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Kinetic and Mathematical Modeling of Drying of *Asparagus officinalis* in Different Drying Methods

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A B S T R A C T

Asparagus officinalis is a spring vegetable contains flavonoids, amino acid derivatives, glycolic acid, tyrosine, vitamins, saponins and essential oils and it has health benefits such as prevention of cancer, mutation, inflammation, and liver damage. The aim of this study is to investigate drying kinetics of *Asparagus officinalis.* According to R, χ^2, RMSE and Error values, the model parameters at different temperatures (70°C, 80°C, 90°C), spear thickness (1 mm, 2 mm and 3mm), and microwave power (100 W, 200 W, and 300W) were compared. Midilli and Kucuk equation was found as the best equation to describe drying of *Asparagus officinalis*. R values of Midilli and Kucuk Equation changed between 0.8886 and 0.9989 for hot air drying and between 0.9568 and 0.9999 for a microwave drying.

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Introduction

Asparagus officinalis is a vegetable, having a special flavour and therapeutic properties, native of European, African and Asian countries with two main types of spears produced: green and white. Green asparagus is a good source of flavonoids, sterols, saponins, oligosaccharides, carotenoids, sulfurated acids, amino acids and essential oils (Siomos, 2018). Because of this, it is used in different treatments for illnesses like a cough, nose cancer, leukaemia, lung cancer, breast cancer, lymphatic gland cancer, neuritis, and rheumatism. In addition to this, its extract has a wide range of therapeutic activities such as anti-diabetic, anti-tumour, antifungal, diuretic (Sergio et al, 2017). Drying, known as one of food preservation methods, is a crucial unit operation for the control of moisture. In other words, drying is used to reduce the moisture content of food materials under safe limits (Kucuk et al., 2014). Hot-air drying is the most common drying method for foods, but it has some disadvantages including long process time, high-quality loss, and cost, so other methods have been examined. Microwave drying is more rapid and more highly energy efficient system than conventional hot air drying (Al-Harahsheh et al., 2009; Mcloughlin et al., 2003). As a result, comparison of different methods for drying is one of the key steps for process optimization. Another stage for process evaluation and optimization is the mathematical models used for that process. From point of this fact, it can be concluded that mathematical modelling of drying processes is an important aspect of drying technology for describing the change of water content throughout the food material during the drying process (Bi et al., 2015). There are many mathematical models for drying processes including Page, Henderson and Pabis, Midilli and Kucuk, Newton. According to the newest studies, the Weibull model can be also used to describe the drying kinetics of certain foods because this model is one of the simplest equations with two parameters (Blasco et al., 2006; Corzo et al., 2008; Coşkun et al., 2016; Karacabey and Buzrul, 2017). The objectives of the study were (i) to find drying of asparagus spears for two drying methods (hot air oven and microwave oven) (ii) to study the effects of spear thickness (1 mm,2 mm and 3mm), microwave power (100 W, 200 W, and 300W), hot air oven temperature (70°C, 80°C, 90°C), (iii) to investigate kinetic modelling of drying of *Asparagus officinalis* by using Exponential, Page, Modified Page, Henderson and Pabis, Weibull, Midilli and Kucuk and Simplified Fick's Diffusion models (iv) to compare mathematic models for finding the most suitable model for drying of *Asparagus officinalis* spears.

Materials and Methods

Asparagus spears were obtained from the local market and stored at +4°C. The spears were stripped and then cut to desired dimensions (30 mm × 40 mm and thickness of 1, 2 and 3 mm) by using an adjustable chopper. Initial moisture of asparagus was measured as 94.19±0.89% (Baltacıoğlu, 2017).

Drying

Hot air oven drying was performed in the preheated oven (Nuve, EN 400, Turkey) at an air temperature of 70°C, 80°C, and, 90°C to evaluate the influences of temperature on the drying process. Asparagus spears were spread as a single layer on the tray attached to the balance (KERN, EW-1500-2M, Germany). During drying, the weight of the sample was recorded at a regular time interval (5 minutes for hot air oven). Drying process continued until desired moisture content was attained (<10%, w/w).

A programmable domestic microwave oven (Samsung, MW71E, Malaysia) with a maximum output of 800 W and frequency of 2.450 MHz was used for another drying method of asparagus spears. The dimensions of the microwave cavity were 307×185×292mm. Three spear thicknesses (1, 2 and 3 mm) and three power levels (100, 200 and 300 W) were examined to determine their effects on drying time. Weighed asparagus spears were spread in a glass dish (fixed weighed before use) as a single layer and placed in the centre of microwave oven. The samples were taken out at and weighed at every 30 s interval by switching off the microwave oven and after the weight of the sample was recorded, it was replaced in the oven. Drying process proceeded until desired moisture content was attained (<10%, w/w).

Kinetic Modelling

The experimental data obtained from conventional and microwave oven drying was tried to explain by using different models commonly used for the description of drying curves in the literature (Table 1). The parameters of interested models were determined using non-linear regression procedure using Sigma Plot software package (SigmaPlot Ver.10, Chicago, IL, USA). The coefficient of determination (R), reduced chi-square (χ^2), root mean square error (RMSE) and error were used to inspect the goodness of fit of the selected mathematical models to the experimental data. The model with the higher values of R and the lower values of χ^2, RMSE and Error is considered more suitable. (Midilli and Kucuk, 2003; Akpinar et al., 2006). The following equations were used to calculate the above-mentioned parameters:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (1)$$

$$R^2 = 1 - \left[\frac{\Sigma\left(MR_{Prd} - \Sigma\, MR_{Exp}\right)^2}{\Sigma\left(\overline{MR}_{Prd} - \Sigma\, MR_{Exp}\right)^2}\right] \quad (2)$$

$$X^2 = \frac{\Sigma\left(MR_{Exp} - MR_{Prd}\right)^2}{N - n} \quad (3)$$

$$RMSE = \left(\frac{\Sigma\left(MR_{Prd} - MR_{Exp}\right)^2}{N}\right)^{1/2} \quad (4)$$

Table 1 Mathematical models used to describe drying curve.

MN	Model Name	Model Equation	References
1	Page	$MR = \exp(-kt^y)$	Page (1949)
2	Modified Page	$MR = \exp(-(kt)^y)$	White et al. (1981)
3	Lewis	$MR = \exp(-kt)$	Bruce (1985)
4	Henderson and Pabis	$MR = a \exp(-kt)$	Henderson and Pabis (1961)
5	Midilli and Kücük	$MR = a \exp(-kt^n) + bt$	Midilli et al. (2002)
6	Simplified Fick’s Diffusion	$MR = a \exp(-c(t/L^2))$	Diamante and Munro (1991)
7	Weibull	MR= 〖10〗 ^[-(t/exp[C_0+C_1/T])^n]	Karacabey and Buzrul (2017)

MN: Model Number;

Results and Discussion

Drying of *Asparagus officinalis* was investigated and microwave oven drying, and conventional hot air oven were compared to represent the potential application of microwave technology in the drying of asparagus spears. Compared to the conventional process, microwave technology exhibited high potency as a drying technique with valuable results like shorter drying time, higher drying rate and product quality. In fact, air temperature in hot air oven has a noticeable effect on the moisture content of asparagus whereby higher temperature resulted in the higher loss of moisture and consequently drying time reduced. This may be due to the increase in heat transfer between the sample and air temperature (Akpinar, 2006; Akpinar and Bicer, 2008; Ali et al., 2014; Hee and Chong, 2015; Sacilik and Elicin, 2006; Simal et al., 2000; Toğrul and Pehlivan, 2003; Tunde-Akintunde, 2011). Drying time required to reduce the moisture content of asparagus spear under 10% (w/w) was decreased almost 55.5 folds by operating microwave oven at the power of 200 W for drying compared to drying in a conventional oven at 80°C for same spear thickness. Data from moisture content versus time were converted to dimensionless moisture ratio so as to normalize the drying curves. Changes the moisture ratio with the time at the different drying conditions were shown in Figure 1 and 2. It can be seen that the moisture contents decrease as the drying time increases. The model parameters at different temperatures, spear thickness, and microwave power levels were calculated and tabulated together with R, χ^2, RMSE and Error values in Table 2 and 3.

Table 2 Model results from statistical analyses of *Asparagus officinails* spears at the hot air oven

Drying Method	Model Number	Model Constants	R	χ^2	RMSE	Error
HA-DM-1	1	k=0.0000577 y=1.839	0.9971	0.00046675	0.0199	0.0216
	2	k=0.005 y=1.839	0.9971	0.00046675	0.0199	0.0216
	3	k=0.0048	0.9927	0.00105057	0.0312	0.0325
	4	a=1.1087 k=0.0054	0.9938	0.00098241	0.0288	0.0314
	5	a=0.9837 k=0.0001 y=0.5563 b=-0.0005	0.9989	0.00021320	0.0121	0.0147
	6	a=1 k=0.003 L=0.001	0.9938	0.00102560	0.0295	0.0314
	7	d=317.7614 n=1.839	0.9971	0.00046675	0.0199	0.0216
HA-DM-2	1	k=0.0448 y=0.7068	0.9870	0.00288382	0.0486	0.0537
	2	k=0.0123 y=0.7068	0.9870	0.00288476	0.0486	0.0537
	3	k=0.0115	0.9851	0.00294336	0.0517	0.0543
	4	a=0.8911 k=0.0097	0.9880	0.00240806	0.0468	0.0517
	5	a=1.0139 k=0.0736 y=0.5563 b=-0.0005	0.9951	0.00143520	0.0302	0.0376
	6	a=0.8911 k=0.0000009 L=0.001	0.9880	0.00300805	0.0468	0.0517
	7	d=263.9089 n=0.7068	0.9870	0.00259544	0.0486	0.0537
HA-DM-3	1	k=0.1773 y=0.0284	0.9965	0.00042000	0.0181	0.0205
	2	k=0.1649 y=0.9598	0.9965	0.00042000	0.0181	0.0205
	3	k=0.163	0.9982	0.00038000	0.0184	0.0195
	4	a=0.9992 k=0.1629	0.9982	0.00043500	0.0184	0.0209
	5	a=1.0002 k=0.1553 y=1.037 b=0.0006	0.9993	0.00023470	0.0114	0.0153
	6	a=0.9992 k=0.000065 L=0.001	0.9982	0.00507930	0.0184	0.0209
	7	d=14.45597 n=0.9598	0.9983	0.00042130	0.0181	0.0205
HA-DM-4	1	k=0.0002 y=1.5781	0.9924	0.00231896	0.0436	0.0269
	2	k=0.004 y=1.5781	0.9924	0.00073518	0.0245	0.0269
	3	k=0.003	0.9683	0.00266789	0.0492	0.0517
	4	a=1.0591 k=0.0035	0.9861	0.00132206	0.0329	0.0363
	5	a=1.0289 k=0.0003 y=1.3658 b=-0.0008	0.9948	0.00096360	0.0248	0.0252
	6	a=1.0591 k=0.0000014 L=0.002	0.9861	0.00147930	0.0328	0.0363
	7	d=419.7277 n=1.5781	0.9924	0.00723100	0.0243	0.0269
HA-DM-5	1	k=0.2208 y=0.6037	0.9977	0.00421820	0.0181	0.0205
	2	k=0.0819 y=0.6037	0.9977	0.00042181	0.0181	0.0205
	3	k=0.0073	0.9646	0.00558140	0.0704	0.0747
	4	a=0.9108 k=0.0652	0.9723	0.00439076	0.0625	0.0708
	5	a=0.9986 k=0.2357 y=0.5675 b=-0.0005	0.9978	0.00055810	0.0176	0.0236
	6	a=0.9723 k=0.000026 L=0.002	0.9723	0.00585435	0.0625	0.0708
	7	d=48.60889 n=0.6037	0.9977	0.00042181	0.0181	0.0205
HA-DM-6	1	k=0.2131 y=0.4867	0.9750	0.00523914	0.0655	0.0724
	2	k=0.0417 y=0.4867	0.9750	0.00523913	0.0655	0.0724
	3	k=0.0418	0.8886	0.02010049	0.1352	0.1418
	4	a=0.7687 k=0.0217	0.9298	0.01438037	0.1085	0.1199
	5	a=1.0005 k=0.3505 y=0.2759 b=-0.0012	0.9887	0.00311110	0.0445	0.0555
	6	a=0.7687 k=0.000000869 L=0.002	0.9298	0.01617790	0.1085	0.1199
	7	d=46.9785 n=0.649	0.9750	0.00523913	0.0655	0.0724
HA-DM-7	1	k=0.1893 y=0.649	0.9954	0.00007629	0.0254	0.0276
	2	k=0.0769 y=0.649	0.9954	0.00076297	0.0254	0.0276
	3	k=0.0713	0.9771	0.00343179	0.0563	0.0586
	4	a=0.9343 k=0.0656	0.9800	0.00327460	0.0526	0.0572
	5	a=0.9974 k=0.1454 y=0.7635 b=0.0007	0.9979	0.00042130	0.0171	0.0204
	6	a=0.9343 k=0.0000059 L=0.003	0.9800	0.00360204	0.0526	0.0572
	7	d=46.9785 n=0.649	0.9954	0.00076296	0.0254	0.0276
HA-DM-8	1	k=0.0401 y=0.7252	0.9836	0.00351676	0.0536	0.0593
	2	k=0.0118 y=0.7252	0.9836	0.00351698	0.0536	0.0593
	3	k=0.0116	0.9649	0.00670011	0.078	0.0819
	4	a=0.9065 k=0.0101	0.9790	0.00448552	0.0606	0.067
	5	a=1.0087 k=0.0913 y=0.4148 b=-0.0018	0.9940	0.00166230	0.0325	0.0408
	6	a=0.9065 k=0.0000009 L=0.003	0.9790	0.00504451	0.0606	0.067
	7	d=266.9496 n=0.7252	0.9836	0.00351659	0.0536	0.0593
HA-DM-9	1	k=0.323 y=0.6349	0.9976	0.00172336	0.0383	0.0218
	2	k=0.1683 y=0.6349	0.9976	0.00183584	0.0383	0.0218
	3	k=0.1427	0.9882	0.00209367	0.0434	0.0458
	4	a=0.9778 k=0.1394	0.9885	0.00229319	0.0428	0.0479
	5	a=1.0008 k=0.2584 y=0.752 b=0.0008	0.9996	0.00938330	0.0791	0.0109
	6	a=0.9778 k=0.0000125 L=0.003	0.9885	0.00324950	0.0494	0.0479
	7	d=22.1087 n=0.6349	0.9976	0.00047350	0.0195	0.0218

HA-DM-1: Oven at 70°C with 1 mm thickness; HA-DM-2: Oven at 80°C with 1 mm thickness; HA-DM-3: Oven at 90°C with 1 mm thickness; HA-DM-4: Oven at 70°C with 2 mm thickness; HA-DM-5: Oven at 80°C with 2 mm thickness; HA-DM-6: Oven at 90°C with 2 mm thickness; HA-DM-7: Oven at 70°C with 3 mm thickness; HA-DM-8: Oven at 80°C with 3 mm thickness; HA-DM-9: Oven at 90°C with 3 mm thickness

Table 3 Model results from statistical analyses of *Asparagus officinalis* spears at microwave oven

Drying Method	Model Number	Model Constants	R	χ^2	RMSE	Error
MO-DM-1	1	k=0.0000577 y=1.839	0.9942	0.00124000	0.0344	0.0377
	2	k=0.005 y=1.839	0.9942	0.00144567	0.0344	0.0377
	3	k=0.0048	0.9497	0.01093200	0.1001	0.1046
	4	a=1.1087 k=0.0054	0.9601	0.00957188	0.0893	0.0978
	5	a=0.9837 k=0.0001 y=1.6103 b=0.0008	0.9989	0.00117790	0.028	0.0185
	6	a=1 k=0.003 L=0.001	0.9601	0.00381970	0.0895	0.0978
	7	d=317.7614 n=1.839	0.9942	0.00140000	0.0335	0.0377
MO-DM-2	1	k=0.0448 y=0.7068	0.9934	0.00150489	0.0361	0.0388
	2	k=0.0123 y=0.7068	0.9934	0.00150504	0.0361	0.0388
	3	k=0.0115	0.9736	0.00551044	0.0717	0.0742
	4	a=0.8911 k=0.0097	0.9862	0.00311433	0.052	0.0558
	5	a=1.0139 k=0.0736 y=0.5563 b=-0.0005	0.9974	0.00063370	0.0234	0.0264
	6	a=0.8911 k=0.0000001 L=0.001	0.9862	0.00337328	0.0519	0.0558
	7	d=263.9089 n=0.7068	0.9934	0.00150477	0.0361	0.0388
MO-DM-3	1	k=0.3111 y=1.2935	0.9636	0.15667600	0.358	0.200
	2	k=0.451 y=1.2935	0.9636	0.15640000	0.3578	0.200
	3	k=0.0559	0.9988	0.00069591	0.0215	0.0264
	4	a=1.0012 k=0.0559	0.9988	0.33600000	0.628	0.0373
	5	a=1 k=0.0129 y=1.413 b=-0.0003	0.9999	0.00001445	0.0022	0.0010
	6	a=1 k=0.0179 L=0.001	0.9636	0.04000000	0.0577	0.2000
	7	d=9.375 n=2.7202	0.9636	0.01000000	0.346	0.2000
MO-DM-4	1	k=0.0706 y=0.7093	0.9936	0.00198323	0.0131	0.0139
	2	k=0.0238 y=0.7093	0.9936	0.00018617	0.0125	0.0139
	3	k=0.0254	0.9864	0.00028620	0.0163	0.0195
	4	a=0.9335 k=0.022	0.9925	0.00012210	0.0116	0.0151
	5	a=1.026 k=0.0772 y=0.6961 b=0.0000247	0.9957	0.00015620	0.0107	0.0125
	6	a=0.9791 k=0.0000005 L=0.002	0.9925	0.00017470	0.0118	0.0151
	7	d=2739.881 n=0.8047	0.9936	0.00018032	0.013	0.0139
MO-DM-5	1	k=0.0193 y=0.8989	0.9965	0.00083894	0.0236	0.0290
	2	k=0.0124 y=0.8989	0.9965	0.00083846	0.0236	0.0290
	3	k=0.0124	0.9951	0.00093789	0.028	0.0306
	4	a=0.9808 k=0.0121	0.9956	0.00084705	0.0266	0.0325
	5	a=0.9998 k=0.0745 y=0.4539 b=-0.0023	0.9993	0.00034650	0.0107	0.0186
	6	a=0.9696 k=0.00000009 L=0.002	0.9956	0.01392437	0.0834	0.0325
	7	d=203.846 n=0.8989	0.9965	0.00067074	0.0236	0.0290
MO-DM-6	1	k=0.0706 y=0.7093	0.9931	0.00176500	0.0384	0.0420
	2	k=0.0238 y=0.7093	0.9931	0.00176505	0.0384	0.0420
	3	k=0.0254	0.9778	0.00513023	0.0686	0.0716
	4	a=0.9335 k=0.022	0.9807	0.00445884	0.0639	0.0700
	5	a=1.026 k=0.0772 y=0.6961 b=0.0000247	0.9934	0.00201280	0.0366	0.0458
	6	a=0.9335 k=0.0000009 L=0.002	0.9807	0.00544957	0.0639	0.0700
	7	d=135.9857 n=0.7093	0.9931	0.00160454	0.0384	0.0420
MO-DM-7	1	k=0.0003 y=1.418	0.9945	0.00132402	0.0332	0.0239
	2	k=0.0031 y=1.418	0.9945	0.00059019	0.0222	0.0239
	3	k=0.0026	0.9756	0.00226612	0.0456	0.0476
	4	a=1.0466 k=0.0028	0.9810	0.00197194	0.0405	0.0442
	5	a=0.9895 k=0.00009 y=1.4372 b=-0.0001	0.9962	0.0005228	0.0187	0.0222
	6	a=1.0466 k=0.000000255 L=0.003	0.9810	0.00216956	0.0403	0.0442
	7	d=587.4791 n=1.418	0.9945	0.00056927	0.0218	0.0239
MO-DM-8	1	k=0.0311 y=0.6457	0.9975	0.00026484	0.0147	0.0163
	2	k=0.0046 y=0.6457	0.9975	0.00026577	0.0147	0.0163
	3	k=0.0057	0.9568	0.00408570	0.0609	0.0639
	4	a=0.9246 k=0.0049	0.9796	0.00195071	0.0421	0.0466
	5	a=1.0042 k=0.0281 y=0.6935 b=0.0003	0.9979	0.00029090	0.0136	0.0170
	6	a=0.9246 k=0.00000044 L=0.003	0.9796	0.00243768	0.0421	0.0466
	7	d=786.9481 n=0.6457	0.9975	0.00023827	0.0147	0.0163
MO-DM-9	1	k=0.0311 y=1.0656	0.9983	0.00055870	0.0200	0.0236
	2	k=0.0234 y=1.0656	0.9983	0.00055860	0.0200	0.0236
	3	k=0.0238	0.9980	0.00531260	0.0213	0.0230
	4	a=1.0049 k=0.0239	0.9980	0.00063228	0.0213	0.0251
	5	a=1.001 k=0.0212 y=1.0235 b=-0.0008	0.9984	0.00868200	0.0193	0.0295
	6	a=1.0049 k=0.000002 L=0.003	0.9980	0.00079025	0.0213	0.0251
	7	d=93.356 n=1.0656	0.9983	0.00055852	0.0200	0.0236

MO-DM-1: Microwave at 100W with 1 mm thickness; MO-DM-2: Microwave at 200W with 1 mm thickness; MO-DM-3: Microwave at 300W with 1 mm thickness; MO-DM-4: Microwave at 100W with 2 mm thickness; MO-DM-5: Microwave at 200W with 2 mm thickness; MO-DM-6: Microwave at 300W with 2 mm thickness; MO-DM-7: Microwave at 100W with 3 mm thickness; MO-DM-8: Microwave at 200W with 3 mm thickness; MO-DM-9: Microwave at 300W with 3 mm thickness

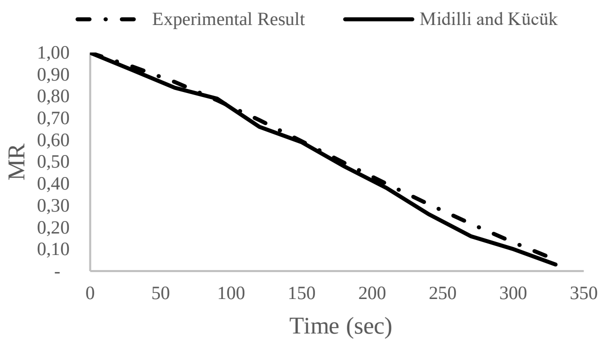

Figure 1 Comparison of experimental and fitted model of *Asparagus officinalis* spears for microwave oven at 100W and 1mm

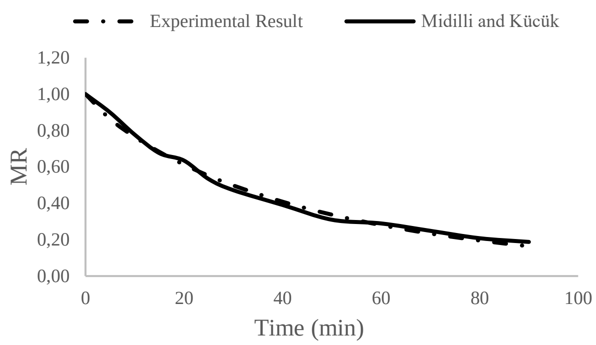

Figure 2 Comparison of experimental and fitted model of *Asparagus officinalis* spears for hot air oven at 70°C and 1mm

Accordingly, the models for different drying conditions revealed high values of R varying between 0.8886 and 0.9989 for hot air drying and between 0.9568 and 0.9999 for a microwave drying. The highest R-value was calculated as 0.9999 for Midilli and Kucuk Equation for microwave drying at 300W for 1 mm thickness of asparagus. All tested models could adequately describe the behaviour of drying asparagus spears using hot air and microwave oven. It can be seen from Table 2 and 3 the highest values of R as well as the lowest values of χ^2 and RMSE for the various drying conditions and spears thickness were obtained for Midilli and Kucuk drying model. Three models Midilli and Kucuk's one in terms of prediction performance are Lewis, Henderson-Pabis and Weibull Model for hot air oven and microwave oven. Thus, Midilli and Kucuk Model's equation was selected as a suitable model to predict the drying behaviour of asparagus spears for hot air oven and microwave oven. The correlation between the experimental data and the corresponding predicted values by the most suitable model at different drying conditions are shown in Figure 1 and 2. According to these figures, it can be seen Midilli and Kucuk Equation fitted well with the drying conditions of asparagus spears. The obtained results are in agreement with the past studies about drying of asparagus roots with tray dryer and Midilli and Kucuk Equation gave the highest R^2 value (Bala et al., 2010). In addition, Midilli and Kucuk Equation has been reported as a suitable model to describe plant leaf drying so it is suitable for drying of the plant origin material (Alara et al., 2017; Mohamed et al., 2005; Sobukola et al., 2007).

Conclusion

In this study, the effects of the drying conditions and thickness of asparagus spears were investigated. Microwave oven and hot air oven were used to dry the asparagus spears. Temperatures of the oven were selected as 70°C, 80°C and 90°C and power level of the microwave oven was identified as 100 W, 200 W and 300 W. In addition to these drying parameters, spear thickness of 1 mm, 2 mm and 3 mm was also examined. Seven different models were adopted to describe the change of moisture ratio values of asparagus spears with time for different drying methods and drying parameters. The model that had the best fit with highest values of R and lowest value of RMSE and χ^2 was the Midilli and Kucuk Equation for microwave and hot air oven. Thus this model was selected as being suitable to describe the asparagus drying process for the experimental conditions considered.

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