J. BIOL. ENVIRON. SCI.,
2019, 13(37), 19-30

Original Research Article

Mathematical Modeling of Ultrasound Pretreated Carrot Slices

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Received: 07.03.2019; Accepted: 20.03.2019; Published Online: 25.05.2019

ABSTRACT

In this study, the effects of ultrasound pretreatment, air drying temperature and slice thickness on the drying kinetics of carrot were analyzed. Ultrasound pretreatments were applied to carrot samples of different slice thicknesses with for 0 (control), 20 and 40 minutes. All products were dried in the convection oven with constant air speed 1 m s^{-1}. The drying times varied from 260 to 110 minutes depending on the varying slice thicknesses, temperatures and the applied ultrasound pretreatments. In order to determine a suitable thin layer model for drying applications, 10 different mathematical models were fitted to the experimental results. The model was selected as the best model with the highest value of R^2 (Regression coefficient), lowest RMSE (Root mean square error) and χ^2 (Chi-square). As a result of the statistical evaluation, it was determined that the Midilli et al. model is the most suitable model for explaining the convective drying characteristics of carrot according to other models. Consequently, ultrasound pretreatment can be used as a favorable method for reducing the drying time of the carrots in the convective process.

Keywords: Carrot, Drying, Modeling, Ultrasound Pretreatment

INTRODUCTION

Carrot, is named *Daucus carota* L. in Latin, is one of the most important root vegetables grown in the world. According to FAO data, carrot production in the world is 42.831.958 tons in 2017 and China is the leading country in this production. Turkey ranking of world production of 571.301 tons is located at ninth (FAO 2019). Carrot is an important product with its pleasant taste, high nutritional value, antioxidant, anticancer and calmative properties. In addition to having the highest carotenoid content among food products, it is an important source of β-carotene, which has been reported to prevent cancer. Carrot also in holds vitamin A, C, vitamin B_6, cholesterol lowering pectin, folic acid, thiamine, magnesium and potassium (Barroca et al. 2017). The consumption of carrot and its products have been increased due to the fact that they are considered to have an important source of antioxidants, natural nutrients and health-improving properties. In recent years, the processing of carrot products (freshly cut, dried, juice, powder and snacks) has been investigated comprehensively. As consumers are conscious of a healthy and comfortable life, they prefer natural, low-fat, sodium-less, fiber, vitamin-rich and health-promoting products (Peng et al. 2018).

Drying used in many food industries is one of the oldest food preservation processes. The purpose of drying is to draw the water in the product to the point where the degradation reactions and microbial spoilage are substantially reduced (Chen et al. 2017). Hot air drying is the most widely used method to decrease the moisture content of agricultural products. However, this method includes contamination problems, long-term drying time, low energy efficiency, high energy consumption and high costs which are undesirable for the food industry (Darvishi et al. 2016). Quality losses occur in products exposed to hot air for a long time. To prevent from these losses, pretreatment is used in the food industry. Pretreatment before drying on some agricultural products prevented the occurrence of some undesirable conditions. The ultrasound technology is used in drying processes in two different ways as ultrasound-assisted drying or as a pre-treatment. The effects of ultrasound can be different according to the physical condition of the system. In ultrasound assisted drying, the mechanical waves generated in the air and the product move through the product to affect the structure of the product and thus reduce the external resistance on the product surface and increase the mass transport in the fluid. On the other hand, a different way is followed in the use of ultrasound as a pretreatment. The product to be dried is immersed in a liquid medium with distilled water or osmotic solution and ultrasound are applied at specified times. The products are then dried by suitable drying methods. The ultrasonication process creates micro channels in the product during the pretreatment application and it provides to decrease the internal resistance of the product

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structure (Ricce et al. 2016). In literature, there are ample studies that are used the ultrasonic bath as a pretreatment (Çakmak et al. 2016 and Cao et al. 2018). This research aimed to examine the effects of ultrasound pretreatment, drying temperature and different slice thicknesses on drying behavior of samples and to select the best drying model for carrots.

MATERIALS AND METHODS

Carrot samples were used in this study were bought from in local grocery stores of Bursa, Turkey. Fresh products were stored in the refrigerator (+4 °C) until drying experiment. Mature and healthy carrots were peeled, sliced 2 and 4 mm with using dicer (Börner, Wingene, Belgium) and dried in this form (Sonmete et al. 2017). The initial moisture content of carrot was determined as an 8.75 d.b. by using the forced-air convective oven (M3025P, Electromag, Turkey) set to work 70 °C for a duration of 24 hours.

Ultrasonic pretreatment was applied to carrot slices at room temperature by using the ultrasound bath (25-KHz, 300 W output power, Intersonic, Istanbul/Turkey). Carrot slices were directly put in metal mesh and submitted to ultrasonic waves for 0, 20 and 40 minutes. The ratio of fruit and distilled water was 1:4 (w/w). The unpretreated samples were subjected to drying after immersion in water. Pretreated samples from each group drained with filter paper to remove excess water from the surface. Then the products were submitted to the modified laboratory convective-microwave oven (Whirlpool AMW 545, Italy). The drying process was carried out in the oven with dimensions of 210 x 450 x 420 mm and a rotary glass plate with a diameter of 400 mm at the located base. The loss of moisture was recorded by taking the carrot sample from the oven at 10-min intervals and weighing it on a digital balance (Shimadzu, Japan) that has a precision level of 0.01 g; the sample was returned to the oven within 20 s for continued drying (Kayisoglu and Ertekin 2011). The oven was set convective mode at 60 and 70 °C air temperatures in return and at 1 m s^{-1} air velocity. Each drying application was performed triplicate.

Data obtained from experiments were fitted 10 thin layer drying model. The moisture ratio (*MR*) and drying rate (*DR*) are defined as follows (Kaveh et al. 2017):

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

In the preceding formula M_o corresponds the moisture content level at the beginning, M_t corresponds the moisture content level at a given time, M_e corresponds the equilibrium level of moisture content, M_{t+dt} is the moisture content at $t+dt$ and t is the drying time (min). After analyzing the formula, the values of M_e are rather small concerning M_t or M_o. Ultimately as proposed by some of the researchers, the moisture ratio formula was shortened in this way:

$$MR = \frac{M_t}{M_o} \quad (3)$$

The study was realized by the aid of randomized plots of factorial design. In the course of calculation of the inspected items, three replicates were utilized. While interpreting the outcomes, JMP (SAS Institute Inc., USA) and MATLAB (MathWorks Inc., MA) software technologies were employed. Significance levels of mean differences were tested and the least significant difference (LSD) test resulted in a 5% significance level. It has been determined that the most convenient model that expresses the drying attributes of lime samples in a thin layer is the one that has lowest reduced chi-squared (χ^2) value, lowest root mean square error $(RMSE)$ value and the highest coefficient of determination (R^2). The mentioned statistical values are described as below:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})}{N}} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N - z} \tag{5}$$

Here, $MR_{\exp,i}$, means the experimental *MR*, $MR_{pre,i}$, means the predicted *MR*, N means the observation number and *z* stands for the number of constants.

RESULTS AND DISCUSSION

Influence of applied different ultrasound times (0, 20 and 40 minutes), drying temperature and slice thickness on drying rate versus moisture content and moisture content with drying time are shown in Figure 1 and 2. As it is seen in Figure 1; decreasing slice thickness, increasing drying temperature and ultrasound pretreatment time decreased the drying time of the product. The longest period during drying was observed control samples, while the least time was obtained in US40 applications in each drying experiments (constant temperature and slice thickness). The longest drying time was found 60 °C-4 mm-control experiment with a 260 min. Specific to this experiment, applied US20 and US40 pretreatments decreased time by 3.85% and 7.69%, respectively. The effect of the ultrasound pretreatment on the drying time was the highest in the group of 70 °C-2 mm applications. Drying rates were found to be of the same character in general. In the initial stages of drying, the moisture was removed quickly and then the drying rate decreased with the increase in drying time. It was observed that drying rates were greater in dried at a high temperature and low slice thicknesses of carrot. Ultrasound pretreatment had no significant impact on drying rate of samples. A similar observation has been seen by Horuz et al. (2017) with tomato drying. It was also experienced that the 120W microwave power and 40 minutes ultrasound treatment applied to the product reduced the drying time by 7.38% compared to the unpretreated (control) sample at the same microwave power level. Nowacka et al. (2012) applied an ultrasound pretreatment to the apple cubes and dried samples at a temperature of 70 °C and an air velocity of 1.5 m s^{-1}. They found that the drying time of ultrasound-treated products decreased by 31% compared to the untreated products. These findings are similar to our study.

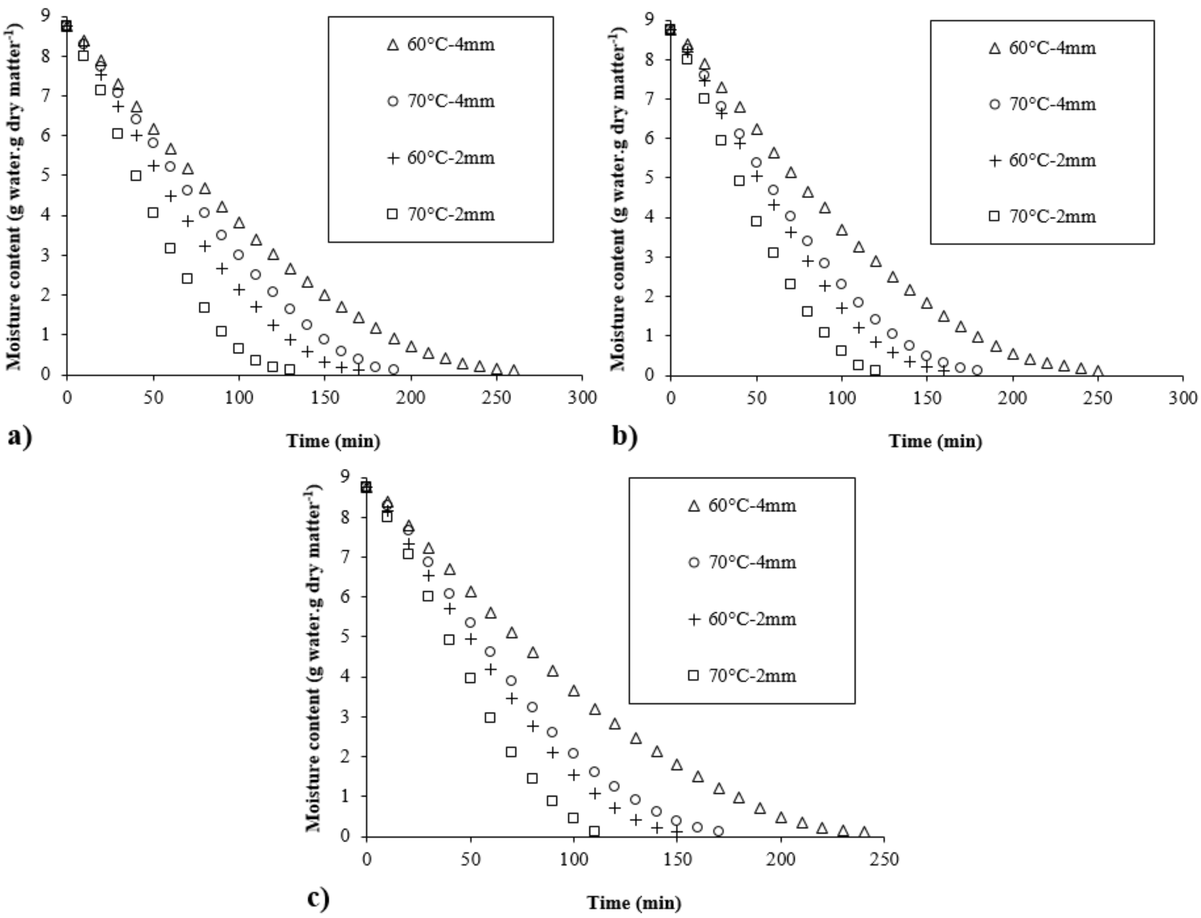

Figure 1. Drying curves for convective dried carrot slices with pretreatment by (a) Control; (b) US 20; and (c) US 40.

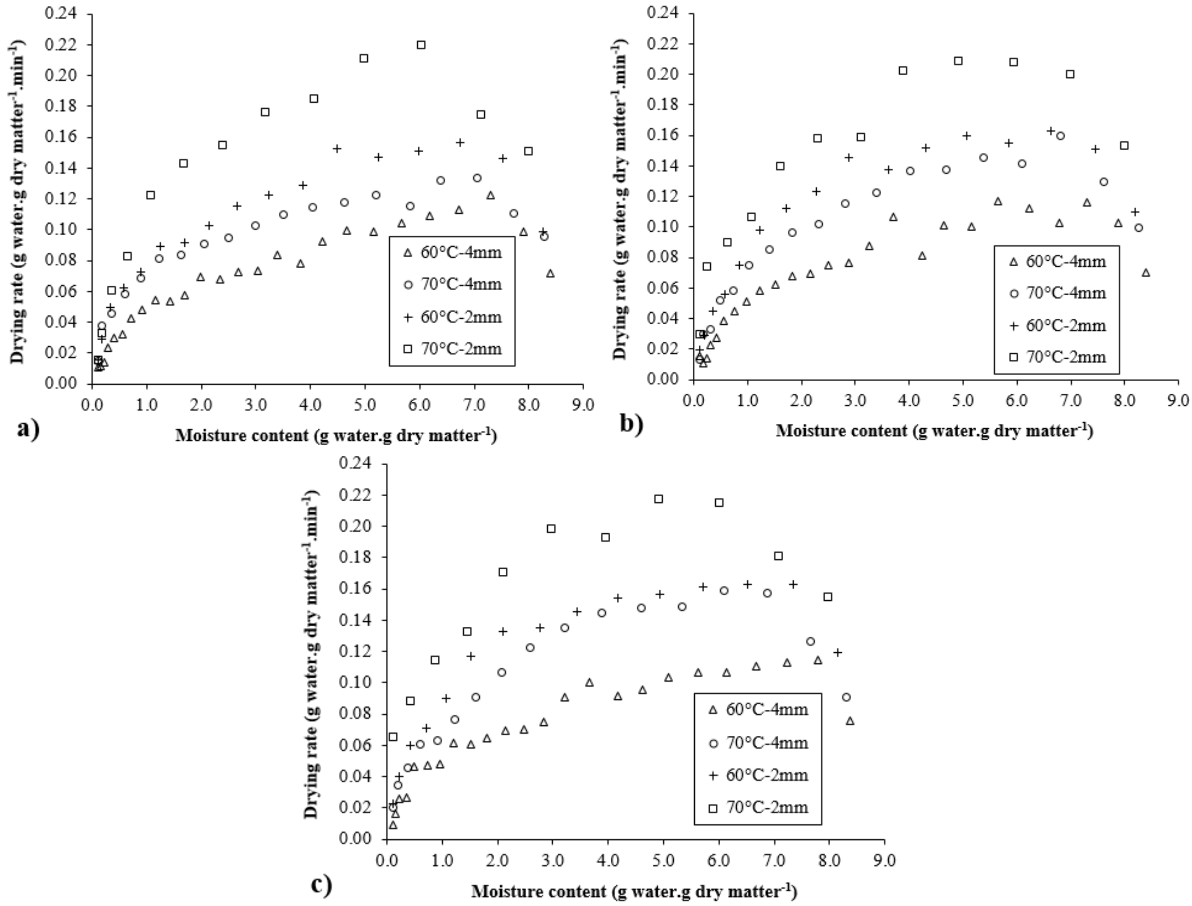

Figure 2. The drying rate changes of carrots with pretreatment by (a) Control; (b) US 20; and (c) US 40.

Table 1 shows ten thin layer models used by Demiray and Tulek (2014), Saxena and Dash (2015), Murthy and Manohar (2014), Mota et al. (2010), Bhattacharya et al. (2015), Evin (2011), Arumuganathan et al. (2009), Taskin et al. (2017), Faal et al. (2015) and Midilli et al. (2002) which were applied to experimental moisture rate with respect to drying times. The best model was selected based on the highest R^2 and the lowest χ^2 and RMSE values. The values obtained as a result of all statistical calculations are given in the Tables 2-4. The R^2, χ^2 and RMSE values ranged from 0.9058 to 0.9999, 0.00002908 to 0.01014310 and 0.0041 to 0.1067, respectively. As examining the tables, it was observed that the Midilli model was best suited to the experimental moisture ratio than the other models for all cases because R^2, χ^2 and RMSE values were between 0.9991-0.9999, 0.00002038-0.00009932 and 0.0041-0.0102, in return. Comparison of an appropriate model to experimental moisture ratios experimental and predicted moisture ratio and using the Midilli et al. model for carrot slices was shown in Figure 3 and 4, respectively. As it observed, experimental and predicted temporal profile was in good agreement. This proved that fittingness of Midilli et al. model defining the drying characteristics of carrot slices (Doymaz 2017). Kaveh et al. (2018) aimed to determinate the best model and to estimate the drying process of almond kernels with using 15 mathematical models. Similar to our result, they found that Midilli et al. was the best model to describe drying characteristic. Nowacka et al. (2012) also observed the simular findings to our result.

Table 1. Used drying models.

No	Name	Model	References
1	Henderson and Pabis	$MR = a\exp(-kt)$	Demiray and Tulek (2014)
2	Newton	$MR = \exp(-kt)$	Saxena and Dash (2015)
3	Page	$MR = \exp(-kt^{n})$	Murthy and Manohar (2014)
4	Logarithmic	$MR = a\exp(-kt) + c$	Mota et al. (2010)
5	Two Term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Bhattacharya et al. (2015)
6	Two Term Exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Evin (2011)
7	Wang and Singh	$MR = 1 + at + bt^{2}$	Arumuganathan et al. (2009)
8	Diffusion Approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Taşkın et al. (2017)
9	Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Faal et al. (2015)
10	Midilli et al.	$MR = a\exp(-kt^{n}) + bt$	Midilli et al. (2002)

Table 2. The statistical results for drying of carrot at different conditions for pretreatment by US 0 (control).

No	60ºC-2mm				60ºC-4mm				70ºC-2mm				70ºC-4mm			
	Model coefficients	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**
1	a=1.109 k=0.01476	0.9643	0.0612	36.5185	a=1.105 k=0.01031	0.9737	0.0521	36.0550	a=1.106 k=0.02003	0.9578	0.0717	35.7712	a=1.112 k=0.0125	0.9598	0.0661	66.0655
2	k=0.01333	0.9516	0.0736	56.2552	k=0.00935	0.9619	0.0628	55.7710	k=0.01819	0.9472	0.0801	53.6611	k=0.01123	0.946	0.0766	78.5804
3	k=0.001356 n=1.518	0.9971	0.0181	2.8085	k=0.001231 n=1.423	0.9967	0.0185	1.5094	k=0.001636 n=1.585	0.9975	0.0173	0.5100	k=0.0009726 n=1.536	0.9949	0.0234	10.2447
4	a=1.494 k=0.007417 c=-0.4506	0.9957	0.0219	5.8591	a=1.35 k=0.006001 c=-0.3083	0.9972	0.0171	8.5241	a=1.464 k=0.01042 c=-0.417	0.9912	0.0328	10.4079	a=1.677 k=0.005285 c=-0.641	0.9971	0.0178	7.9318
5	a=-33.68 k_o=0.004427 b=34.61 k_1=0.004581	0.9658	0.0618	32.5829	a=-16.18 k_o=0.001612 b=17.08 k_1=0.001838	0.9731	0.0528	5.7625	a=0.5944 k_o=0.02005 b=0.5092 k_1=0.01992	0.9493	0.0785	3.3533	a=0.5559 k_o=0.01247 b=0.5517 k_1=0.01243	0.9548	0.0701	23.5053
6	a=0.00005247 k=253.9	0.9486	0.0758	57.4687	a=0.00006153 k=151.9	0.9604	0.0640	57.6468	a=0.0000603 k=301.9	0.9428	0.0834	56.3670	a=0.00007 k=160.4	0.9430	0.0787	85.1498
7	a=-0.00941 b=0.00002012	0.9960	0.0212	6.3707	a=-0.006743 b=0.00001103	0.9981	0.0138	8.3594	a=-0.01287 b=0.0000383	0.9928	0.0295	9.6667	a=-0.007752 b=0.0000125	0.9969	0.0185	7.6284
8	a=0.08977 k=7.641 b=0.001587	0.9097	0.1005	13.6481	a=0.1217 k=7.23 b=0.001138	0.9114	0.0957	10.8789	a=-16.91 k=0.03961 b=0.9433	0.9931	0.0289	2.7085	a=-21.87 k=0.02204 b=0.965	0.9867	0.03797	18.2005
9	a=14.07 k=0.02656 g=0.0285	0.9939	0.0261	31.8743	a=54.09 k=0.01833 g=0.01863	0.9948	0.0231	29.3644	a=-4.771 k=0.004097 g=0.005684	0.9889	0.0367	23.8672	a=-6.744 k=0.001805 g=0.002574	0.9955	0.0220	51.6499
10	a=0.9959 k=0.002121 n=1.384 b=-0.0004517	0.9997	0.0060	0.8480	a=0.997 k=0.002026 n=1.291 b=-0.0002912	0.9994	0.0080	0.6113	a=0.9882 k=0.001978 n=1.514 b=-0.0003601	0.9992	0.0102	0.2908	a=0.9955 k=0.001862 n=1.345 b=-0.0006375	0.9995	0.0074	3.8142

Table 3. The statistical results for drying of carrot at different conditions for pretreatment by US 20.

No	60ºC-2mm				60ºC-4mm				70ºC-2mm				70ºC-4mm			
	Model coefficients	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**
1	a=1.115 k=0.01582	0.9598	0.06824	44.9462	a=1.114 k=0.01064	0.9708	0.0557	29.9805	a=1.101 k=0.0202	0.9587	0.0701	48.4495	a=1.112 k=0.01423	0.9652	0.06238	32.0821
2	k=0.01423	0.9463	0.07887	62.5187	k=0.009574	0.9569	0.0676	45.8135	k=0.01839	0.9488	0.0781	60.5028	k=0.01283	0.9520	0.0732	54.4044
3	k=0.001184 n=1.572	0.9975	0.0171	3.0743	k=0.001007 n=1.473	0.9977	0.0155	2.6344	k=0.001879 n=1.558	0.9973	0.0179	3.4604	k=0.001252 n=1.522	0.9978	0.0155	2.6167
4	a=1.515 k=0.007838 c=-0.4662	0.9935	0.0275	6.3954	a=1.379 k=0.00607 c=-0.3288	0.9957	0.0213	3.3752	a=1.568 k=0.009476 c=-0.5288	0.9944	0.0259	4.7423	a=1.453 k=0.007491 c=-0.4052	0.9947	0.0243	4.4587
5	a=-71.41 k_o=0.007925 b=72.34 k_1=0.007986	0.9318	0.0889	79.1744	a=-16.18 k_o=0.002207 b=24.65 k_1=0.002365	0.9701	0.0563	31.3673	a=-43.64 k_o=0.0109 b=44.59 k_1=0.01103	0.9285	0.0923	85.1540	a=-46.25 k_o=0.0073 b=47.18 k_1=0.007378	0.9323	0.0870	76.4435
6	a=0.00005243 k=271.4	0.9427	0.0815	66.7051	a=0.00005972 k=160.3	0.9551	0.0690	47.7403	a=0.00006195 k=296.8	0.9441	0.0816	66.0223	a=0.00005088 k=252	0.9492	0.0754	57.6220
7	a=-0.01 b=0.00002251	0.9937	0.0269	7.5849	a=-0.006888 b=0.00001137	0.9964	0.0194	3.6021	a=-0.01286 b=0.00003648	0.9949	0.0247	5.7564	a=-0.009122 b=0.0000193	0.9952	0.0231	5.3816
8	a=1.617 k=0.01392 b=0.9647	0.9388	0.0842	66.5104	a=0.1096 k=7.289 b=0.001171	0.9097	0.0979	91.8380	a=0.08304 k=10.69 b=0.001579	0.9058	0.1059	101.4310	a=0.09517 k=7.641 b=0.00152	0.9082	0.1012	97.5717
9	a=-4.072 k=0.002753 g=0.004226	0.9909	0.0324	11.0004	a=-6.082 k=0.002669 g=0.003317	0.9935	0.02619	6.6677	a=-15.15 k=0.004068 g=0.004629	0.9926	0.0298	8.3745	a=-17.43 k=0.00335 g=0.003679	0.9925	0.0289	8.4348
10	a=0.9913 k=0.001605 n=1.474 b=-0.0003711	0.9995	0.0078	0.8635	a=0.9936 k=0.001425 n=1.377 b=-0.0002289	0.9995	0.0070	0.5506	a=0.9945 k=0.002745 n=1.431 b=-0.0006061	0.9997	0.0059	0.4265	a=0.9925 k=0.001715 n=1.426 b=-0.0003238	0.9997	0.0058	0.4149

Table 4. The statistical results for drying of carrot at different conditions for pretreatment by US 40.

No	60ºC-2mm				60ºC-4mm				70ºC-2mm				70ºC-4mm			
	Model coefficients	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**	**Model coefficients**	**R^2**	**RMSE**	**$\chi^2(10^{-4})$**
1	a=1.109 k=0.01632	0.9569	0.0705	47.4068	a=1.106 k=0.01069	0.9705	0.0555	30.6869	a=1.105 k=0.02036	0.9480	0.0793	60.2714	a=1.124 k=0.01478	0.9596	0.0685	41.1737
2	k=0.01473	0.9447	0.0799	62.8898	k=0.009669	0.9581	0.0660	44.1224	k=0.01841	0.9372	0.0871	74.4565	k=0.01317	0.9434	0.0811	62.4635
3	k=0.001253 n=1.572	0.9960	0.0216	4.3751	k=0.001143 n=1.45	0.9964	0.0194	3.7832	k=0.001362 n=1.643	0.9966	0.0203	4.0315	k=0.000952 n=1.595	0.9984	0.0135	1.6963
4	a=1.604 k=0.007376 c=-0.5638	0.9944	0.0255	5.1535	a=1.421 k=0.005735 c=-0.3818	0.9973	0.0168	2.0924	a=1.918 k=0.00731 c=-0.881	0.9938	0.0274	5.5831	a=1.536 k=0.007267 c=-0.4786	0.9931	0.0284	5.6353
5	a=-71.41 k_o=0.009232 b=43.92 k_1=0.009324	0.9244	0.0935	86.6728	a=-36.56 k_o=0.003097 b=37.47 k_1=0.003197	0.9676	0.0581	33.9441	a=-60.85 k_o=0.03816 b=61.85 k_1=0.03757	0.9871	0.0395	14.8585	a=-47.15 k_o=0.007904 b=48.09 k_1=0.007983	0.9274	0.0918	80.3190
6	a=0.00005406 k=272.5	0.9408	0.0827	67.3999	a=0.00006127 k=157.8	0.9563	0.0675	46.0582	a=0.00006074 k=303	0.9309	0.0914	81.9258	a=0.00005272 k=249.9	0.9398	0.0836	66.3868
7	a=-0.01024 b=0.00002263	0.9947	0.0247	6.0663	a=-0.006915 b=0.00001126	0.9979	0.0149	2.1637	a=-0.0124 b=0.00002828	0.9934	0.0282	7.5731	a=-0.009233 b=0.00001883	0.9922	0.0301	8.4639
8	a=0.07647 k=13.5 b=0.001008	0.9062	0.1041	99.5592	a=0.1042 k=7.25 b=0.001194	0.9138	0.0948	86.4818	a=0.0432 k=9.164 b=0.001919	0.9058	0.1067	100.7923	a=0.07207 k=7.582 b=0.001613	0.9063	0.1043	97.7858
9	a=-7.155 k=0.002744 g=0.003675	0.9925	0.0294	8.5859	a=-4.088 k=0.002339 g=0.0033	0.9959	0.0206	4.1715	a=-3.887 k=0.001895 g=0.004058	0.9918	0.0315	9.5014	a=-4.373 k=0.002449 g=0.003744	0.9895	0.0349	11.6555
10	a=0.9899 k=0.001855 n=1.443 b=-0.0005438	0.9991	0.0102	0.9932	a=0.9956 k=0.001944 n=1.305 b=-0.0003633	0.9995	0.0072	0.4318	a=0.992 k=0.002033 n=1.5 b=-0.0008116	0.9996	0.0069	0.3934	a=0.9962 k=0.001318 n=1.499 b=-0.0003083	0.9999	0.0041	0.2038

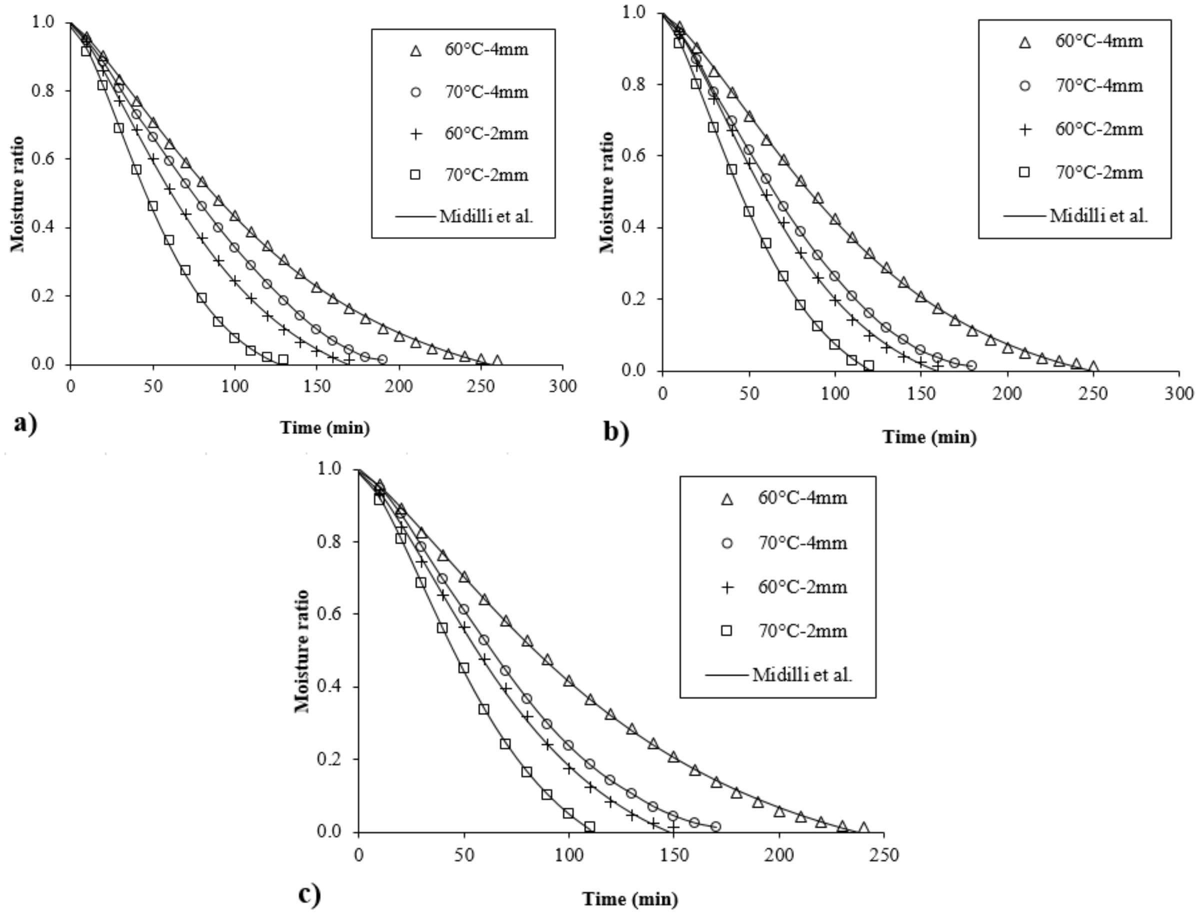

Figure 3. Comparison of the best model to experimental moisture ratios of carrot slices with pretreatment by (a) Control; (b) US 20; and (c) US 40.

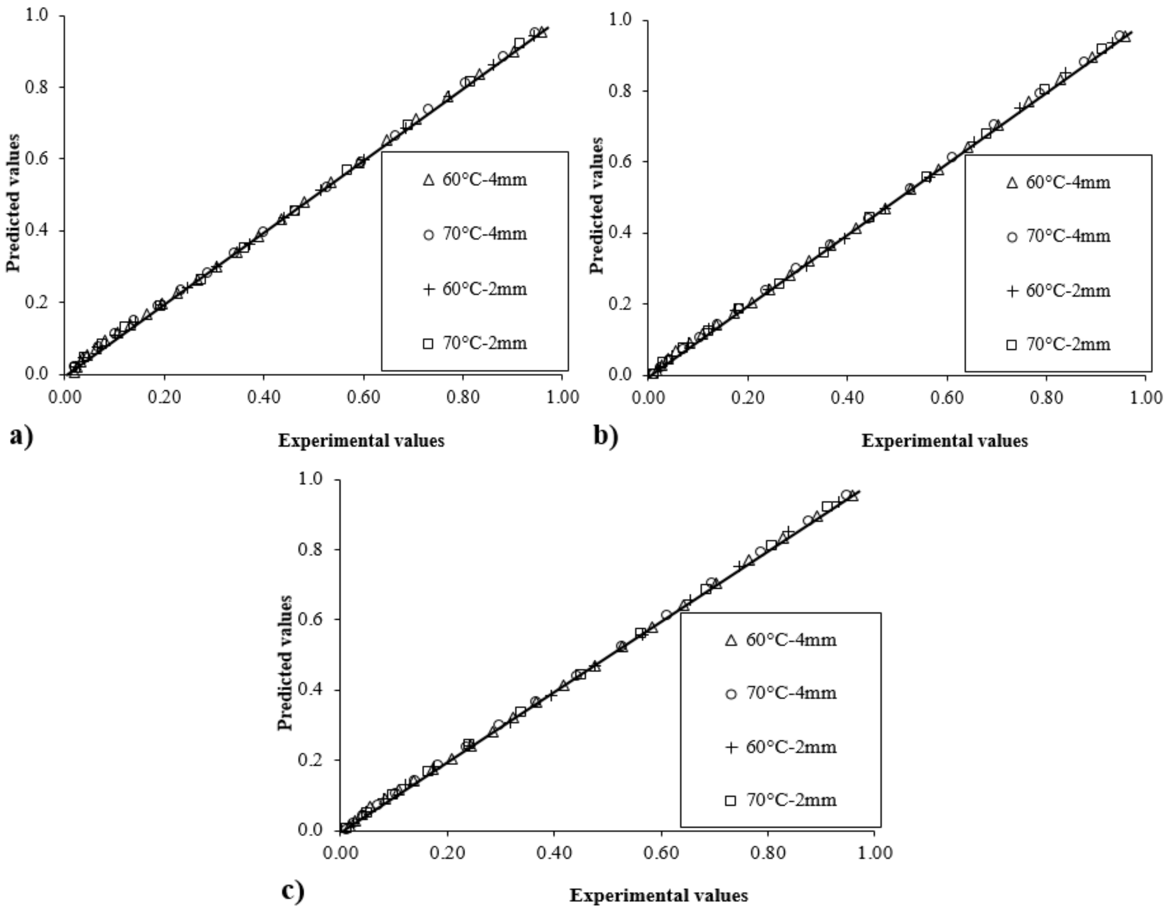

Figure 4. Comparison of predicted by the best model and experimental moisture ratios at drying conditions for pretreatment by (a) Control; (b) US 20; and (c) US 40.

CONCLUSIONS

As a result of the experiments, it was determined that ultrasound pretreatment decreases drying time. Also, it was observed that the drying time of the carrot slices decreased as the duration of the applied ultrasound pretreatment increased. The shortest drying time was seen 110 minutes at 70 °C-2mm-US40 experiment whereas the longest drying time was found 260 minutes at 60 °C-4mm-control experiment. Drying process was carried out with rising, constant and falling rate period, in return. Drying rate increased with increasing temperature. Reducing the slice thicknesses of the products caused a decrease in drying time. As a result of the statistical evaluations of 10 different thin layer drying methods applied, Midilli et al. best fits the experimental moisture ratio for all drying conditions. In this study, it is concluded that the presence of ultrasound pretreatment can contribute to energy efficiency that used in drying industry by decreasing the drying time.

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