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Microwave drying behaviour of apple slices

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Abstract

In this study, microwave drying behaviour of apple slices was investigated experimentally to determine the effect of microwave power on drying, energy consumption and colour quality. Microwave drying behaviour was simulated by a theoretical drying model. Suitability of several empirical and semi-empirical models in defining the microwave drying behaviour of apple slices was determined by statistical analysis. The experimental results show that the drying time, energy consumption and the colour quality of apple slices decrease considerably with an increase of microwave power. The modelling results indicate that theoretical model simulates microwave drying behaviour of apple slices very well and among the empirical and semi-empirical models, the Page model yields the best fit with the experimental data. The modelling results also show that the excess pressure inside the apple slices shows first an increasing trend and then begins to decrease as the moisture content takes lower values.

Keywords

Microwave drying, apple, moisture content, moisture ratio, colour analysis

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Introduction

Drying has been one of the mostly used preservation techniques as it removes the majority of water from fruits and vegetables and extends the shelf life of the products resulting from reduced water activity. In conventional methods such as convective air drying, drying is a time consuming, energy intensive and expensive process. Drying is also performed at high temperatures. Therefore, product is exposed to high temperatures for longer time and a decrease occurs in the quality of the dried products. As a result of all these disadvantageous, microwave drying has gained popularity in recent years as an alternative drying method for a wide variety of food and agricultural products. Microwave energy is rapidly absorbed by water molecules which, consequently, results in rapid evaporation of water and thus higher drying rates, therefore microwave drying offers significant energy savings, with a potential reduction in drying times.[1]

There are a number of studies in the literature related to the microwave drying behaviour of fruits and vegetables. In one of these studies, microwave drying of parsley for eight different microwave power levels was investigated by Soysal.[2] The results show that by performing drying at 900 W output power instead of 30 °C, 40 °C, 50 °C and 60 °C hot air drying, drying time can be shortened by 111, 92, 37 and 31 fold, respectively. Soysal[3] also investigated microwave drying kinetics of mint and modelled the drying behaviour by several empirical and semi-empirical models. The results show that by working at 10 W/g instead of 4 W/g drying time can be shortened by 2.7 fold and Midilli et al. model gives the best fit with experimental data. The microwave drying behaviour of fish was investigated by Pianroj et al.[4] Their results show that the drying process also shows a dependence of fish surface temperature, moisture content on the radiation time and microwave power. Microwave drying behaviour of red pepper was investigated by Erdem[5] to determine the pulsing ratio on drying time and energy consumption. The results show that 45 s/45 s pulsing ratio must be preferred compared to other pulsing ratios. Microwave drying kinetics of rosehips was investigated and modelled by several empirical and semi-empirical models by Evin.[6] The results show that the Page model can be used for defining the drying behaviour of rosehips. Microwave drying kinetics of leek was investigated by Dadali and Ozbek.[7] They used 10 thin layer drying models to simulate drying and found that Midilli model yields a better fit for all drying conditions applied. The drying characteristics and

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modelling of mint leaves undergoing microwave drying were investigated by Özbek and Dadalı[8] and it was reported that among the 10 drying models, the semi-empirical Midilli model gives a better fit. Ozkan et al.[9] studied the microwave drying characteristics of spinach and found that semi-empirical Page model can be used to describe the drying kinetics of spinach. Microwave drying kinetic and physical properties of lentil was investigated by Işık et al.[10] The drying data were fitted to the various thin-layer models. Among the models proposed, semi-empirical Page models were found to give a better fit.

As it can be concluded from the literature above, in most of the studies on microwave drying, empirical or semi-empirical models were used to simulate drying behaviour. In this study, microwave drying behaviour of apple slices was investigated experimentally for various values of microwave power and a theoretical drying model was used to simulate drying. The suitability of some empirical and semi-empirical models was also specified for drying simulation of apple slices. Furthermore, a colour analysis was conducted to investigate the effects of microwave drying on the product colour quality.

Analysis

If the microwave power absorbed in the unit volume of the material is assumed as an internal heat source, energy equation for a material subjected to the microwave energy can be written as[11]

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{h_{fg}}{c}\frac{\partial m}{\partial t} + \frac{q_v}{c\rho} \tag{1}$$

where t is the time, T the temperature, h_{fg} the specific heat of the phase transition, c the specific heat, ρ the density, m the moisture content, α the thermal diffusivity and q_v the internal heat source.

The preheating of the product up to the point of phase transition ($T = T_p$) is usually performed at a high rate with little evaporation.[12] Therefore, it is possible to assume that drying begins after the temperature of the system reaches the T_p. The temperature remains constant during drying at $T = T_p$. Experiments also show negligible magnitude of the moisture content gradients as well as the temperature in high-frequency heating and drying.[13] In this case, energy equation becomes as[11]

$$\frac{\mathrm{d}\bar{m}}{\mathrm{d}t} = -\frac{q_v}{h_{fg}\rho} \tag{2}$$

where $\bar{m}$ is the average moisture ratio. The internal heat source q_v is defined as[14]

$$q_v = 2\pi f \varepsilon_o \varepsilon'' E^2 \tag{3}$$

where f is the electromagnetic field frequency of the microwave oven, ε_o the absolute dielectric constant, ε'' the dielectric loss factor of the material and E the electric field strength inside of the material.

The electric field strength is extremely difficult to predict because of the several reasons such as the complexity of the interaction between the material parameters and the oven characteristics.[14] Therefore, it was assumed that it is uniform inside the material and can be given as

$$E = k_1\bar{m}^2 + k_2\bar{m} + k_3;\;\; k_1, k_2, k_3 = \text{constant} \tag{4}$$

The internal heat generation in microwave drying results in a build-up of vapour pressure inside the product. The pressure distribution can be found from the solution of the following equation[11]

$$\frac{\partial p}{\partial t} = a_p \nabla^2 p + q_p,\;\; q_p = -\frac{1}{C_v}\frac{\partial \bar{m}}{\partial t} = \frac{1}{C_v}\frac{q_v}{h_{fg}\rho} \tag{5}$$

where p is the pressure, a_p the convective diffusivity and $C_v = (\varphi/\rho)(\mathrm{d}\rho_v/\mathrm{d}p)$ the specific vapour capacity. The equation is subjected to the following initial and boundary conditions

$$p = p_0 \text{ at } t = 0 \text{ and } p = p_0 \text{ at } x = \pm\ell \tag{6}$$

where ℓ is the half-thickness of the product. The solution of equation (6) is as follows[15]

$$p = p_0 + \frac{q_p \ell^2}{a_p 2}\left\{1 - \frac{x^2}{\ell^2} - \frac{32}{\pi^3}\sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)^3} \cos\frac{(2n+1)\pi x}{2\ell}\exp\left[-\frac{a_p(2n+1)^2\pi^2 t}{4\ell^2}\right]\right\} \tag{7}$$

The excess pressure at the centre of the body can, therefore, be expressed as

$$p_c - p_0 = +\frac{q_p \ell^2}{a_p 2}\left\{1 - \frac{32}{\pi^3}\sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)^3} \times \exp\left[-\frac{a_p(2n+1)^2\pi^2 t}{4\ell^2}\right]\right\} \tag{8}$$

In order to be able to use this solution, it is necessary to know the convective diffusivity a_p or vapour permeability coefficient K_p, which is related to the a_p as follows[11]

$$K_p = a_p C_v \rho \tag{9}$$

The vapour permeability coefficient of apple was specified by Khalloufi et al.[16] This vapour permeability coefficient was adapted to this study. Microwave energy causes the permeability to increase

Table 1. Empirical and semi-empirical drying models.[19]

Model	Model equation
Newton	$mr = \exp(-kt)$
Page	$mr = \exp(-kt^n)$
Henderson and Pabis	$mr = a\exp(-kt)$
Wang and Singh	$mr = 1 + at + bt^2$
Two-term exponential	$mr = a\exp(-kt) + (1-a)\exp(-kat)$
Logarithmic	$mr = a_0 + a\exp(-kt)$
Logistic	$mr = a_0/(1 + a\exp(kt))$
Diffusion approach	$mr = a\exp(-kt) + (1-a)\exp(-kbt)$

considerably, for example several thousand times for wood species,[17] by the formation of narrow voids. This effect was also taken into account in this study. The other property needed is porosity and it is $\varphi = 0.7$ for the apple.[18]

In this study, empirical and semi-empirical models were also taken into account in simulating the microwave drying process. The empirical and semi-empirical models require small amounts of time compared to theoretical models, and do not require assumptions of the geometry of a typical food or its thermo-physical properties.[19] Therefore, they are useful for automatic control processes. The empirical and semi-empirical models taken into consideration in this study are given in Table 1. The moisture ratio (mr) in the model equations is defined as

$$mr = \frac{\bar{m}}{\bar{m}_o} \tag{10}$$

The coefficients in the models are determined by regression analysis, and therefore, by minimizing the sum of the squared differences between the experimental moisture ratios and the theoretical ones. The determination coefficient (r^2) is one of the primary criteria in determining the best fit. In addition to the determination coefficient, the standard deviation (e_s) and mean squared deviation (φ^2) are used to determine the suitability of the fit. These parameters are defined as follows[20]

$$r^2 = \frac{S_{reg}}{S_{cor}} \tag{11}$$

$$e_s = \sqrt{\frac{\sum_{i=1}^{n_o} (mr_{pre,i} - mr_{exp,i})^2}{n_o - n_c}} \tag{12}$$

$$\chi^2 = \frac{\sum_{i=1}^{n_o} (mr_{pre,i} - mr_{exp,i})^2}{n_o - n_c} \tag{13}$$

where S_{reg} is the regression sum of squares, S_{cor} the corrected sum of squares, $mr_{pre,i}$ the ith predicted moisture ratio, $mr_{exp,i}$ the ith experimental moisture ratio, n_o the number of observations and n_c the number of coefficients in the drying model.

In this study, a colour analysis was also conducted to assess the colour quality of the dried apple slices. For this aim, L (lightness), a (redness) and b (yellowness) of the product were measured at the beginning and at the end of drying. The total colour difference (Δe) was also calculated after measurements. In addition to the parameters a, b and L, colour density C and hue angle H were also determined. These parameters are defined as

$$C = \sqrt{a^2 + b^2} \tag{14}$$

$$H = \arctan\frac{b}{a} \tag{15}$$

The change in the colour parameters can be calculated by the following relations

$$\Delta a = a_{fresh} - a \tag{16}$$

$$\Delta b = b_{fresh} - b \tag{17}$$

$$\Delta L = L_{fresh} - L \tag{18}$$

$$\Delta e = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{19}$$

where Δe represents the change in the total colour.

Material and method

In this study, Granny Smith variety apple was used to specify the experimental microwave drying behaviour. The chemical properties of this variety of apple are given in Table 2. The experiments were carried out in a microwave oven of 2450 MHz frequency, 800 W power and of 19 L capacity. The schematic view of the experimental setup is shown in Figure 1. The weight of the apple slices during the drying process was measured by a digital scale of ±0.001 g and a capacity of 620 g. The energy consumption during drying was measured by an energy meter.

The mean diameter and weight of the apple used in the experiments were 6 ± 0.3 cm and 40 ± 2 g, respectively. The moisture content of apple with respect to the wet basis is 83.5%. For determination of the moisture content, apple slices were initially dried in an oven of 105 °C for 24 h and dry mass was measured. Before the experiments, the apples were cut into the slices of 5 mm and were placed on a glass plate connected to the scale on the microwave oven. Then, the drying experiments were conducted for various microwave power levels. Weights of the apple slices during drying were transferred to a computer at regular intervals of time by Balint software. The drying was continued until the moisture content was reached to the 12% with respect to the wet basis. The energy consumptions during drying were also measured and

Table 2. Chemical properties of apple (Granny Smith).[21]

pH	Acidity (%)	Glucose (g/100 g)	Saccharose (g/100 g)	Fructose (g/100 g)
3.41	0.76	5.5	3.25	4.00

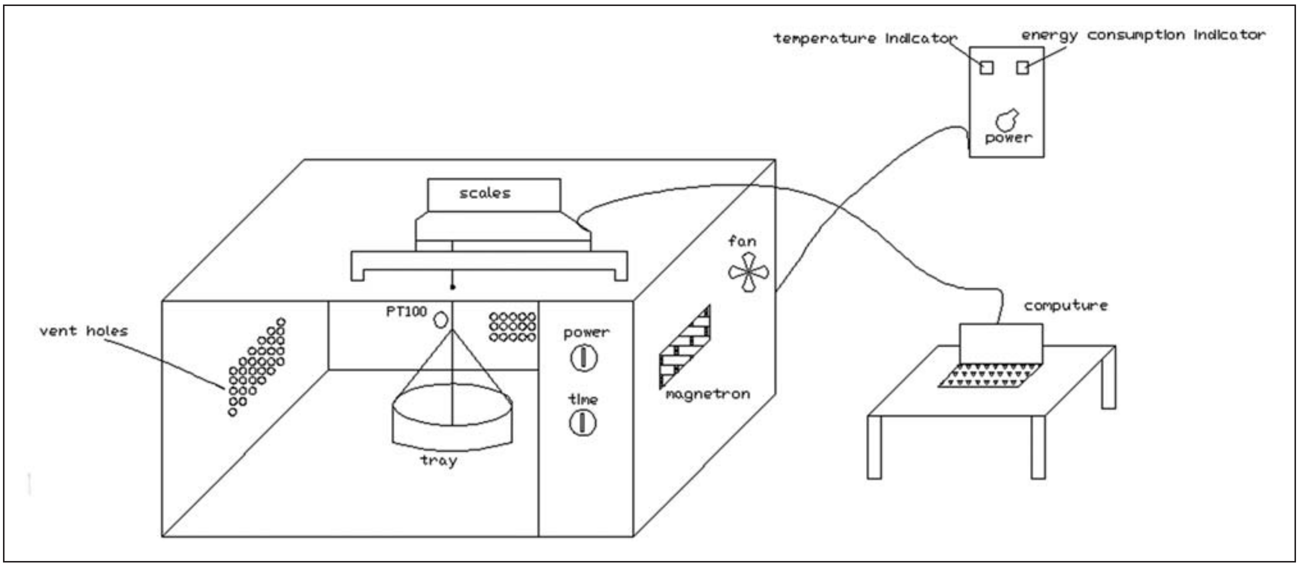

Figure 1. Experimental setup.

Table 3. Density of apple slices at the beginning and at the end of the drying.

Power (W)	V_o (cm^3)	V (cm^3)	m_o (g)	m (g)	ρ_o (g/cm^3)	ρ (g/cm^3)
90	64	17	4.1	0.7	6.4×10^{-02}	4.1×10^{-02}
180	64	12	4.1	0.7	6.4×10^{-02}	5.8×10^{-02}
360	64	9	4.1	0.7	6.4×10^{-02}	7.8×10^{-02}
600	64	6	4.1	0.6	6.4×10^{-02}	10.0×10^{-02}

recorded. Each test was repeated three times and the results were averaged to keep the uncertainties at minimum levels.

Results and discussions

In this study, microwave drying behaviour of apple slices was modelled using both a theoretical model and empirical and semi-empirical models. For theoretical modelling, equation (2) was used, which governs the moisture removal from the material and depends on the specific heat of the phase transition ($h_{fg} = 2258.10^3$ J/kg) and density of the material. The density of food materials varies during the drying depending on the moisture content and this variation can be assumed to be linear.[19]A linear variation for density was also assumed in this study. The values of the density obtained by the measurements at the beginning and at the end of drying are given in Table 3. Equation (2) also depends on the heat source and heat source depends on the electromagnetic field frequency of the microwave oven, the absolute dielectric constant ε, the dielectric loss factor of the material ε'' and the electric field strength inside of the material E. The electromagnetic field frequency of the microwave oven used in the experimental study

Table 4. Constants of electrical field strength.

Power (W)	a	b	c	err
90	−260	306	72	1.41×10^{-3}
180	−857	851	117	2.79×10^{-3}
360	−1513	1344	274	2.01×10^{-3}
600	−2590	2313	321	1.84×10^{-3}

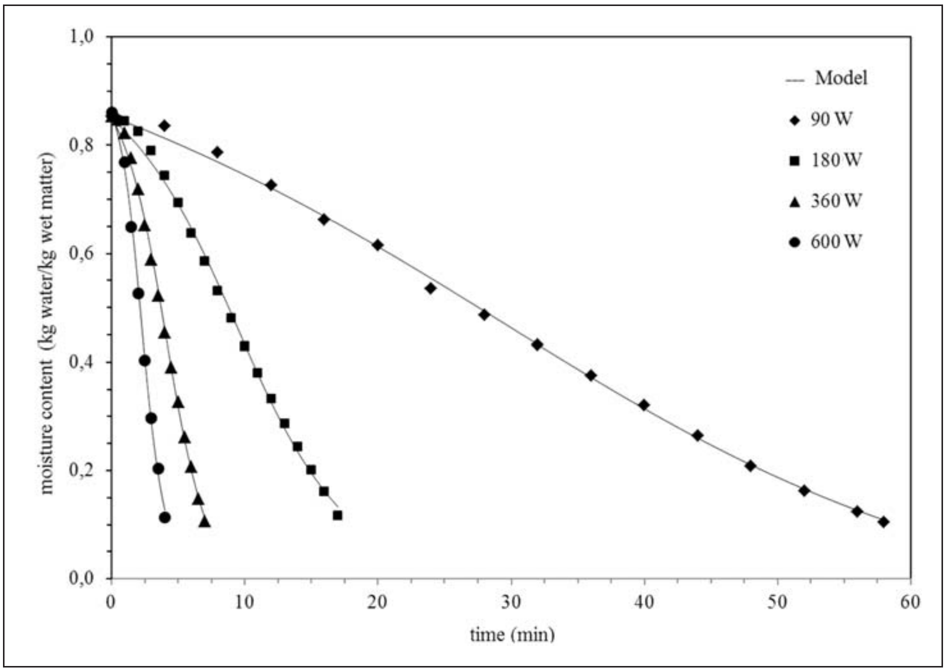

Figure 2. Drying curves based on the theoretical model.

is $f = 2450$ MHz and the absolute dielectric constant is $\varepsilon_o = 8.854 \times 10^{-12}$. Using the data available in the literature, Sipahioglu and Barringer[22] proposed the following equation for the dielectric loss factor of vegetables and fruits as a function of temperature, ash and moisture content

$$\varepsilon'' = 33.41 - 0.4415\,T + 0.001400\,T^2 - 0.1746\,m + 1.438\,A + 0.001578\,mT + 0.2289AT \qquad (20)$$

where T is the temperature (°C), m the wet basis moisture content (%) and A the wet basis ash (%). This equation was adapted to this study. The wet basis ash for the apple is 0.26%.[22] Therefore, k_1, k_2 and k_3 are the only unknowns in equation (2). These constants were obtained by minimizing the sum of squared differences between the experimental and theoretical moisture contents. Theoretical moisture contents were specified by solving equation (2). Solution of this equation was found numerically using the forth-order Runge Kutta method by a code developed by Fortran programming language. The constants obtained for various microwave power levels are given in Table 4, where *err* is the sum of the squared differences.

The predicted drying curves for apple slices are shown along with the experimental moisture ratios in Figure 2. It can be concluded that the theoretical model describe the drying behaviour of the apple slices in a microwave dryer very well. As it can also be concluded from Figure 2 that microwave power is a significant factor affecting the drying rate. The drying time decreases from 58 to 6 min with the increase of the microwave power from 90 to 360 W, which corresponds to an approximately 90% decrease.

Table 5. Energy consumptions.

Power (W)	Energy consumption (Wh)
90	122.77
180	24.08
360	7.58
600	3.67

The values of energy consumption during the drying for various microwave power level are shown in Table 5. The energy consumption decreases with an increase of microwave power level considerably depending on the decrease of drying time. Increasing microwave power from 90 to 360 W decreases energy consumption from approximately 122.77 to 3.67 Wh.

Variation of the excess pressure at the centre of the apple slices is shown in Figure 3 for various microwave power level. In this study, the preheating period was ignored and it was assumed that the drying begins as soon as the microwave power was applied. Therefore, there is a jump in the excess pressure at the beginning of the drying. The excess pressure shows an increasing trend as the drying proceeds and then begins to decrease as the moisture content of the apple slices takes lower values. As it can also be observed from Figure 3 that the microwave power has a considerable effect on the excess pressure inside the apple slices and the excess pressure shows a significant increase with the increase of the microwave power.

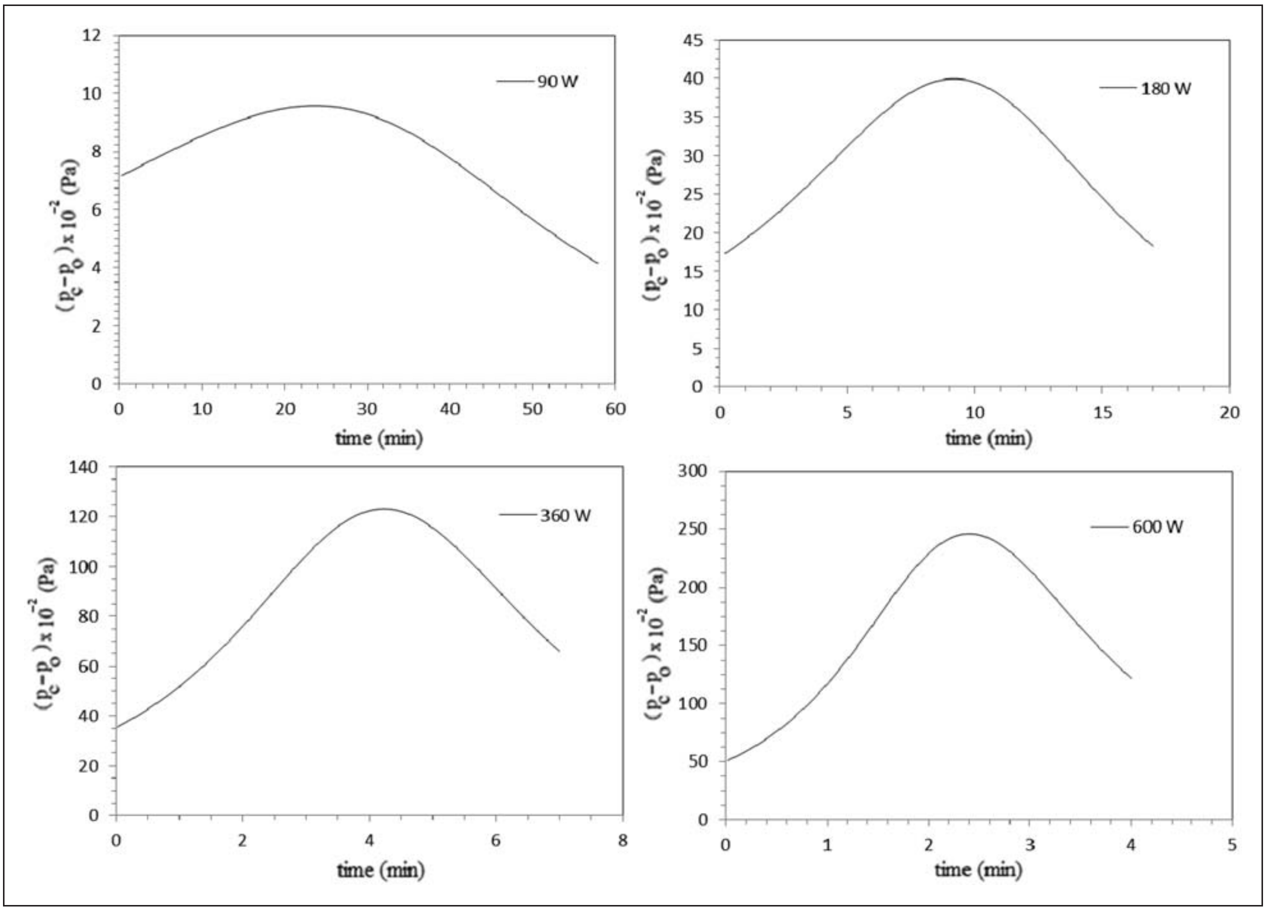

Figure 3. Variation of the excess pressure at the centre of the apple slices.

Table 6. Regression analysis results for the empirical and semi-empirical drying models.

Model	M.P. (W)	Coefficients	r^2	e_s	χ^2
Newton	90	$k = 0.023$	0.965	8.0×10^{-2}	6.4×10^{-3}
	180	$k = 0.073$	0.958	9.2×10^{-2}	8.4×10^{-3}
	360	$k = 0.176$	0.944	1.1×10^{-1}	1.1×10^{-2}
	600	$k = 0.308$	0.936	1.1×10^{-1}	1.3×10^{-2}
Page	90	$k = 0.002$, $n = 1.649$	0.996	1.9×10^{-2}	3.7×10^{-4}
	180	$k = 0.011$, $n = 1.816$	0.999	9.3×10^{-3}	8.7×10^{-5}
	360	$k = 0.041$, $n = 1.977$	0.999	1.0×10^{-2}	1.0×10^{-4}
	600	$k = 0.120$, $n = 2.004$	0.999	9.5×10^{-3}	9.0×10^{-5}
Henderson and Pabis	90	$a = 1.113$, $k = 0.027$	0.955	6.7×10^{-2}	4.5×10^{-3}
	180	$a = 1.139$, $k = 0.087$	0.945	7.2×10^{-2}	5.3×10^{-3}
	360	$a = 1.147$, $k = 0.212$	0.928	8.8×10^{-2}	7.7×10^{-3}
	600	$a = 1.130$, $k = 0.361$	0.922	9.9×10^{-2}	9.9×10^{-3}
Wang and Singh	90	$a = -0.014$, $b = 0.000$	0.998	1.6×10^{-2}	2.8×10^{-4}
	180	$a = -0.038$, $b = -0.001$	0.992	2.9×10^{-2}	8.8×10^{-4}
	360	$a = -0.083$, $b = -0.007$	0.992	3.2×10^{-2}	1.0×10^{-3}
	600	$a = -0.144$, $b = -0.021$	0.988	4.2×10^{-2}	1.8×10^{-3}
Two-term exponential	90	$a = -0.499$, $k = -0.011$	0.998	1.8×10^{-2}	3.2×10^{-4}
	180	$a = -0.299$, $k = -0.061$	0.992	3.3×10^{-2}	1.1×10^{-3}
	360	$a = -0.237$, $k = -0.180$	0.990	3.7×10^{-2}	1.4×10^{-3}

(continued)

Table 6. Continued.

Model	M.P. (W)	Coefficients	r^2	e_s	χ^2
	600	$a=-0.246$, $k=-0.303$	0.986	4.7×10^{-2}	2.2×10^{-3}
Logarithmic	90	$a_0=-17{,}964$, $a=-17{,}965$, $k=0.000$	0.999	8.8×10^{-7}	1.4×10^{-4}
	180	$a_0=-36{,}099$, $a=36{,}099$, $k=0.000$	0.994	2.3×10^{-2}	5.4×10^{-4}
	360	$a_0=-61{,}671$, $a=61{,}673$, $k=0.000$	0.991	3.2×10^{-2}	9.9×10^{-4}
	600	$a_0=-94{,}566$, $a=94{,}567$, $k=0.000$	0.987	4.4×10^{-2}	1.9×10^{-3}
Logistic	90	$a_0=1.172$, $a=0.170$, $k=0.063$	0.997	1.6×10^{-2}	2.6×10^{-4}
	180	$a_0=1.159$, $a=0.136$, $k=0.225$	0.999	1.2×10^{-2}	1.4×10^{-4}
	360	$a_0=1.108$, $a=0.092$, $k=0.617$	0.999	1.2×10^{-2}	1.4×10^{-4}
	600	$a_0=1.113$, $a=0.091$, $k=1.080$	0.998	1.7×10^{-2}	2.8×10^{-4}
Diffusion approach	90	$a=-2115.0$, $k=-0.002$, $b=0.996$	0.998	1.8×10^{-2}	3.0×10^{-4}
	180	$a=-501.6$, $k=-0.014$, $b=0.992$	0.992	3.1×10^{-2}	9.9×10^{-4}
	360	$a=-1114.4$, $k=-0.047$, $b=0.997$	0.991	3.5×10^{-2}	1.2×10^{-3}
	600	$a=-1785.1$, $k=-0.078$, $b=0.998$	0.987	4.7×10^{-2}	2.2×10^{-3}

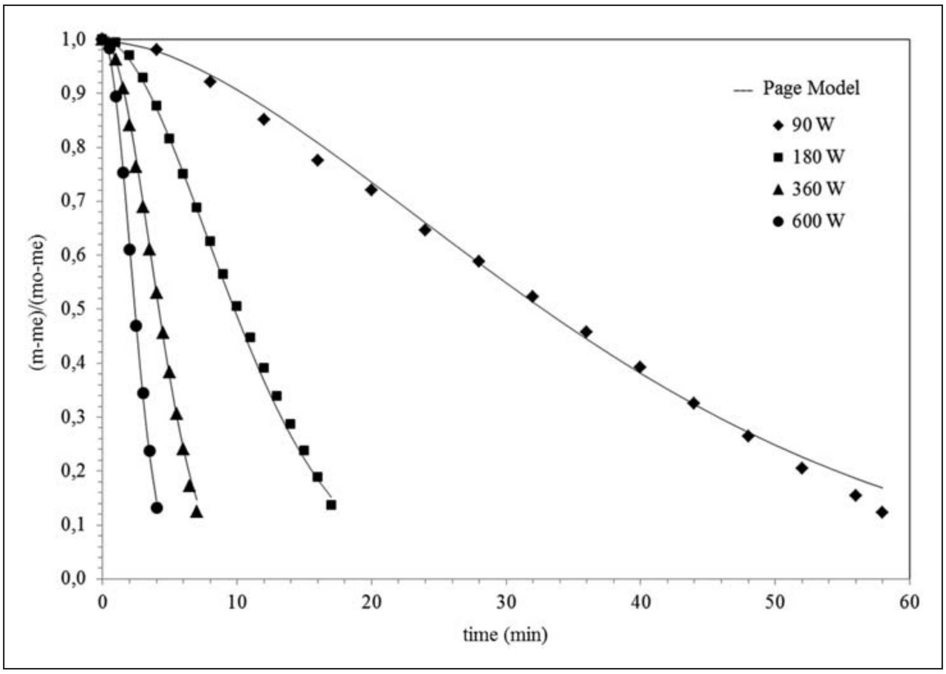

Figure 4. Drying curves based on the Page model.

As it is stated before, the empirical and semi-empirical models are also taken into consideration in this study to simulate drying. The regression analysis results for these empirical and semi-empirical drying models are given in Table 6. As it can be seen from this table that the semi-empirical Page model yields the best fit. The logistic model has also good fit results. But the Page model has fewer coefficients than the logistic model. Therefore, it can be considered as the most suitable model for simulation of drying. The acceptability of the drying model is based on a value for the determination coefficient r^2, which should be close to 1, and low values for the standard error e_s and the mean squared deviation χ^2. The drying curves based on the Page model are presented along with the experimental moisture ratios in Figure 4. As it may be concluded from this figure that the Page model satisfactorily represents the microwave drying process of apple slices.

The colour parameters of apple slices dried in a microwave drier are shown in Table 7. The brightness decreases and the change in the colour increases significantly as the microwave power increases. For microwave powers of 360 and 600 W, darkening develops in the product due to the burning. Therefore, a microwave power lower than 360 W

Table 7. Colour parameters.

	a	b	L	C	H	Δa	Δb	ΔL	Δe
Fresh	$-19.5^{0.24}$	$30.2^{0.37}$	$87.6^{0.33}$	36.0	0.99	–	–	–	–
90 W	$-7.0^{0.48}$	$26.9^{0.25}$	$70.4^{0.12}$	27.8	1.31	12.4	3.3	17.2	21.5
180 W	$-8.5^{1.15}$	$20.0^{0.33}$	$61.6^{0.27}$	21.7	1.16	10.9	10.2	26.0	30.0
360 W	$-7.4^{0.3}$	$24.3^{0.18}$	$60.8^{0.12}$	25.4	1.27	12.1	5.9	28.8	31.8
600 W	$-9.4^{0.5}$	$22.6^{0.35}$	$53.9^{0.19}$	24.5	1.17	10.1	7.6	33.7	36.0

The power represents standard deviation.

have to be preferred if the product colour quality is taken into consideration.

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Appendix

Notation

a	redness and greenness
a_p	convective diffusivity (m^2/s)
A	wet basis ash (%)
b	blueness and yellowness
c	specific heat (J/(kg °C))
C	colour density
C_v	specific vapour capacity (Pa^{-1})
e	total colour
err	sum of the squared differences
e_s	standard deviation

E	electric field strength (V/m)
f	electromagnetic field frequency (Hz)
h_{fg}	specific heat of phase transition (J/kg)
H	colour tone
k	drying constant
K_p	vapour permeability coefficient (s)
L	brightness
m	wet basis moisture content (g/g)
mr	moisture ratio
n_c	number of coefficients in the drying model
n_o	number of observations
p	pressure (Pa)
q_v	internal heat source
r^2	determination coefficient
S	sum of squares
t	time (min)
T	temperature (°C)
T_p	transition point
V	volume (cm^3)
x	coordinate (cm)
α	thermal diffusivity (m^2/s)
ε_o	absolute dielectric constant (F/m)
ε''	dielectric loss factor
ρ	density (kg/m^3)
φ	porosity
χ^2	mean squared deviation
ℓ	half-thickness (cm)

Subscripts

ave	average
c	centre
cor	corrected
exp	experimental
o	initial
pre	predicted
reg	regression
v	vapour
0	atmospheric

Superscript

–	average