1b), and 110°C (Figure 1c). In conventional drying, as green almond is exposed to hot air, the heat energy is transferred first by the convection to the surface of the almond and then by conduction to the inside of the sample. Simultaneously, mass (water) is transferred from the internal parts of samples to their surface by diffusion or capillary mechanism, followed by evaporation of moisture from the surface in airflow (Kian-Pour and Karatas, 2019). Therefore, as drying progressed the moisture content and moisture ratio of the food sample decreased. However, the decrease in the MR at higher temperatures is faster than at lower temperatures due to the higher heat transfer. Also, microwave starch blanching, followed by microwave water blanching was more effective in decreasing MR compared with blanching in water and starch solution (No microwave) (Figure 1a). It can be explained by the effect of microwaves on the rotation of polar molecules which causes collide with other molecules. Besides, due to the electric field, the ions start to move and transfer their kinetic energy to the water molecules. In a very short time, a huge amount of collision takes place which produces friction resulting in generation of heat (Guzik et al. 2021). Therefore, due to the higher and faster transfer of thermal energy in microwave blanching, the decreases in the MR were faster than in non-microwave blanching. Our results are in agreement with other studies about hot air drying of apples (Kian-Pour and Karatas, 2019), mushrooms (Wang et al. 2019), apricot (Polat and Izli, 2022), and celery roots (Kian-Pour et al. 2022). As expected, all blanching pretreatments decreased the drying time of green almonds compared with the control sample. Microwave blanching in starch solution was the most effective pretreatment to decrease the drying time which can be related to the combined effect of microwave and starch solution on the green almond. During blanching, releases of trapped air from the intracellular structure of the sample and/or increases in the permeability of the cell due to heating are the main factor for improving the drying characteristics of samples. Also, as microwave power increased in both microwave water and microwave starch blanching, the drying time decreased. Wang et al. (2017) showed that as the microwave power increased from 650 to 900 W, the drying time of red bell pepper decreased (Wang et al. 2017). It can be related to the effect of microwave blanching on the microstructure of samples. The friction generated by microwaves at the molecular level can produce internal cell pressure, resulting in cell rupture. Microwave blanching can produce destructive changes in the cell wall which can alter the capillary-porous characteristics. Breakage of cell wall integrity leads to a decrease in the structural resistance against the movement of water during dehydration which increased the drying rate and decreases the MR and drying time (Latorre et al. 2013; Wang et al. 2019). Also, the use of starch solutions (MW-S-600, MW-S-450, MW-S-300) in microwave blanching compared with water solution (MW-W-600, MW-W-450, MW-W-300) decreased the drying time for samples dried at 70, 90, and 110°C. Starch is a polymer composed of amylose (AM) and amylopectin (AMP) molecules. As the starch solution is heated, it undergoes many microstructural changes known as gelatinization. When, blanching takes place at a high temperature, which is higher than the gelatinization temperature of starch, starch granules start to absorb water, swell, break down the AMP crystalline structure, leaching the AM molecules from swollen granules, and produce a densely packed network which entrapping water (Kian-Pour et al. 2022). Therefore, during blanching affinity of starch molecules to absorb water can help to decrease the water content of samples more than water-blanched samples which leading to decreases in drying time (Figure 1a, 1b, and 1c). Kian-Pour et al. (2022) reported that starch-blanching pretreatment of celery chips significantly decreased the dehydration time of samples compared with water-blanched samples. Decreases in the drying time at the samples blanched at a microwave power of 450 and 600 W (for drying at 70°C), and all microwave power (for drying at 90°C) were higher than SB (non-microwaved) samples at the same temperature which demonstrated the benefit of microwave blanching in reduction of drying time. However, as the drying temperature increased to 110°C, there were no differences in drying time between microwave treatment at 600 W and non-microwave (SB) treatment. It was stated that change in the dielectric properties of the starch solution under microwave irradiation is more pronounced compared with solid powder starch due to change in the polarization mechanism of starch. The dielectric properties of starch show the response of starch to microwave heating which is related to the microstructural changes of starch during microwave treatments. Due to the polarization effect of microwave radiation, generally, the microwave-treated samples improved the drying behavior of green almonds in comparison with non-microwave (SB) samples. However, after blanching, the drying condition also influences the drying characteristics of the sample. Therefore, showing the same drying time at 110°C can be related to the high drying temperature of 110°C which can produce surface hardening due to rapid drying at high temperatures. Therefore, the change in the microstructure of both microwave-starch and non-microwave starch blanched samples is more predominate mechanism in the controlling of drying operation than a microwave or non-microwave pre-treatment.

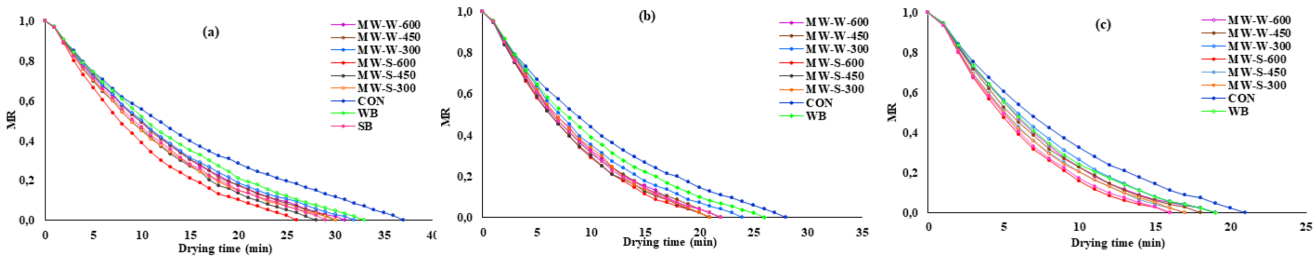

Figure 1. Change of moisture ratio during drying (a) 70°C (b) 90°C (c)110°C

Furthermore, as drying progressed, continuous decreases in the drying rate were observed (Figure 2). Generally, the drying start at a falling rate period which demonstrated that diffusion is a predominant mechanism in water transfer from the interior to the surface of the sample. The high water content at the beginning of drying produces a large moisture gradient and driving force. The drying rate of MW-S-600 and MW-W-600 samples in all temperatures, and MW-S-450 and MW-S-300 samples dried at 90 and 110 °C were started from a high level which can be related to the positive effect of high power microwave radiation on the structural change of samples cell wall which makes the facility in the removal of water from green almond. Furthermore, the drying rate of SB samples at all temperatures started from a higher level than CON and WB samples which demonstrated that blanching in the starch solution can improve the drying behavior of green almonds. However, moisture content gradually decreases during drying which can decrease the driving force and moisture gradient, which caused a reduction in the drying rate. Improving the drying rate of blanched samples is related to two mechanisms: 1) removing air from the intracellular of green almonds, and 2) enhancing the permeability of the cell wall. These outcomes are in agreement with other studies (Tepe and Tepe, 2020; Kian-Pour et al. 2022).

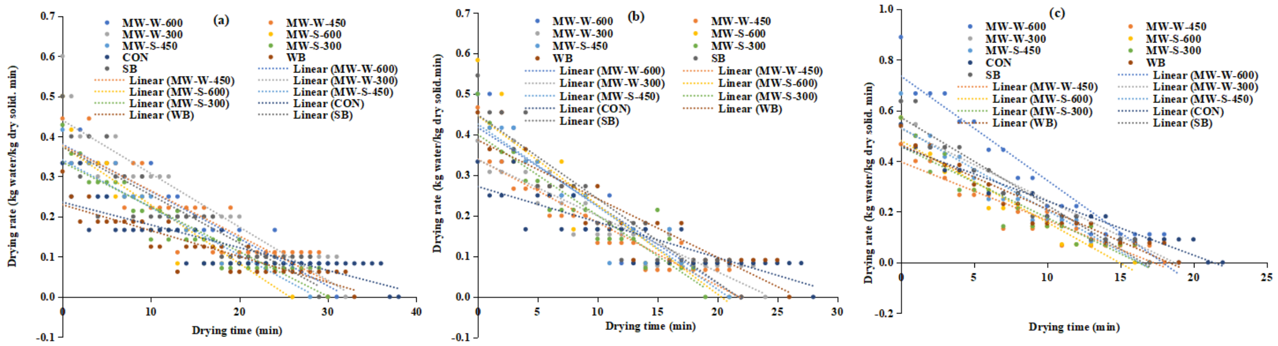

Figure 2. Drying rate vs drying time (a)70°C (b) 90°C (c)110°C

The moisture diffusion of samples ranged from 2.238×10^{-9} to 6.434×10^{-9} m^2 /s (Table 1) which was in the general range for food products of 10^{-12} to 10^{-8} m^2/s (Dadali et al. 2007). In each temperature, all blanching pretreatment significantly ($p<0.05$) increased *Deff* values, representing the pretreatments improved drying rate of green almonds. Cell structural modification due to blanching influenced the diffusion coefficient. Generally, as microwave power increased, the *Deff* increased. Maximum increases in the *Deff* (50.75%) in comparison with control samples was observed at MW-S-600-110 samples while minimum increases in *Deff* values in each temperature, was observed at water-blanched sample. The highest *Deff* values were3.502×10^{-9},4.643×10^{-9} and 6.434×10^{-9} m^2/s for samples dried at 70, 90, and 110 °C, respectively, which belonged to the MW-S-600 samples. It can be related to the effect of microwave radiation on the rapid heating of samples due to the rotation and movement of polar molecules and ions. Furthermore, the samples undergoing microwave treatment may expose microstructural change which can facilitate the removal of moisture at the drying step. Our results revealed that the use of the starch solution as the blanching medium was more efficient in the improvement of *Deff* with the use of only water and the samples blanched in starch solutions had higher Deff than water-blanched samples in all drying temperatures (Table 1). Besides, MW-S samples showed higher Deff in comparison with MW-W samples in all temperatures which can be explained by the structural change, water absorption, and gelatinization of starch which influence the behavior of the sample during drying. Also, the use of a high drying temperature (110°C) with the acceleration of the drying process caused maximum moisture transfer from inside to the surface of samples (MW-S-600-110) which increased *Deff*. Dipolar and ionic mechanisms in the microwave treatment change the microwave energy to heat (Chandrasekaran et al. 2013; Guzik et al. 2021) and due to internal heating, it achieves high heating rates which can be the main factor to increase *Deff* of samples. Also, the affinity of starch to swelling and absorption of water during microwave-starch blanching may be other factors that affect the *Deff*. These outcomes are in consistency with other studies. Wang et al. (2017) blanched red bell pepper in a microwave and the results revealed that as microwave power increased *Deff* increased. Kian-Pour et al. (2022) reported that starch-blanching of celery chips significantly increased the *Deff*. The results of this study showed that microwave-starch blanching of samples can significantly modify the drying characteristics of green almonds.

Table 1. Drying characteristics of pretreated green almond

Sample	Pre-treatment step			Drying Step			
	Code	Solution of water or 0.5%w/w starch	Microwave power (W)	Drying temperature (°C)	Diffusion coefficient Deff * $10^{-9} m^2/s$ ± SD	Change in Deff (%)	Change in drying time (%)
A1-70	MW-W-600-70	Water	600	70	3.106 ± 0.009^{cd}	+ 38.78	- 16.21
A2-70	MW-W-450-70	Water	450		3.015 ± 0.0402^{cd}	+ 32.24	-18.92
A3-70	MW-W-300-70	Water	300		2.955 ± 0.002^{c}	+ 32.04	-13.51
B1-70	MW-S-600-70	Starch	600		3.502 ± 0.071^{f}	+ 56.69	-29.73
B2-70	MW-S-450-70	Starch	450		3.361 ± 0.009^{e}	+ 50.18	-24.32
B3-70	MW-S-300-70	Starch	300		3.282 ± 0.075^{ef}	+ 46.65	-18.92
C-70	CON-70	-	-		2.238 ± 0.0287^{a}	0	0
D-70	WB-70	Water	-		2.778 ± 0.0039^{b}	+ 24.13%	-10.81
E-70	SB-70	Starch	-		3.128 ± 0.0134^{d}	+ 39.77%	-21.62
A1-90	MW-W-600-90	Water	600	90	4.331 ± 0.027^{d}	+ 37.75	-21.43
A2-90	MW-W-450-90	Water	450		4.282 ± 0.019^{d}	+ 36.20	-21.43
A3-90	MW-W-300-90	Water	300		4.038 ± 0.134^{c}	+ 28.43	-14.28
B1-90	MW-S-600-90	Starch	600		4.643 ± 0.055^{f}	+ 47.68	-25.00
B2-90	MW-S-450-90	Starch	450		4.536 ± 0.027^{ef}	+ 44.27	-25.00
B3-90	MW-S-300-90	Starch	300		4.447 ± 0.023^{def}	+ 41.44	-25.00
C-90	CON-90	-	-		3.144 ± 0.005^{a}	0	0
D-90	WB-90	Water	-		3.598 ± 0.019^{b}	+ 14.44	-7.14
E-90	SB-90	Starch	-		4.369 ± 0.019^{de}	+ 38.96	-21.43
A1-110	MW-W-600-110	Water	600	110	5.572 ± 0.084^{bc}	+ 30.55	-9.52
A2-110	MW-W-450-110	Water	450		5.568 ± 0.025^{bc}	+ 30.46	-14.29
A3-110	MW-W-300-110	Water	300		5.291 ± 0.077^{b}	+ 23.96	-9.52
B1-110	MW-S-600-110	Starch	600		6.434 ± 0.009^{d}	+ 50.75	-23.81
B2-110	MW-S-450-110	Starch	450		5.854 ± 0.011^{c}	+ 37.16	-19.05
B3-110	MW-S-300-10	Starch	300		5.751 ± 0.069^{c}	+ 34.75	-19.05
C-110	CON-110	-	-		4.268 ± 0.203^{a}	0	0
D-110	WB-110	Water	-		5.265 ± 0.002^{b}	+ 23.36	-9.52
E-110	SB-110	Starch	-		6.236 ± 0.089^{d}	+ 46.11	-19.05

Different letters at the same temperature demonstrate significant differences at p<0.05. (+): Increases. (-): Decreases

The activation energy was shown in Table 2. It ranged from 12.32 to 15.39 kJ/ kg mol which was in the general range of E_a for food products (12.7-110 kJ/mol) (Kian-Pour and Karatas, 2019). CON, WB and SB samples showed higher *Ea* in comparison with microwave-water and microwave-starch-blanched samples which means that *Deff* of CON, WB, and SB samples showed higher sensitivity to the drying temperature. The outcomes were in agreement with other studies about the drying of food materials such as green peppers (Kholmanskiy et al. 2013), and olive pomace (Ahmad-Qasem et al. 2013).

Table 2. Activation energy of green almond sample

Sample	A1	A2	A3	B1	B2	B3	C	D	E
Code	MW-W-600	MW-W-450	MW-W-300	MW-S-600	MW-S-450	MW-S-300	CON	WB	SB
E (kJ/ kg mol)	12.94	13.58	12.94	13.60	12.32	12.45	14.35	14.37	15.39

Mathematical modeling

Mathematical modeling was performed by using semi-theoretical and empirical models and model parameters are detailed in Table 3. The R^2, *RMSE*, and X^2 values are in good fit ranging from 0.9775 to 0.9997, 0.00542 to 0.04790, and 0.000031 to 0.002600, respectively. For all samples at the given drying temperatures, the Midilli & Kucuk model with the highest values of R^2 and lowest values of *RMSE* and X^2 show the best model for describing the drying process of green almonds. The best fitting of experimental data to the Midilli &Kucuk model may be attributed to the existence of both an exponential and a linear term in the model to describe the moisture ratio (Ertekin and Firat, 2017). The same results about the suitability of the Midilli &Kucuk model for apple (Kian-Pour and Karatas, 2019), banana (Macedo et al. 2020; Taskin et al. 2022), yam slice (Sahoo et al. 2022), and celery root (Kian-Pour et al. 2022) were reported.

Table 3. Model parameters obtained by nonlinear regression analysis and statistical criteria for selecting ideal model

	Code	Temperature(°C)					R^2	RMSE	X^2
A1	Wang &Singh	70	a= -0.054	b= 0.001			0.9942	0.02236	0.000533
		90	a= -0.073	b= 0.001			0.9885	0.03297	0.001190
		110	a= -0.088	b= 0.002			0.9830	0.04123	0.001889
	Midilli &Kucuk	70	a= 1.058	b= -0.002	k=0.044	n=1.167	0.9997	0.00559	0.000036
		90	a= 1.080	b= -0.003	k=0.059	n=1.221	0.9995	0.00659	0.000053
		110	a= 1.068	b= -0.001	k=0.055	n=1.378	0.9995	0.00707	0.000063
A2	Wang &Singh	70	a= -0.053	b= 0.001			0.9933	0.02476	0.000655
		90	a= -0.076	b= 0.001			0,9882	0.03297	0.001190
		110	a= -0.090	b= 0.002			0.9824	0.04168	0.001941
	Midilli &Kucuk	70	a= 1.058	b= -0.002	k=0.041	n=1.191	0.9996	0.00568	0.000037
		90	a= 1.097	b= -0.003	k=0.071	n=1.162	0.9991	0.00933	0.000105
		110	a= 1.090	b= -0.002	k=0.067	n=1.295	0.9995	0.00725	0.000067
A3	Wang &Singh	70	a= -0.053	b= 0.001			0.9949	0.02132	0.000484
		90	a= -0.070	b= 0.001			0.9904	0.02966	0.000957
		110	a= -0.083	b= 0.002			0.9861	0.03674	0.001500
	Midilli &Kucuk	70	a= 1.064	b= -0.003	k=0.048	n=1.121	0.9997	0.00550	0.000034
		90	a= 1.082	b= -0.002	k=0.062	n=1.180	0.9996	0.00632	0.000048
		110	a= 1.085	b= -0.003	k=0.065	n=1.248	0.9995	0.00707	0.000063
B1	Wang &Singh	70	a= -0.066	b= 0.001			0.9891	0.03162	0.001080
		90	a= -0.079	b= 0.002			0.9871	0.03503	0.001350
		110	a= -0.100	b= 0.002			0.9775	0.04790	0.002600
	Midilli &Kucuk	70	a= 1.079	b= -0.002	k=0.054	n=1.203	0.9992	0.00861	0.000087
		90	a= 1.087	b= -0.002	k=0.065	n=1.230	0.9995	0.00674	0.000056
		110	a= -1.089	b= -0.002	k=0.068	n=1.371	0.9994	0.00767	0.000077
B2	Wang &Singh	70	a= -0.058	b= 0.001			0.9925	0.02626	0.000741
		90	a= -0.079	b= 0.002			0.9883	0.03303	0.001200
		110	a= -0.093	b= 0.002			0.9825	0.04150	0.001938
	Midilli &Kucuk	70	a= 1.067	b= -0.003	k=0.048	n=1.172	0.9996	0.00587	0.000040
		90	a= 1.090	b= -0.003	k=0.069	n=1.191	0.9995	0.00674	0.000056
		110	a= 1.101	b= -0.003	k=0.077	n=1.257	0.9994	0.00745	0.000071
B3	Wang &Singh	70	a= -0.058	b= 0.001			0.9932	0.02517	0.000679
		90	a= -0.073	b= 0.001			0.9890	0.02724	0.000793
		110	a= -0.095	b= 0.002			0.9817	0.04216	0.002000
	Midilli &Kucuk	70	a= 1.070	b= -0.002	k=0.051	n=1.156	0.9996	0.00577	0.000038
		90	a= 1.078	b= -0.004	k=0.059	n=1.210	0.9990	0.00803	0.000074
		110	a= 1.108	b= -0.003	k=0.082	n=1.241	0.9989	0.01054	0.000143
C	Wang &Singh	70	a= -0.045	b= 0.001			0.9958	0.01826	0.000353
		90	a= -0.060	b= 0.001			0.9955	0.01948	0.000407
		110	a= -0.074	b= 0.001			0.9906	0.02939	0.000950
	Midilli &Kucuk	70	a= 1.094	b= -0.004	k=0.069	n=0.910	0.9997	0.00527	0.000031
		90	a= 1.091	b= -0.004	k=0.074	n=1.003	0.9996	0.00587	0.000040
		110	a= 1.093	b= -0.004	k=0.073	n=1.126	0.9995	0.00674	0.000056
D	Wang &Singh	70	a= -0.050	b= 0.001			0.9956	0.01955	0.000406
		90	a= -0.066	b= 0.001			0.9925	0.02582	0.000720
		110	a= -0.085	b= 0.002			0.9837	0.04000	0.001778
	Midilli &Kucuk	70	a= 1.063	b= -0.003	k=0.046	n=1.103	0.9997	0.00542	0.000033
		90	a= 1.095	b= -0.003	k=0.071	n=1.079	0.9996	0.00609	0.000043
		110	a= 1.085	b= -0.002	k=0.063	n=1.291	0.9995	0.00707	0.000063
E	Wang &Singh	70	a= -0.056	b= 0.001			0.9937	0.02380	0.000607
		90	a= -0.076	b= 0.001			0.9884	0.03297	0.001190
		110	a= -0.089	b= 0.002			0.9808	0.04410	0.002188
	Midilli &Kucuk	70	a= 1.064	b= -0.003	k=0.048	n=1.156	0.9996	0.00577	0.000038
		90	a= 1.085	b= -0.002	k=0.064	n=1.208	0.9995	0.00659	0.000053
		110	a= 1.081	b= -0.003	k=0.061	n=1.346	0.9995	0.00745	0.000071

Transport phenomena

Convective drying of food material is a complex unit operation in which simultaneous mass, heat, and momentum transfer occur (Kian-Pour and Karatas, 2019). The results of transport phenomena are presented in Table 4. As excepted with increase the drying temperature the F_D and h_{heat} increased while h_{mass} slightly decreased. Due to the thin layer of water on the surface, there is no internal or external heat transfer resistance during the constant rate period, and external heat transfer controls the drying process. However, internal mass transfer controls the drying during the falling rate period because moisture is moving from the inside to the surface (Kumar et al. 2022). The decreases in the h_{mass} may be related to the non-homogeneous structure of green almond because the outer surface has a more rigid structure compared with an inner surface which can affect transport phenomena. Our outcomes were in agreement with other studies (Kian-Pour and Karatas, 2019; Kumar et al. 2022).

Table 4. Transport phenomena in the drying process of green almond

Temperature (°C)	Reynolds number	$F_D \times 10^{-6}$ (N)	h_{heat} (W/m^2 K)	h_{mass} (m/s)
70	379.6	3.965	66.29	0.03428
90	380.1	3.969	66.38	0.03418
110	380.7	3.972	66.47	0.03410

Thermophysical properties

The thermophysical properties of the samples were shown in Table 5. Thermal conductivity, specific heat, and density of samples varied from 0.544-0.586 (W/m K), 3643.85-3900.00 (J/kg K), and 835.80-899.44 (kg/m^3), respectively.

Table 5. Thermophysical properties of green almond

Sample	Code	Solution of water or 0.5%w/w starch	Microwave power (W)	Drying temperature(°C)	Thermal conductivity *k* (W/m K)	Specific heat *Cp* (J/kg K)	Density *ρ* (Kg/ m^3)
A1-70	MW-W-600-70	Water	600	70	0.577	3846.77	879.21
A2-70	MW-W-450-70	Water	450		0.581	3868.77	886.85
A3-70	MW-W-300-70	Water	300		0.586	3900.00	899.44
B1-70	MW-S-600-70	Starch	600		0.563	3761.03	855.67
B2-70	MW-S-450-70	Starch	450		0.566	3778.84	860.33
B3-70	MW-S-300-70	Starch	300		0.566	3778.01	860.13
C-70	CON-70	-	-		0.563	3761.03	856.29
D-70	WB-70	Water	-		0.550	3683.84	841.80
E-70	SB-70	Starch	-		0.573	3823.15	871.93
A1-90	MW-W-600-90	Water	600	90	0.562	3754.80	854.94
A2-90	MW-W-450-90	Water	450		0.546	3658.85	837.95
A3-90	MW-W-300-90	Water	300		0.557	3721.96	848.40
B1-90	MW-S-600-90	Starch	600		0.562	3754.80	854.94
B2-90	MW-S-450-90	Starch	450		0.566	3776.22	859.71
B3-90	MW-S-300-90	Starch	300		0.554	3703.68	845.12
C-90	CON-90	-	-		0.558	3728.06	849.55
D-90	WB-90	Water	-		0.571	3805.71	867.07
E-90	SB-90	Starch	-		0.567	3782.44	861.18
A1-110	MW-W-600-110	Water	600	110	0.585	3891.65	895.84
A2-110	MW-W-450-110	Water	450		0.544	3643.85	835.80
A3-110	MW-W-300-110	Water	300		0.569	3794.39	864.13
B1-110	MW-S-600-110	Starch	600		0.549	3675.59	840.49
B2-110	MW-S-450-110	Starch	450		0.562	3754.80	854.94
B3-110	MW-S-300-10	Starch	300		0.567	3782.44	861.18
C-110	CON-110	-	-		0.569	3794.39	864.13
D-110	WB-110	Water	-		0.559	3735.00	850.89
E-110	SB-110	Starch	-		0.561	3748.40	853.60

The maximum thermophysical values were observed at MW-W-300, while the minimum was belonged to the MW-W-450 sample, which can be related to the amount of moisture content (Kian-Pour et al. 2022). The results revealed that the moisture content of the sample pretreated by microwave water-blanching at 300 W increased which can related to the absorption of higher amount of water during blanching at low power of microwave. While increase the power of microwave to 450 W decreased the moisture content of sample. Our results show good agreement with another study (Kian-Pour et al. 2022).

CONCLUSION

In this study, different blanching methods were used to modify the drying properties of green almonds. Various blanching pretreatment of green almonds had a significant impact on the drying times and diffusion coefficients (*Deff*) compared with control samples. Microwave blanching in starch solution significantly increased the *Deff* and decreased the dehydration time of samples. Also, as microwave power increased, a better improvement in the drying kinetics of the sample was observed. According to the experimental data, maximum decreases in the drying time were observed in the samples blanched in starch solution by the microwave at 600 W. Mathematical modeling of experimental results revealed that Midilli &Kucuk model is the suitable equation for predicting the drying process of green almond. Increases in the drying time increased the heat transfer coefficient. The data on transport phenomena and thermophysical characteristics can be used in simulation of drying an industrial scale. The best blanching and drying conditions for the achievement of the highest *Deff* and lowest drying time was blanching in 0.5% w/w native corn starch solution in the microwave with 600 W followed by drying at the lowest temperature (70°C) which can be used at the industrial scale.

Acknowledgement

Thanks to Prof. Dr. Ersin ARSLAN for his consultancy during the writing of the article.

Conflict of Interest

The author declared that there is no conflict of interest.

REFERENCES

Ahmad-Qasem MH, Barrajon-Catalan E, Micol V, Carcel JA, Garcia-Perez JV, 2013. Influence of air temperature on drying kinetics and antioxidant potential of olive pomace. Journal of Food Engineering, 119: 516-524.

Association of Official Analytical Chemists, 1990. Official Method of Analysis. 19th edition, Maryland.

Çengel YA, 2007. Heat & Mass Transfer: A Practical Approach. 2nd edition. India.

Chandrasekaran S, Ramanathan S, Basak T, 2013. Microwave food processing—A review. Food Research International, 52: 243–261.

Dadali G, Demirhan E, Özbek B, 2007. Microwave heat treatment of spinach: drying kinetics and effective moisture diffusivity. Drying Technology, 25: 1703-1712.

Ertekin C, Firat MZ, 2017. A comprehensive review of thin-layer drying models used in agricultural products. Critical Reviews in Food Science and Nutrition, 57: 701-717.

Guzik P, Kulawik P, Zając M, Migdał W, 2021. Microwave applications in the food industry: an overview of recent developments. Critical Reviews in Food Science and Nutrition, 1-20.

Islam MZ, Saha T, Monalisa K, Hoque MM, 2019. Effect of starch edible coating on drying characteristics and antioxidant properties of papaya. Journal of Food Measurement and Characterization, 13: 2951–2960.

Kholmanskiy A, Tilov A, Sorokina E, 2013. Drying kinetics of plant products: Dependence on chemical composition. Journal of Food Engineering, 117: 378-382.

Kian-Pour N, Akdeniz E, Toker O, 2022. Influence of coating-blanching in starch solutions, on the drying kinetics, transport properties, quality parameters, and microstructure of celery root chips. LWT - Food Science and Technology, 160:113262.

Kian-Pour N, Karatas S, 2019. Impact of different geometric shapes on drying kinetics and textural characteristics of apples at temperatures above 100 °C. Heat and Mass Transfer, 55: 3721–3732.

Kumar A, Kandasamy P, Chakraborty I, Hangshing L, 2022. Analysis of energy consumption, heat and mass transfer, drying kinetics and effective moisture diffusivity during foam-mat drying of mango in a convective hot-air dryer. Biyosystems Engineering, 219: 85-102.

Latorre ME, Plá MFdE, Rojas AM, Gerschenson LN, 2013. Blanching of red beet (Beta vulgaris L. var. conditiva) root. Effect of hot water or microwave radiation on cell wall characteristics. LWT - Food Science and Technology, 50: 193-203.

Lavasani HS, Motie JB, 2022. Evaluation of some engineering properties of green almond for mechanical harvesting. Agriculture, Environment & Society, 2: 31-39.

Macedo LL, Vimercati WC, Araújo CdS, Saraiva SH, Teixeira, LJQ, 2020. Effect of drying air temperature on drying kinetics and physicochemical characteristics of dried banana. Journal of Food Processing Engineering, 43: e13451.

Mujumdar AS, 2006. Handbook of Industrial Drying. 3rd edition. CRC Press, Taylor and Francis Group,LLC.

Murathan ZT, Kaya A, Erbil N, Arslan M, Dıraz E, Karaman Ş, 2020. Comparison of Bioactive Components, Antimicrobial and Antimutagenic Features of Organically and Conventionally Grown Almond Hulls. Erwerbs-Obstbau, 62: 463–472.

Pasban A, Sadrnia H, Mohebbi M, Shahidi SA, 2017. Spectral method for simulating 3D heat and mass transfer during drying of apple slices. Journal of Food Engineering, 212: 201-212.

Polat A, Izli N, 2022. Determination of drying kinetics and quality parameters for drying apricot cubes with electrohydrodynamic, hot air and combined electrohydrodynamic-hot air drying methods. Drying Technology, 40: 527-542.

Sahoo M, Titikshya S, Aradwad P, Kumar V, Naik SN, 2022. Study of the drying behaviour and color kinetics of convective drying of yam (Dioscorea hispida) slices. Industrial Crops & Products, 176: 114258.

Souza AUd, Correa JLG, Tanikawa DH, Abrahao FR, Junqueira JRdJ, Jimenez EC, 2022. Hybrid microwave-hot air drying of the osmotically treated carrots. LWT - Food Science and Technology, 156: 113046.

Taskin O, Polat A, B. E. & Izli, N., 2022. Energy and exergy analysis, drying kinetics, modeling, microstructure and thermal properties of convective-dried banana slices. Journal of Thermal Analysis and Calorimetry, 147: 2343–2351.

Tepe TK, Tepe B, 2020. The comparison of drying and rehydration characteristics of intermittent-microwave and hot-air dried-apple slices. Heat and Mass Transfer, 56: 3047–3057.

Wang J, Yang X-H, Mujumdar AS, Wang, D, Zhao JH, Fang X-M, Zhang Q, Xie L, Gao Z-J, Xiao H-W, 2017. Effects of various blanching methods on weight loss, enzymes inactivation, phytochemical contents, antioxidant capacity, ultrastructure and drying kinetics of red bell pepper (Capsicum annuum L.). LWT - Food Science and Technology, 77: 337-347.

Wang Q, Li S, Han X, Ni Y, Zhao D, Hao J, 2019. Quality evaluation and drying kinetics of shitake mushrooms dried by hot air, infrared and intermittent microwave–assisted drying methods. LWT - Food Science and Technology, 107: 236–242.