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Mathematical Modeling and Evaluation of Microwave Drying Kinetics of Mint (*Mentha spicata* L.)

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Abstract: The overall objective of this research was to improve the basic knowledge about the important parameters of the microwave drying of leafy herbs. Specific objectives were to determine the effects of microwave power density on drying time and drying rate, improve the product quality in terms of colour, compare the fitting ability of several drying equations to express the drying kinetics of mint leaves with the most suitable drying model and to describe the whole process in a general drying model by embedding the effects of microwave power density on the coefficients of the best fitting model for the purpose of simulation and scaling up of the process. The microwave drying of mint (*Mentha spicata* L.) leaves have been studied at different operating parameters of drying using mathematical models. Experiments were conducted using seven levels of microwave power density, 4, 5, 6, 7, 8, 9 and 10 W g^{-1}. Eleven mathematical models describing drying kinetics have been investigated.

Key words: Microwave power density, modeling, mint, colour, drying rate

INTRODUCTION

The members of Labiatae family are common herbs mainly grown in the mountainous areas of the Mediterranean region of Turkey[1]. These herbs are largely collected from the wild and then exported to the world markets. Among them, mint, thyme and parsley are widely used as culinary, medicinal and aromatic herbs. The fresh or dried leaves and flowering tops of these plants are used in the food, cosmetic and pharmaceutical industries to produce spice, essential oils and drugs.

The fresh or dried leaves and flowering tops of the mint (*Mentha spicata* L.) are particularly used as a garnish for meats and desserts, an ingredient to flavour soups, sausages and candies. Traditionally, it is used as an herbal tea against cold, spasms, cramps and digestive problems[2]. The essential oil of mint is used for flavouring of toothpaste, mouthwashes and chewing gums. It is also used in aromatic soaps, perfumery, detergents, repellents and pesticides for various insects[3].

Mint, like many other herbs, is highly seasonal in nature. In order to preserve this seasonal and highly perishable plant and make them available to consumers all year round at low prices, it is subjected to post harvest technological treatments such as drying and freezing. Drying is one of the oldest preservation techniques. Natural drying (drying in the shade) and hot air drying are still most known and widely used methods of drying. Natural drying has many disadvantages due to the inability to handle the large quantities and to achieve consistent quality standards[4]. High ambient temperature and relative humidity during the harvesting and drying season and long drying time promote the insect and mould development in harvested and/or dried crops. Therefore, continuous and batch dryers are generally used depending on the daily processed product tonnage. Some industrial sectors, such as instant food and dried soup producers are interested only in colour, not flavour[5]. The dried mint should have a bright green colour. Therefore it should be dried quickly in order to inactivate the enzyme chlorophyllase which breaks down the chlorophyll and turns the leaf yellow[6]. However, temperatures above 60°C will remove the volatile oils reducing flavour[7]. Thus, to produce green mint, drying temperatures below 60°C are generally suggested[8]. In addition to this, other major drawbacks of hot air drying are low energy efficiency and a lengthy drying time during the last stage of drying. For example, Parker[9] carried out the drying experiments for sweet basil, pesto basil, marjoram, lemongrass and parsley in a hot air dryer with a capacity of 500 g fresh leaf materials. It is reported that the hot air drying of parsley leaves to attain the moisture content of 10% wet basis (wb) took 18, 15, 6 and 5 h for 30, 40, 50 and 65°C drying air temperatures, respectively. It is also stated that the drying temperature of 40°C was the most ideal for drying parsley regarding that colour is

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of primary importance in dried herbs. Soysal and Öztekin[4], performed batch drying experiments in a tray type dryer with 145 kg of *Mentha piperita* and 120 kg of *Hypericum perforatum*. The drying process which reduced the product moisture content below 15% wb took 6 h for *H. perforatum* and 9 h for *M. piperita*, respectively.

Compared to conventional hot air drying process, microwave or hybrid microwave drying techniques (microwave-hot air drying; microwave-freeze drying, microwave-vacuum drying; osmotic pretreatment before combined microwave-hot air drying) can greatly reduce the drying time of biological materials without quality degradation[10,11]. For example, Soysal[12] studied on microwave drying of parsley leaves with different microwave output power levels ranging from 360 to 900 W. It is showed that by performing microwave drying at 900 W output power instead of 30, 40, 50 and 65°C hot air drying up to the moisture content of 0.10 db, the drying time can be shortened by 111, 92, 37 and 31 fold, respectively. No significant difference was found between the colour of fresh and microwave dried leaf materials, except some decrease in the colour brightness[12]. Hence, application of microwave energy to dry agricultural materials may be a good approach to overcome certain drawbacks of conventional drying techniques[13].

There has been extensive research on microwave drying examining a broad spectrum of fruits and vegetables[10-18]. However, little data currently exist on microwave drying of leafy herbs. In addition, a number of successful drying models have been developed to explain the convective drying kinetics of various agricultural products for use in design, construction and control of drying systems. However, less effort has been made on the modelling of microwave drying process including the process parameters embedded into the drying model to explain the influence of process variables on microwave drying kinetics. Only the Newton and the Page equations were used in some studies to describe the microwave drying kinetics of the several materials including: banana[16], pear[19], carrot[20], kiwi[21], garlic[22], corn[23], grape[24], parsley[12], model fruit gel[25] and olive pomace[26].

The introduction of a microwave drying technique which reduces drying time considerably and produces a high quality end-product could offer a promising alternative and significant contribution for the herb processing industry. Therefore, the overall objective of this study was to improve the basic knowledge about the important parameters of the microwave drying of leafy herbs. Specific objectives were to:

- determine the effects of microwave power density on drying time and drying rate
- improve the product quality in terms of colour;
- compare the fitting ability of several drying equations to express the drying kinetics of mint leaves with the most suitable drying model and
- describe the whole process in a general drying model by embedding the effects of microwave power density on the coefficients of the best fitting model for the purpose of simulation and scaling up of the process.

MATERIALS AND METHODS

Material: Fresh green mint (*Mentha spicata* L.) leaves used for the drying experiments were obtained from the local market in the Hatay region of Turkey. The whole samples were stored at 4±0.5°C before they were used in experiments. Prior to each of drying experiments, the whole material samples were taken out of storage and leaves from stems were separated. The moisture content of each tested sample was measured individually. Three 30.00 (±0.01) g leaf samples were dried in an oven at 105°C for 24 h to assess their initial moisture contents. The initial moisture contents (mc) of the mint leaves were ranged from 7.74 (±0.07) to 7.79 (±0.04) dry basis (db).

Drying equipment and experimental procedure: A programmable domestic microwave oven (Galanz WP900AL23-Z1, China) with maximum output of 900 W at 2450 MHZ was used for the drying experiments. The dimensions of the microwave cavity were 215×350×330 mm. The oven was fitted with a glass turntable (314 mm diameter) and had a digital control facility to adjust the microwave output power by the 10% decrements and the time of processing. Seven different microwave output powers corresponding to power densities of 4, 5, 6, 7, 8, 9 and 10 W g^{-1} were investigated. In each drying experiment, 90.00 (±0.01) g of fresh leaf materials were uniformly spread on the turntable inside the microwave cavity, for an even absorption of microwave energy. Three replicates were carried out for each experiment according to preset time schedule based on the preliminary tests. Moisture loss was recorded periodically during drying at the end of power-on time by removing the turntable from the microwave and placing this, along with the leaf sample on the digital balance[12,16,27]. For the mass determination, a digital balance with an accuracy of 0.01 g (Sartorius; Model: GP3202) was used. The microwave power was applied until the mass of the sample reduced to a level corresponding to a moisture content of about 0.10 db. The moisture content of the samples at the end of each drying period was calculated according to the loss of mass and the initial moisture content value.

Table 1: Mathematical models given by various authors for drying curves

Model No.	Model equation	Name	References
1	MR=exp (–kt)	Newton	[28, 29, 32, 33]
2	MR=exp (–kt^n)	Page	[12, 28, 29, 34, 35]
3	MR=aexp (–kt)	Henderson and Pabis	[28, 29, 35, 36]
4	MR=aexp (–kt)+b	Logarithmic	[28, 29, 37, 38]
5	MR=aexp (–kt^n)+bt	Midilli *et al.*	[29, 39]
6	MR=1+at=bt^2	Wang and Singh	[29, 33, 40, 41]
7	MR=b/(1+aexp (kt)	Logistic	[33]
8	MR=aexp (–kt)+bexp (–k$_1$t)	Two term	[29, 33, 42, 43, 44]
9	MR=aexp (–kt)+(1–a) exp (–bt)	Verma *et al.*	[28, 29, 33, 38, 43]
10	MR=aexp (–kt)+(1–a) exp (–kat)	Two term exponential	[28, 29, 38]
11	MR=aexp (–kt)+(1–a) exp (–kbt)	Diffusion approximation	[28, 29, 38]

MR, moisture ratio (dimensionless); k and k_1 drying coefficients in min^{-1}; n, exponent (dimensionless); t, time in min^{-1}; a and b, coefficients (dimensionless)

In addition to the microwave drying experiments, thin layer of fresh mint leaves were spread on a plastic mat and dried in-shade for seven days to determine the extent of the colour changes. Final moisture contents of traditionally dried mint leaves were then determined as 0.14 (±0.50) db. Colour properties of this leaf material were measured to describe the colour change during drying.

Mathematical modelling of microwave drying curves: To determine the most suitable drying equation, the drying curves were fitted to experimental data using eleven different Moisture Ratio (MR) equations (Table 1). The MR, however, was simplified to M/M_0 instead of the $(M-M_e)/(M_0-M_e)$[12,16]. The Root Mean Square Error (RMSE) and the modelling efficiency (EF) were used as the primary criterion to select the best equation expressing the microwave drying curves of mint[28,29]. The RMSE gives the deviation between the predicted and experimental values. The lower the values of the RMSE, the better the goodness of fit. The EF, on the other hand, determines the fitting ability of the equation and it is required to reach 1 for the best results. These statistical criterions can be calculated as follows:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \quad (1)$$

$$EF = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{exp_{mean},i}\right)^2 - \sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{exp_{mean},i}\right)^2} \quad (2)$$

where, the $MR_{exp,i}$ is the *i*th experimental moisture ratio, $MR_{pre,i}$ is the *i*th predicted moisture ratio, N is the number of observations and $MR_{expmean,i}$ is the mean value of the experimental moisture ratio.

In this study, the effect of microwave power density on the coefficients of the drying expression was also investigated by multiple regression analysis. The coefficients of the best fitting model involving the material load were determined by investigating multiple combinations of the different type of equations as simple linear, logarithmic, exponential, power, arhenius and rational.

Colour measurement: Sample colour was measured before and after drying by using a colour meter (Minolta Co.; Model: Chroma CR-100). The colour meter was calibrated against a standard calibration plate of a white surface and set to CIE Standard Illuminant C. The display was set to CIE L, a and b colour coordinates. Ten random readings per sample were recorded and the average values of colour parameters with standard deviation values were reported. The colour brightness coordinate L measures the whiteness value of a colour and ranges from black at 0 to white at 100. The chromaticity coordinate a measures red when positive and green when negative, while the coordinate b measures yellow when positive and blue when negative. Also, the metric hue angle H (Eq. 3) and the total colour difference from the fresh material ΔE (Eq. 4) were calculated from the values for L, a and b and used to describe the colour change during drying;

$$H = \tan^{-1}(b/a) \quad (3)$$

$$\Delta E = \sqrt{(L_o - L)^2 + (a_o - a)^2 + (b_o - b)^2} \quad (4)$$

Where, subscript o refers to the colour reading of fresh material which is used as the reference. Larger ΔE denotes greater colour change from the reference material[16].

RESULTS AND DISCUSSION

Effect of microwave power density on drying kinetics: The microwave drying process which reduced the material moisture contents from 7.74-7.79 db to moisture content of 0.10 db took 6.25-16.00 min, depending on the drying conditions (Fig. 1). The microwave drying can greatly reduce the drying time of mint leaves compared to the published drying data for mint by Soysal and Öztekin[4], which states that about 9 h was required to reach the moisture content of 14.31% wb for hot air drying at 46°C.

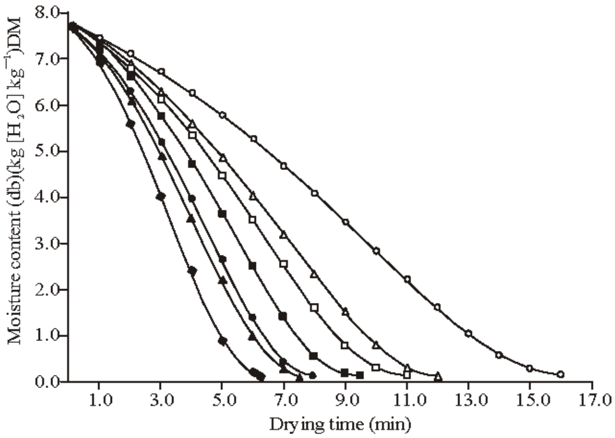

Fig. 1: Relationship between the moisture content (db) and drying time at different microwave power densities; ◆, 10 W g^{-1}; ▲, 9 W g^{-1}; •, 8 W g^{-1}; ■, 7 W g^{-1}; □, 6 W g^{-1}; △, 5 W g^{-1}; ○, 4 W g^{-1}

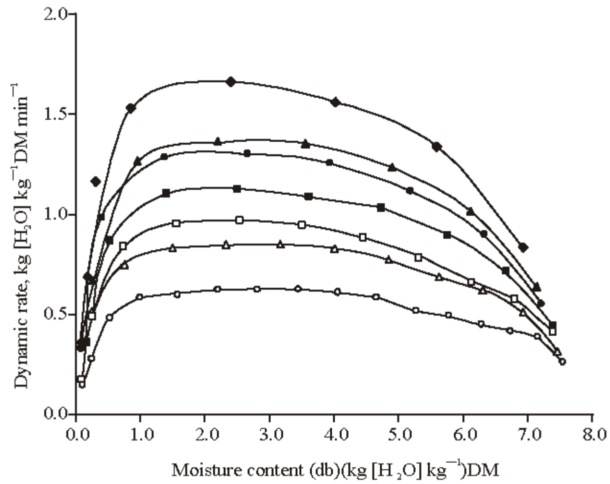

Fig. 2: Relationship between the drying rate and moisture content (db) at different microwave power densities; ◆, 10 W g^{-1}; ▲, 9 W g^{-1}; •, 8 W g^{-1}; ■, 7 W g^{-1}; □, 6 W g^{-1}; △, 5 W g^{-1}; ○, 4 W g^{-1}

It is clear that by performing microwave drying at 10 W g^{-1} microwave power density instead of 46°C hot air drying up to the moisture content of 0.10 db, the drying time can be shortened by 86.4 fold.

The lower the microwave power density, the longer the drying time of mint leaves. As the variation in initial moisture contents of the material used in drying experiments were relatively very small, the difference in drying time requirements was considered to be mainly due to the difference in applied microwave power density. By working at 10 W g^{-1} instead of 4 W g^{-1}, the drying time up to the moisture content of 0.10 db could be shortened by 2.7 fold for mint leaves (Fig. 1).

The drying rate was calculated as the quantity of moisture removed per unit time per unit Dry Matter (DM) (kg [H_2O] kg^{-1} DM min^{-1}). Depending on the drying conditions, average drying rates of mint leaves ranged from 0.48 to 1.14 kg [H_2O] kg^{-1} DM min^{-1} for the microwave power densities between 4 and 10 W g^{-1}, respectively (Fig. 2). The moisture content of the material was very high during the initial phase of the drying which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a decrease in the drying rate. Higher drying rates were obtained at higher microwave power densities. Thus, the applied microwave power density had a crucial effect on the drying rate of mint leaves. Similar findings were reported in several previous studies[10,12,16,22].

Depending on the drying conditions after a short heating period, a relatively long constant rate period was observed when drying the leaf materials (Fig. 2). These results were in good agreement with the study by Soysal[12] who claims that removal of 40.5% of the water takes place in constant rate period for microwave drying of parsley leaves. Similarly, both constant and falling rate periods were reported in some studies[18,30,31]. Although the length of the constant rate period for the leaf material dried at various material loads differed between samples, the constant rate-drying period was from about 5.75 db to about 0.75 db moisture contents. Depending on the drying conditions 60 to 65% of the water in product was removed in this period. The rapidly decreasing falling rate period followed the constant rate period and started below the 0.75 db mc.

Modelling of drying curves: The results of the statistical computations for the microwave drying data given in Fig. 1, undertaken to assess the fitting ability of 11 drying models expressing the changes in the moisture ratios with drying time, are presented in Table 2 as the values of the coefficients and statistical parameters found for the respective models. Among the all drying models used in this study, the Midilli *et al.*[39] model gave the best fit for all the experimental data points with values for the EF of greater than 0.99821 and the RMSE of lower than 0.00037. Thus, this model represented the experimental values satisfactorily.

It is also determined that the value of the drying coefficient (k) increased with the increase in applied microwave power density. This signifies that, with the increase in microwave power density drying curve

Table 2: Statistical parameters and the values of the coefficients specific to each model for various microwave power densities

Model No.	Microwave power density (W g^{-1})	k (min^{-1})	k_1	n	a	b	RMSE	EF
1	4	0.1027					0.05645	0.87753
	5	0.1383					0.05387	0.87366
	6	0.1545					0.05245	0.87466
	7	0.1862					0.05238	0.87731
	8	0.2136					0.04543	0.87915
	9	0.2363					0.04376	0.88698
	10	0.2944					0.04161	0.89136
2	4	0.0102		2.0377			0.00395	0.99142
	5	0.0161		2.1071			0.00292	0.99314
	6	0.0194		2.1239			0.00281	0.99328
	7	0.0263		2.1450			0.00215	0.99497
	8	0.0380		2.1272			0.00208	0.99447
	9	0.0473		2.0831			0.00191	0.99506
	10	0.0703		2.0910			0.00182	0.99526
3	4	0.1199			1.1504		0.04171	0.90951
	5	0.1607			1.1491		0.04048	0.90505
	6	0.1782			1.1441		0.04027	0.90376
	7	0.2132			1.1463		0.04053	0.90507
	8	0.2422			1.1294		0.03613	0.90387
	9	0.2655			1.1271		0.03512	0.90928
	10	0.3260			1.1174		0.03455	0.90981
4	4	0.0020			34.3731	−33.3191	0.00324	0.99297
	5	0.0030			30.7200	−29.662	0.00387	0.99092
	6	0.0078			13.3810	−12.324	0.00484	0.98844
	7	0.0082			14.6660	−13.614	0.00508	0.98811
	8	0.0108			13.0940	−12.041	0.00445	0.98815
	9	0.0085			17.4710	−16.4300	0.00360	0.99071
	10	0.0228			8.0181	−6.9793	0.00384	0.98998
5	4	0.0103		1.8640	0.9840	−0.0110	0.00058	0.99873
	5	0.0165		1.9382	0.9877	−0.0117	0.00053	0.99875
	6	0.0185		2.0158	0.9808	−0.0098	0.00075	0.99821
	7	0.0267		2.0173	0.9854	−0.0091	0.00060	0.99860
	8	0.0375		1.9837	0.9877	−00.0129	0.00055	0.99855
	9	0.0487		1.9008	0.9896	−0.0140	0.00037	0.99904
	10	0.0724		1.9022	0.9902	−0.0146	0.00045	0.99882
6	4				−0.0536	−0.0008	0.00384	0.99166
	5				−0.0714	−0.0014	0.00481	0.98872
	6				−0.0818	−0.0014	0.00583	0.98606
	7				−0.0997	−0.0012	0.00649	0.98481
	8				−0.1140	−0.0022	0.00537	0.98570
	9				−0.1274	−0.0015	0.00447	0.98845
	10				−0.1605	−0.0006	0.00458	0.98804
7	4	0.3602			0.0568	1.0273	0.00240	0.99480
	5	0.4939			0.0532	1.0316	0.00203	0.99523
	6	0.5565			0.0495	1.0241	0.00175	0.99583
	7	0.6529			0.0503	1.0308	0.00154	0.99639
	8	0.7556			0.0528	1.0348	0.00148	0.99606
	9	0.7928			0.0578	1.0396	0.00136	0.99648
	10	0.9670			0.0571	1.0391	0.00136	0.99646
8	4	0.1242	0.1190		0.0462	1.1018	0.04174	0.90945
	5	0.1650	0.1601		0.0754	1.0723	0.04049	0.90503
	6	0.4120	0.3662		−10.7000	11.6650	0.01073	0.97436
	7	0.4911	0.4369		−10.9900	11.9610	0.00989	0.97683
	8	0.5697	0.5045		−10.3560	11.335	0.00870	0.97685
	9	10.008	0.2775		−0.2355	1.2276	0.02373	0.93871
	10	0.3400	0.3260		0.0661	1.0530	0.03457	0.90974
9	4	0.2373			10.3860	0.2683	0.01248	0.97293
	5	0.3247			10.8960	0.3666	0.01107	0.97403
	6	0.3613			11.2640	0.4062	0.01114	0.97338
	7	0.4333			11.9720	0.4853	0.01016	0.97620
	8	0.5013			11.2750	0.5649	0.00887	0.97640
	9	0.5426			11.6430	0.6087	0.00827	0.97864
	10	0.6642			10.4964	0.7573	0.00781	0.97961
10	4	25.1823			0.0040		0.05737	0.87554
	5	54.5350			0.0025		0.05434	0.87255
	6	59.6650			0.0026		0.05290	0.87358

Table 2: (Continued)

	7	46.3460	0.0039		0.05313	0.87556
	8	51.7710	0.0040		0.04612	0.87731
	9	54.1660	0.0043		0.04444	0.88521
	10	65.3071	0.0044		0.04224	0.88972
11	4	−0.0429	−0.7073	−0.3409	0.00428	0.99071
	5	−0.0421	−1.2584	−0.2129	0.00509	0.98806
	6	−0.0408	−1.3748	−0.2806	0.00607	0.98550
	7	0.5452	−3.3178	0.7166	0.01080	0.97470
	8	0.5665	−9.8962	0.8831	0.00886	0.97643
	9	0.6103	−10.2850	0.8875	0.00826	0.97867
	10	0.7509	−10.9510	0.8918	0.00780	0.97964

becomes steeper indicating faster drying of the product. These results were in good agreement with the drying rate data, which follow the similar trends.

Further regressions were undertaken to account for the effect of microwave power density on the Midilli *et al.*[39] model coefficients. The effect of microwave power density on the coefficients of a and b, exponent n and drying coefficients k were also included in the model by multiple regression analysis (Table 3). The consistency of this model and relationship between the coefficients and applied microwave power density is evident with the values for RMSE of 0.004673 and EF of 0.99571 for the combined data.

On the other hand, the most suitable results of the Midilli *et al.*[39] model depending on the applied microwave power density were given in Table 3. The RMSE values were changed between 0.00067 and 0.00439 and the EF between 0.98970 and 0.99821 depending on the applied microwave power density. It can be seen that this model was in good agreement with the experimental results. However, it should be noted that this expression is only valid for the microwave power densities between 4 and 10 W g^{-1} and can successfully be used to estimate the moisture content of mint leaves at any time during the microwave drying.

Changes of the experimental and predicted moisture ratio values with drying time for different microwave power densities were given in Fig. 3. The established model was validated by comparing the predicted moisture ratios to the experimental values from

Table 3: Effect of microwave power density on Midilli *et al.*[39] model and its results

Microwave power density P (W g^{-1})	(RMSE)	Modelling efficiency (EF)
4	0.00096	0.99791
5	0.00439	0.98970
6	0.00134	0.99680
7	0.00100	0.99765
8	0.00067	0.99821
9	0.00180	0.99535
10	0.00211	0.99416

$$^{*}MR = \frac{M}{M_0} = (0.0.9701P^{0.0083})\exp(-(0.0006P^{2.026})t^{(1.8661P^{0.0201})}) + (-0.0053P^{0.3528})t;\ RMSE = 0.00467;\ EF = 0.99571$$

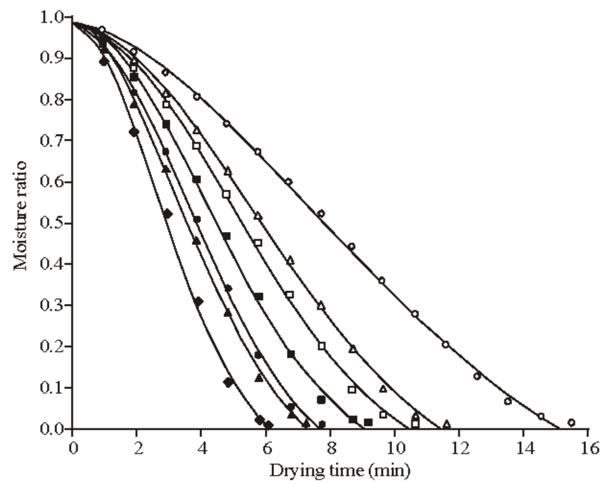

Fig. 3: Moisture ratio versus time at different material load dried at different microwave power densities; comparing experimental curve with the predicted one (-) through Midilli et al. [39] model [Eq. 5] for mint (*Mentha spicata* L.) leaves; ◆, 10 W g^{-1}; ▲, 9 W g^{-1}; •, 8 W g^{-1}; ■, 7 W g^{-1}; □, 6 W g^{-1}; △, 5 W g^{-1}; ○, 4 W g^{-1}

all drying experiments. The predicted data banded over the straight line of the 1:1 ratio, with a value for the determination coefficient (R^2) of 0.99571 (Fig. 4). The linear regression of these results gave the expression as $MR_{pre}=0.9949MR_{exp}+0.0013$.

Colour assessment: The colour of the dried product is an important quality indicator for the acceptance in the market. Dried mint leaves should have a bright green colour. The results of the colour measurements of fresh, microwave dried and traditionally in-shade dried mint leaves are given in Table 4. Total colour change (ΔE) values and the results of the multiple comparison test was used to establish the actually differing applications. It is clear that the colour of in-shade dried mint leaves were considerably differed from the fresh mint leaves ($p<0.01$) (Table 4). The L, a, b and H values of the in-shade dried mint leaves were significantly decreased

Table 4: Effect of microwave power density on the colour of mint (*Mentha spicata* L.) leaves

Microwave power density, P (W g^{-1})	Colour parameters L	a	b	H	ΔE
4	31.19±0.75a*	−3.27±0.23f	14.62±0.19a	102.59±0.87a	14.86
5	32.04±0.67a	−5.07±0.37e	14.61±0.29a	109.13±1.31b	13.04
6	32.07±0.67a	−5.12±0.29de	15.02±0.33a	108.82±0.90b	12.88
7	33.12±0.53ab	−6.14±0.52d	16.86±0.45b	109.97±1.19b	11.11
8	34.13±0.95bc	−7.87±0.47c	17.46±0.56bc	114.24±0.77c	9.15
9	35.30±0.74cd	−9.34±0.42b	18.51±0.37c	116.76±0.85d	7.29
10	36.51±1.22d	−9.82±0.33b	18.72±0.42c	117.68±0.55d	6.07
In-shade dried	34.61±1.60b-d	−5.62±0.63de	13.61±0.45a	112.40±1.82c	11.37
Fresh	41.01±2.27e	−13.85±1.38a	18.15±2.38bc	127.47±1.60e	0.00

*Tukey HSD groupings; same letter(s) in each column indicates that, there is no statistically significant difference among the treatments (p > 0.01)
L, brightness of a colour; a, greenness of a colour when negative; b, yellowness of a colour when positive; H, metric hue angle of a colour in degree

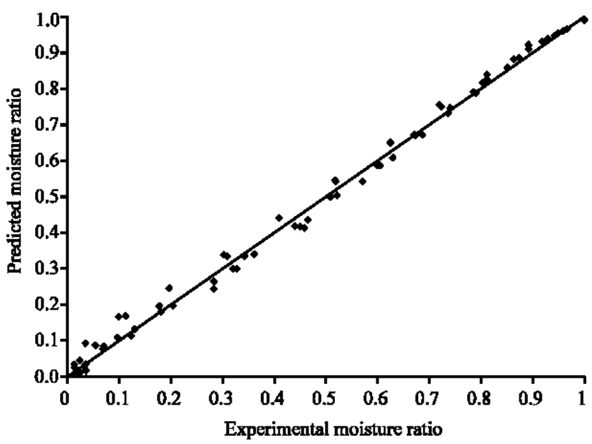

Fig. 4: Experimental and predicted moisture ratio at different microwave power densities

compared to the fresh materials. This suggests that the traditional in-shade drying produced a darker brownish green mint leaves. Thus, in-shade drying had a crucial effect on the colour of the mint leaves.

A significant decrease in L, a and H values of the microwave dried leaf materials was observed compared to colour of fresh mint leaves ($p<0.01$) (Table 4). There is no significant difference among the b values of the fresh and microwave dried mint leaves dried at microwave power densities of 7, 8, 9 and 10 W g^{-1}, respectively ($p>0.01$). These results suggest that, excepting some decrease in brightness and greenness value, microwave drying at 8, 9 and 10 W g^{-1} power densities produced better product colour compared to the traditional in-shade drying (Table 4). The total colour change (ΔE) values, which takes into account the changes in the greenness (a) and yellowness (b) values supports these results (Table 4). The microwave power densities below the 8 W g^{-1} lead to increased colour deterioration, which possibly due to the longer residence time and associated internal heat generation during drying.

CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

- Dying took place mainly in the falling rate period followed by a relatively long constant rate period after a short heating period. About 60 to 65% of the water in product was removed in constant rate period.
- The lower the microwave power density, the longer the drying time of mint leaves. Higher drying rates were obtained at higher microwave power densities. By working at 10 W g^{-1} instead of 4 W g^{-1}, the drying time up to the moisture content of 0.10 db could be shortened by 2.7 fold for mint leaves. In addition to this, the microwave drying can greatly reduce the drying time of mint leaves compared to the published hot-air drying data elsewhere. By performing microwave drying at 10 W g^{-1} microwave power density instead of 46°C hot air drying up to the moisture content of 0.10 db, the drying time can be shortened by 86.4 fold.
- Midilli *et al.*[39] model gave the best fit for all the experimental data points with values for the EF of greater than 0.99821 and the RMSE of lower than 0.00037.
- The value of the drying coefficient (k) increased with the increase in applied microwave power density signifying that with the increase in microwave power density drying curve becomes steeper indicating faster drying of the product.
- The multiple regression on the coefficients of the Midilli *et al.*[39] model for the effects of applied microwave power densities gave the high modelling efficiency value of 0.99571 and low root mean square error of 0.004673 and showed to satisfactorily represent the microwave drying kinetics of mint leaves. This expression can successfully be used to

estimate the moisture content of mint leaves at any time during the microwave drying for the power densities between 4 and 10 W g^{-1}.

- It is determined that both the in-shade drying and the microwave drying techniques used in this study caused some undesirable effects on the colour of mint leaves. Although the microwave drying techniques used in this study lead to some decrease in brightness and greenness value of the leaf colour, microwave drying at 8, 9 and 10 Wg^{-1} power densities produced better product colour compared to in-shade dried product

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