Journal of
Food Chemistry & Nanotechnology

https://doi.org/10.17756/jfcn.2023-161

Research Article

Open Access

Infrared Roasting Salted Pistachio Nut Moisture Loss Kinetic and Mathematical Modeling

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Received: October 18, 2023
Accepted: November 13, 2023
Published: November 17, 2023

Citation: Morshedi A, Karazhian R, Morshedi M, Valdes ME, Mohammadi-Moghaddam T. 2023. Infrared Roasting Salted Pistachio Nut Moisture Loss Kinetic and Mathematical Modeling. *J Food Chem Nanotechnol* 9(4): 150-155.

Published by United Scientific Group

Abstract

The infrared roasting process of Ahmadaghaei pistachio kernel was studied. The process temperature was in the range (120 - 180 °C) and continued until the sample moisture content reached 2%. The process time varied between 7.5 - 20 min in different temperatures. The moisture decreases kinetic during the process time was fitted with different experimental models (Page, Henderson and Pabis, Two-terms, Wang-Sing, Thompson, Weibull, and Lewis). The best experimental model that fitted with the pistachio roasting data was Weibull model; because of the highest R^2, the lowest RMSE and χ^2 (chi square). The value of the effective diffusivity coefficient (D_{eff}) in the process temperature range was 2.39 x 10^{-7} m^2/s - 0.960 x 10^{-10} m^2/s based on Fick's law. This D_{eff} was more than hot-air process that is a routine method in the pistachio processing. The process activation energy (E_a) based on Arrhenius equations was 21.770 KJ/mol.

Keywords

Modeling, Activation energy, Roasting, Infrared, Pistachio kernel

Introduction

Pistachio nut is known as one of the most favorite nuts in the world. According to recent data, USA with 67% (406,646 tons), Iran with 17 % (103,179 tons), and Turkey with 11% (66,763 tons) are the most important pistachio producers [1, 2]. Pistachio production and consumption are increased globally because of its economic value and excellent nutritional properties [3-5]. Most pistachio nuts are consumed as roasted [6-8].

Roasting is a temperature-time dependent method that improves taste, color, texture, and flavors in nuts [7]. There are different roasting methods: hot air, hot plate, microwave, and infrared in which hot air is the most common method. Researchers have studied the combination of these methods, as well [8-12]. Infrared (IR) radiations are safe electromagnetic spectrum that are between ultraviolet and microwave regions with 0.75 - 1000 μm wavelength. It is divided into three different categories: near- infrared (NIR), mid-infrared (MIR), and far-infrared (FIR). IR can be used as a source of heating energy in different technologies like drying, backing, roasting, microbial inactivation, blanching, insect control, etc. IR heating compared to hot air- and freeze-drying methods at the same temperature, uses less time and energy [13, 14].

The IR radiation does not need any medium for energy transfer and can propagate in vacuum conditions. IR waves directly penetrates into inner layers of materials and causes vibration in molecules and finally increase temperature. The energy density of IR is very high because it is directly adsorbed by molecules of material, the temperature of materials surface increases quickly. The penetration depth of IR depends on different factors, e.g., moisture content, radiation wavelength, and thickness of materials [13, 15].

The IR roasting method is approximately a new method and is not studied much in pistachio and other nuts and needs to be researched more. The IR is an electromagnetic energy source that is placed between microwave and visible light. Its frequency is in range 30 - 430 THz and wavelength 0.75 - 1000 μm [7, 16-18]. In different thermal processing methods, moisture and heat transfer, and subsequent energy consumption are different [8, 11, 16, 17, 19].

It has been proven traditional methods like hot plate and hot air methods of roasting have considerably more energy consumption compared to newer roasting methods. The point of roasting process is finding the best combination of temperature and time to have acceptable final product [8, 20].

There are not many studies related to IR roasting of pistachio kernels and the process energy consumption. Therefore, in this study, the IR roasting process of pistachio kernel (Ahmadaghaei variety) is studied, besides the energy consumption and mathematical modeling.

Materials and Methods

Materials

Ahmadaghaei variety pistachio kernel used for this kinetic and modeling study. Five kg of the pistachio nut purchased from local shop in Kerman province (Iran). They cleaned by hand and their outer wood shells removed and kernels obtained. The kernels were packed in nylon bags and kept at 4 °C until experiment time.

Methods

Roasting process

The samples were prepared for the IR roasting process by soaking in saline water (20%) for 10 min and after that, drying with a clean towel for 10 min [6, 21]. The roasting process was done by an IR oven (Sartorius, USA) at 220 V and different temperatures (120 - 180 °C). The samples were put as a thin layer on the sample tray. In other words, individual nuts were exposed to IR radiation and were not piled on top of each other in any way. The nuts were heated until their moisture content reached 2% and the time of each treatment was carefully recorded [8]. The sample weight loss during each treatment was recorded, as well.

Moisture ratio determination

To evaluation of moisture ratio of samples in different treatments equation 1 was used.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

Where, MR is moisture ratio, M_t is present moisture content, M_0 is initial moisture, and M_e is dynamic equilibrium moisture content. Comparing M and M_0, M_e is very small therefore, the equation 1 changes to equation 2, practically [22, 23].

$$MR = \frac{M}{M_0} \tag{2}$$

Mathematical modeling of the IR-roasting process

Fitting different mathematical models for IR-roasting process was done considering pistachio nut moisture loss during the process. To this purpose, samples were put on sample tray of oven (200 g each time) while they were heating by an IR lamp. The sample tray was connected to a PC and the sample weight was monitored during the roasting process. Roasting moisture loss curves were fitted with different non-linear mathematical models: Henderson and Pabis [24], Lewis [25], Page [26] Thompson [26], Two-Term [26], Wang and Singh [26], and Weibull [26]. Finally, among these models, the best model that showed the higher R^2 and lower RMSE, besides χ^2 was chosen.

Effective diffusion coefficient

The effective diffusion coefficient (D_{eff}) was calculated according to second Fick's law [27-29].

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial x^2} \tag{3}$$

Where, C is moisture content in each part (db), t is time, x is the sample shape, D_{eff} is effective diffusion coefficient (m^2/s).

The second Fick's law is used for description of moisture diffusion [19, 23, 27, 28, 30]. Ahmadaghaei pistachio kernels' geometric shape is spherical and Fick's second law for this shape was used for calculating the D_{eff} (equation 4, 5, and 6).

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \exp\left[-n^2 \frac{\pi^2 D_{eff}^t}{R^2}\right] \tag{4}$$

$$D_{eff} = D_0 \exp\left(-\frac{E_0}{RT}\right) \tag{5}$$

$$\ln\left(D_{eff}\right) = \ln\left(D_0\right) - \left(\frac{E_0}{R}\right)\left(\frac{1}{T}\right) \tag{6}$$

Where, D_0 is diffusivity constant, R (m) is the radius of the pistachio nuts, and T (k) is temperature.

Models fitting

The best drying model was chosen considering the most amount of R^2 and the least amounts of RMSE (equation 7) besides χ^2 (equation 8) [28, 31, 32]. The equations 7 and 8 are used in drying fitting models.

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(MR_p - MR_E\right)^2\right]^{1/2} \tag{7}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_P - MR_E\right)^2}{N - Z} \tag{8}$$

Where, MR_P is the predicted moisture ratio, MR_E is the experimental moisture ratio, N is data numbers, and Z is the number of constant coefficients in each mathematical model.

Activation energy

Activation energy (E_a) means the needed energy for doing each reaction [26]. Activation energy can be calculated by Arrhenius-type relationship between effective diffusivity and temperature (equation 9).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT_a}\right) \quad (9)$$

Where, D_0 is a diffusivity constant equivalent to the diffusivity at infinitely high temperature, E_a (KJ/mol) is activation energy, D_{eff} (m^2/s) is the effective diffusivity, R (m) is the radius of pistachio nut, and T_a (K) is absolute temperature.

Statistical analysis

All analysis was done three times in this study. The model's fitting was done with Curve Expert software (Version 2.2) and the diagrams were drawn by Excel (Version 2013).

Results and Discussion

Moisture Ratio

In this research, the infrared roasting process of Ahmadaghaei pistachio kernel was done in a thin layer method. According to figure 1, increasing in the process temperature caused decrease in the process time, obviously. The process time in 180 °C was 2.5 min and in 120 °C was 20 min. During the process, the moisture content changes were recorded in different temperatures (120, 130, 140, 150, 160, 170, and 180 °C) and different times (Figure 2).

Some researchers studied the moisture ratio changes during time of roasting process [6, 21, 23, 32, 33]. This study results were consistent with other research in different roasting methods.

Process kinetics

In table 1, different mathematical models, their equations, and the most important parameters in fitting moisture ratio data with different models are mentioned.

According to R^2, RMSE, and χ^2 changes the best experimental model should have the most R^2, the least RSME and χ^2. Therefore, the best model was the Weibull model for Ahmadaghaei pistachio kernel infrared roasting process. The Weibull model parameters in the infrared roasting of sample are placed in table 2.

Some researchers studied different pistachio thermal process moisture changes kinetics [19, 23, 25, 26, 34, 35]. The fitted models in different heating processes were dissimilar. For example, in Damghan pistachio nut variety hot-air drying process the best model was recognized Modified Page [35]; while, in Uzun pistachio nut variety in the same drying process, the best model recognized the Two-Term model [25]. Dini et al. reported in hot-air drying process of Ahmadaghaei pistachio nut the best model was Weibull [26]. Maghsoudi et al. studied the pistachio IR assisted solar drying method and

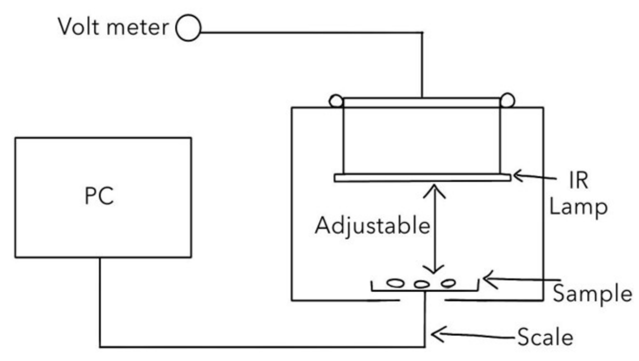

Figure 1: Schematic diagram of IR oven.

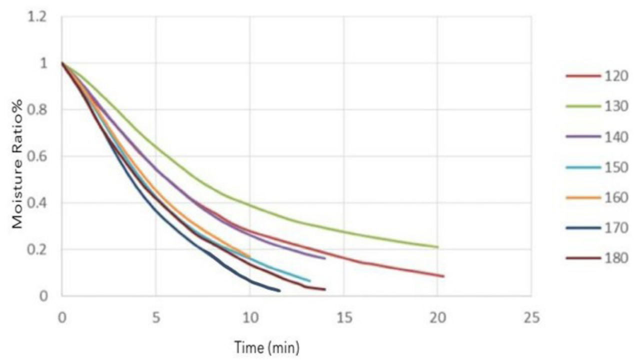

Figure 2: The moisture ratio changes during the Pistachio kernel IR roasting process time.

the best model for prediction moisture changes was Henderson and Pabis [24]. This study results in kinetic of pistachio IR roasting process is as similar as Dini et al. [26].

Effective diffusion coefficient

The D_{eff} calculated in different temperature of the process by drawing the (ln MR) vs time diagram. The slope of this diagram is D_{eff}. Different D_{eff} at process temperatures are mentioned in table 3. The process D_{eff} was in the range 0.96 x 10^{-10} - 2.39 x 10^{-7} m^2/s. This study showed during pistachio nut IR roasting process, increasing in temperature caused increasing in D_{eff}. Comparing D_{eff} in this process with hot-air roasting process demonstrates the amount of the D_{eff} in IR roasting is at least four times more than hot-air roasting process [26].

Different scientists studied effective diffusion coefficient during thermal processing of pistachio nuts or kernels [19, 23-25, 36, 37]. In all studies the hot-air thermal processing D_{eff} is less than IR, ultrasound, solar assisted IR methods. The results of this study are consistent with similar studies.

Activation energy

The activation energy (E_a) of process was calculated based on the D_{eff} changes curve vs time reversal (Figure 3). The curve slope is activation energy, and its amount was 83.76 KJ/mol. There are some studies related to activation energy [38, 39]. The studies demonstrated that in conventional methods of heating, activation energy was lower than newer methods. The activation energy in pistachio conventional drying was 30.79 KJ/mol; in sesame conventional roasting was 9.8 KJ/mol; and in hot-air roasting of hazelnut was 62.3 KJ/mol. This study

Table 1: The kinetics fitting data with different models in Ahmadaghaei pistachio kernel IR roasting process.

Model	Equation	Temperature	R^2	RSME	χ^2
Henderson and Pabis	Y = a*exp (-TX)	120	0.995	0.5427	0.337
		130	0.999	0.6135	0.4302
		140	0.994	0.6861	0.538
		150	0.995	0.7016	0.5624
		160	0.996	0.5249	0.3149
		170	0.994	0.4846	0.2684
		180	0.996	0.736	0.619
Lewis	Y = exp (-TX)	120	0.995	0.5389	0.3098
		130	0.999	0.5313	0.5313
		140	0.993	0.6852	0.5008
		150	0.995	0.6994	0.5218
		160	0.992	0.522	0.2906
		170	0.992	0.4797	0.2455
		180	0.995	0.7336	0.574
Page	$Y = exp (- T^n)$	120	0.995	0.5796	0.3583
		130	0.999	0.5793	0.3579
		140	0.995	0.25	0.667
		150	0.996	0.383	0.1565
		160	0.997	0.6123	0.4
		170	0.997	0.7071	0.5333
		180	0.998	0.433	0.2
Thompson	$Y = aX + bX^2$	120	0.997	3.3071	11.718
		130	0.999	6.0249	38.8927
		140	0.995	5.0798	27.6473
		150	0.992	5.7581	32.7153
		160	0.995	7.0014	39.5002
		170	0.997	7.531	42.1817
		180	0.998	8.9135	51.0876
Two – Term	Y = a exp (-T1X) + b exp (-T2 X)	120	0.999	0.5439	0.3381
		130	0.999	4.0803	19.0274
		140	0.99	2.7757	8.8056
		150	0.99	5.2272	33.629
		160	0.996	5.8021	59.8482
		170	0.996	6.7225	103.2968
		180	0.996	4.2244	23.7948
Wang and Singh	$Y = 1 + aX + bX^2$	120	0.997	0.5205	0.289
		130	0.992	263.1702	73875.81
		140	0.991	290.6452	90106.25
		150	0.994	581.3696	360523.4
		160	0.995	164.0511	28706.9
		170	0.996	113.1676	13660.7
		180	0.996	496.5334	262992.4

Weibull	Y = exp ((-t/a) ^{b})	120	0.995	0.7035	0.528
		130	0.999	0.2488	0.066
		140	0.995	0.6451	0.4439
		150	0.996	0.6522	0.4538
		160	0.997	0.8034	0.6885
		170	0.997	0.8505	0.7716
		180	0.998	0.6264	0.4185

Table 2: Weibull model parameters.

Temperature (°C)	a	b
120	1.28	9.95
130	1.05	1.00
140	8.80	1.07
150	6.81	1.06
160	6.91	1.06
170	6.13	1.12
180	5.83	1.10

Table 3: The IR roasting process D_{eff} in different temperatures.

Temperature (°C)	D_{eff} (m^2/s)
120	0.96 x 10^{-10}
130	0.97 x 10^{-10}
140	1.50 x 10^{-9}
150	1.87 x 10^{-9}
160	1.96 x 10^{-9}
170	2.16 x 10^{-8}
180	2.39 x 10^{-7}

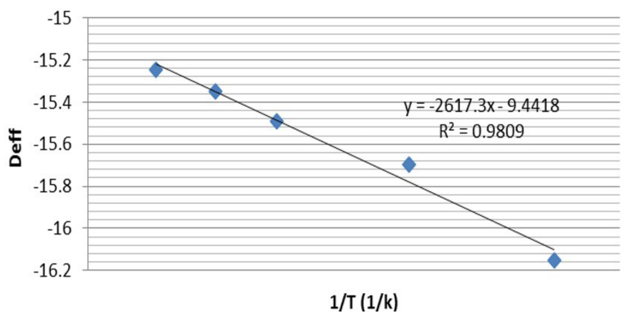

Figure 3: The process activation energy (D_{eff} vs (1/T)).

results showed the activation energy of pistachio IR roasting process is 2.7 times more than activation energy of pistachio hot-air drying method.

Conclusion

The kinetics of Ahmadaghaei pistachio nut IR roasting process studied. The moisture changes during the process were monitored during time and according to R^2 (the greatest amount), RSME (the least amount), and χ^2 (the least amount) the best model was chosen. The best experimental model for moisture changes was the Weibull model. The effective diffusivity of the process changed with the process temperature and showed a direct relation. It was in the range 0.96 x 10 $^{-10}$ - 2.39 x 10 $^{-7}$ (m^2/s). The process D_{eff} was 5 - 4 times more than hot-air roasting process. The logarithm of D_{eff} changes vs (1/T) is usually an Arrhenius-type relation. The slope of D_{eff} vs (1/T) curve is used for activation energy calculation. The activation energy was 83.76 KJ/mol that was more than convectional method, considerably. Totally, concluded the IR roasting process of pistachio nut result is lower time and energy consumption. According to results, it seems the IR roasting process s efficiency is significantly more than hot-air process.

Acknowledgements

None.

Conflict of Interest

None.

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