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Convective hot air drying characteristics of selected vegetables

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ABSTRACT

The objectives of the present work were to investigate and to model the convective hot air-drying characteristics of carrot, zucchini and eggplant at different drying air temperatures (60, 70 and 80 °C). Drying characteristics were determined by the plot of moisture loss of samples versus drying time in 10 min intervals for each drying air temperatures. The experimental moisture data were then fitted to selected thin layer drying models available in the literature, namely Henderson and Pabis, Newton and the two-term models and good agreements between experimental and predicted values of moisture contents were observed (R^2>0.98). Results showed that all drying took place in falling rate period for all samples at all drying air temperatures studied. Increase in drying air temperature from 60 °C to 80 °C resulted in a decrease of total drying time 35%, 45% and 50% for carrot, zucchini and eggplant respectively. Drying rate constants (a, b, k, k_0 and k_1) increased with the increasing drying air temperature. Comparison between experimental and predicted values of moisture content versus drying air temperature indicated that the most suitable models for carrot, zucchini and eggplant drying were two-term, Henderson and Pabis and Newton respectively at 60 °C, two-term, Henderson and Pabis and Newton model at 70 °C and two-term, Henderson and Pabis and Newton model at 80 °C drying air temperature respectively.

1. Introduction

Turkey has a significant potential for fruit and vegetable production and export. Proper climate conditions along with other factors enable vegetable production in almost all regions. Being non-homogenous and porous in nature, fresh vegetables are highly perishable due to high water content in their structure and therefore long-term storage is impossible without being processed for preservation [1]. In this case, preservation technique plays an important role in terms of of nutritional and economical losses. Removing the excess water from structure of vegetables can be possible through drying process.

Drying, for this matter, is one of the oldest preservation methods that is used to preserve fruits and vegetables. Drying is an important method to prolong the storage period by lowering deteriorative quality changes of the fruits and vegetables. Drying of foods requires high energy input and energy share in industrial usage is nearly 15% [2]. Drying, in terms of thermal processing, involves simultaneous mass and heat transfer and therefore accuracy of spatial and temporal distribution of temperature and moisture of food depends highly on effective diffusivity [3].

During drying, the food is in contact with the surrounding hot air and therefore its temperature increases towards to dry bulb temperature as drying proceeds. In the initial period of hot air drying, moisture (un-bounded water) is transferred from the center of the food to the surface by diffusion and surface evaporation is observed while heat is transferred from the surface of the food to the center mainly by conduction as temperature of the food increases. Rate of moisture transfer to surface compensates the rate of evaporation from the surface and surface of food remains wet and wet bulb temperature is observed until the critical moisture level is reached. From this critical moisture point on, surface starts to dry out, dry patches on the surface is observed and temperature raises to dry bulb temperature [4], [5].

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Water removal from food to be dried is based on convective, conductive and radiative transfer of heat. In convective drying, the required heat to remove water is carried by a heated air. The hot air passes through the food and exits from the drier continuously during the process. Depending on the nature of the dried food material, the use of this technique needs different machinery and equipment. Cabin dryers, tunnel dryers, fluid bed dryers and spray dryers constitute common types of dryers used in air drying technique [6]. Air temperature and air flow rate are an important parameters in convectional hot air drying. Drying behavior of food materials, drying costs and effects of drying parameters on nutritional and sensorial properties of foods are better determined by the use of empirical, semi-empirical and theoritical mathematical models that originate from Fick's law of diffusion and Fourier law [2].

In the literature, large number of studies investigating the drying behavior of food products both experimentally and numerically concentrate on the factors affecting drying behavior of the food namely drying air temperature, humidity, speed and pretreatment application [7]. During the drying process of the foods, thin layer drying models are frequently preferred with the aim of determining the moisture content which varies with time as seen in Table 1. Thin layer drying models are models developed to explain the change in moisture content over time during the drying of foods. The thin layer drying models usually cover describing dying process in agricultural materials fall into three categories [8], namely theoretical, semi-theoretical and empirical [9], [10] whereas theoretical models take into account internal resistances to moisture transfer and external influences between food and its environment are taken into account in semi-theoretical and empirical models [11]. The semi-theoretical models gave closer approaches in describing drying curves than the theoretical models and therefore were used more frequently in the literature.

There are many studies in the literature describing the drying behavior of food both experimentally and mathematically. Younis et.al. [12] studied garlic slices, Rushan and Mengeş [13] potatoes, Rabha et.al. [14] bitter pepper, Silva et.al. [15] banana, Aregbesola et.al. [16] hazelnut, Hasan et.al. [17] mushrooms, Alibaş [18] artichoke, Lee and Kim [19] onion slices and Kaya and Aydın [20] experimentally investigated the behavior of the apples.

The aim of this study to investigate and to model the convective hot air drying characteristics of carrot, zucchini and eggplant determined by the plot of moisture loss of samples versus drying time at different drying air temperatures (60 ºC, 70 ºC and 80 ºC) and goodness of the fit was compared with the regression coefficients (R^2) of mathematical models (Newton, Henderson and Pabis, Two terms).

2. Materials and Methods

2.1 Material

In this study, carrot, zucchini and eggplant purchased from local markets in Gaziantep were used as research material. The selected vegetables for drying experiments were free of impurities and stored at the refrigerator temperature (4 ± 0.5 ºC) until they were analyzed.

Table 1. Thin layer drying models used in food drying.

Model name	Model	Reference
Newton	$MR = \exp(-kt)$	*(21)*
Page	$MR = \exp(-ktn)$	*(22)*
Henderson and Pabis	$MR = a\exp(-kt)$	(23)
Logarithmic	$MR = a\exp(-kt) + b$	(24)
Midilli	$MR = a\exp(-ktn) + bt$	(9,25)
Wang and Singh	$MR = 1 + at + bt^2$	(11)
Two Term	$MR = a\exp(-kt) + b\exp(-k_1 t)$	(26)

2.2.Method

2.2.1. Preparation of samples

The selected vegetables were cut into 0.5 cm x 0.5 cm x 0.5 cm cubes before drying and prepared in three parallels for each drying experiment.

2.2.2. Drying experiments

In order to determine the effect of drying air temperature on drying kinetics, drying was carried out at natural convective conditions using drying air temperatures of 60 ºC, 70 ºC and 80 ºC. To determine the variations of moisture content of carrot, eggplant and zucchini samples over time during drying experiments, moisture losses in certain time periods were measured. Drying process was carried out in laboratory type NÜVE brand FN 500 model drying oven at three different temperatures (60, 70 and 80) ºC and with three parallels in natural convective conditions. During the drying process the water losses of the samples were determined with periods of 10 min. For this purpose, the samples taken from the drying cabinet were weighed with an accuracy of 0.0001 g on an AY-220 model analytical precision scale of Shimadzu brand.

2.2.3. Determination of moisture content

The moisture contents of the samples prepared for the determination of drying behavior during drying at different temperatures under natural convective drying conditions are calculated by Equation (1):

$$M_t = \frac{(m - KM)}{KM} \tag{1}$$

where:
M_t: the moisture content at anytime (g water / g dry matter)
m: the weight of sample at the time of t (g)
KM: the amount of dry matter of sample.

2.2.4. Determination of the equilibrium moisture content

In order to determine the equilibrium moisture content of materials at the drying temperatures, the difference between the two sample weighed was continued until the difference was less than 0.01g. The equilibrium moisture content (M_e) was determined from the weight difference where the difference between the weights is negligible.

2.2.5. Calculation of dimensionless moisture content

The dimensionless humidity ratio frequently used in model equations and were given by Equation (2) [27] as follows:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{2}$$

where:
MR: moisture ratio(dimentionless),
M_t: the moisture content at anytime (g water / g dry matter),
M_e: the moisture content at the equilibrium (g water / g dry matter),
M_0: the initial moisture content (g water / g dry matter).

2.3. Modeling of Drying

Thin layer drying methods were used to explain drying characteristics of fruits and vegetables and three semi theoretical models namely Newton, Two-term, Henderson and Pabis models were used for modelling of the drying kinetics at different drying temperatures.

2.3.1.Newton model

Newton model, which is one of the most used models to explain the drying kinetics of foods was given by Equation (3) [28] as:

$$MR = \exp(-kt) \tag{3}$$

where:
k: drying constant (min^{-1}),
t: drying time (min).

2.3.2. Henderson and Pabis model

Henderson and Pabis model was given in Equation (4) [23] as:

$$MR = a\exp(-kt) \tag{4}$$

where:
a: the coefficient of Henderson and Pabis model (unitless),
k: drying constant (min^{-1}),
t: drying time (min).

2.3.3.Two Term model

The two-term model equation was given in Equation (5) as suggested by Babalis et.al. [26] as follows:

$$MR = a\exp(-k_0\, t) + b\exp(-k_1\, t) \tag{5}$$

where:
k_o and k_1: Drying constant ($min\text{-}^1$),
a: the coefficient of the two-term model (unitless),
b: the coefficient of the two-term model (unitless),
t: drying time (min) .

2.4.Mathematical Modeling of Drying Curves

In this study, experimental non-dimensional humidity-drying time change data were used for modeling studies by regression analysis methods. The experimental dimensionless moisture content curves were applied to the thin layer drying models given in Table 2.1 below and the drying constants (k, k_0, k_1), model constants (a, b) and regression coefficients (R^2) were determined by regression analysis. Sigma Plot 10.0 was used for regression analysis. The regression coefficient is the most important parameter that determines model suitability according to previous studies [29].

Table 2. Selected thin layer drying models for drying experiments.

Model Name	**Model Equation**	**Reference**
Newton	MR = exp (-kt)	[30].
Hendersonand Pabis	MR = a exp (-kt)	[23].
Two Term	MR=a.exp(k_o.t)+b.exp (-k_1.t)	[26].

3. Result and Discussion

Convective hot air drying is a process of simultaneous transfer of mass (moisture removal from the surface of the food material being dried) and heat (from the hot air to the surface of the food). Mass transfer is in the direction from center of the food to surface meanwhile heat is transferred from the surface of the food through the center by conduction. Drying experiments is carried on the determine optimum drying conditions for the specific food and operation.

Convective hot air drying characteristics of selected vegetables that are commonly used industrial food materials in hot air drying of foods namely eggplant, zucchini and carrot were studied for three different drying air temperatures (60 ºC, 70 ºC and 80 ºC) as used in commercial driers. Convectional hot air drying were conducted under natural convection conditions.

The results were expressed as the dimensionless moisture ratio that was builded from the resulting weight loss data. Plots from dimensionless moisture ratio to drying time were indicated that all drying experiments were proceeded in falling rate period and constant rate period was not observed for carrot, eggplant and zucchini samples. The total drying time for carrot, eggplant and zucchini decreased by 35%, 50% and 45% respectively when drying air temperature was increased from 60 ºC to 80 ºC. The drying times providing %50 reduction of the dimensionless moisture ratio at three different drying air temperatures studied were 150 min, 100 min, 90 min for carrot samples, 50 min, 40 min, 30 min for eggplant samples and 150, 80, min for zucchini samples, respectively. It has been determined that the increase in drying air temperature in all samples also resulted in an increase in the evaporation rate of the water from the surface of the vegetables as determined by moisture ratio, shortened the drying time and time to reach equilibrium moisture content was shorter as seen in Figure 1.

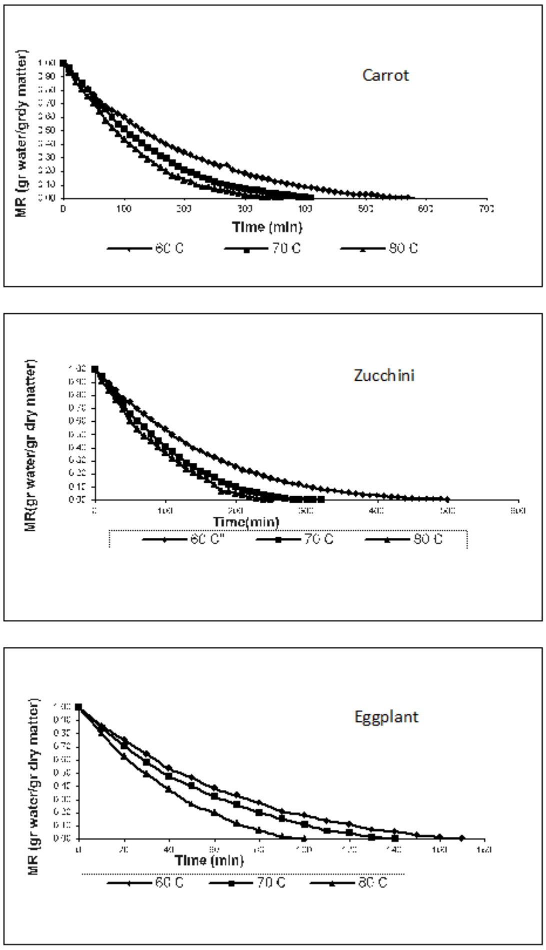

Figure 1. Change in dimensionless moisture ratios of carrot, eggplant and zucchini samples at different drying air temperatures.

Thin layer drying models are frequently used is the literature to design and optimize the hot air drying of food materials. Although they are empirical or semi-empirical in nature or consider some neglegible changes in some model parameters, these models usually show considerably good agreements with the experimental data and fairly easy to use as compared to the models originate from the laws of thermodynamics. Therefore, experimental values of drying experiments were then fitted into the selected thin layer drying models from the literature and the goodness of the fit were determined by regression analyses of the selected models. Regression analyses were performed by the comparison between the experimental and predicted data obtained from drying models. Regression coefficients (R^2) and the drying rate constants namely a, b, k_1 and k_0 were calculated as seen in Table 3. Depending on the results, drying rate constants were increased with increasing drying air temperature.

Based on the data from regression analyses Newton, Henderson and Pabis, Two Terms dryer models were determined to be suitable in describing experimental data of drying carrot, eggplant and zucchini at different drying air temperatures in the range of 60 to 80 °C. Comparisons of experimental and predicted model curves of dimensionless moisture ratio versus drying time at different drying temperatures were given in Figure 2. Each of the three thin layer drying models used was suitable for describing the experimental data obtained at different temperatures. R^2 regression coefficient value is found high ($R^2>0,98$) for each samples dried at different temperatures.

4. Conclusion

In this experimental study, drying kinetics of vegetables (eggplant, zucchini, carrot) were investigated as a function of drying conditions. In convective drying, which occurs at different temperatures in the laboratory type dryer, drying time is shortened as drying air temperature increases for all samples. Different drying behaviors were observed as respect to the drying air temperature. Henderson and Pabis, Newton and the two-term models were in good agreements between experimental and predicted values of moisture contents ($R^2>0.98$). Results showed that all drying took place in falling rate period for all samples at all drying air temperatures studied. Increase in drying air temperature from 60 to 80 ºC resulted in a decrease of total drying time 35%, 45% and 50% for carrot, zucchini and eggplant respectively. Drying rate constants (a, b, k, k_0 and k_1) increased with the increasing drying air temperature. Comparison between experimental and predicted values of moisture content versus drying air temperature indicated that the most suitable models for carrot, zucchini and eggplant drying were Two-term, Henderson and Pabis and Newton respectively at 60 ºC, Two-term, Henderson and Pabis and Newton model at 70 ºC and Two-term, Henderson and Pabis and Newton model at 80 ºC drying air temperature respectivelv.

Table 3. The results of regression analyses of carrot,eggplant, zucchini samples at different drying air temperatures.

	Drying Air Temperature (°C)	**Newton**		**Two Terms**		**Henderson and Pabis**	
		Model Coefficient	R^2	Model Coefficients	R^2	Model Coefficients	R^2
Carrot	60	8.7879E-005	0.9921	a=0.5255 k_0=9.0265E-005 b=0.5021 k_1=9.0266E-005	0.9930	a=1.0227 k=9.0266E-005	0.9930
	70	0.0001	0.9918	a= 0.5387 k_0=0.0001 b=0.5042 k_1=0.0001	0.9936	a=1,0430 k=0.0001	0.9936
	80	0.0001	0.9875	a=0.5234 k_0=0.0001 b=0.5366 k_1=0.0001	1.0000	a=1.0600 k=0.0001	0.9912
Eggplant	60	0.0003	0.9911	a=0.5062 k0=0.0003 b=0.5526 k1=0.0003	1.000	a=1.0289 k=0.0003	0.9921
	70	0.0003	0.9873	a= 0.5315 k0=0.0003 b=0.5064 k1=0.0003	0.9892	a=1,0379 k=0.0003	0.9892
	80	0.0004	0.9820	a=0.5359 k0=0.0005 b=0.5057 k1=0.0005	0.9844	a=1.0417 k=0.0005	0.9844
Zucchini	60	0.0001	0.9929	a=0.5158 k_0=0.0001 b=0.5275 k_1=0.0001	1.000	a=1.0433 k=0.0001	0.9948
	70	0.0002	0.9846	a= 0.5592 k_0=0.0002 b=0.5088 k_1=0.0002	0.9893	a=1.0622 k=0.0002	0.9833
	80	0.0002	0.9790	a=0.5222 k_0=0.0002 b=0.5400 k_1=0.0002	1.0000	a=1.0622 k=0.0002	0.9833

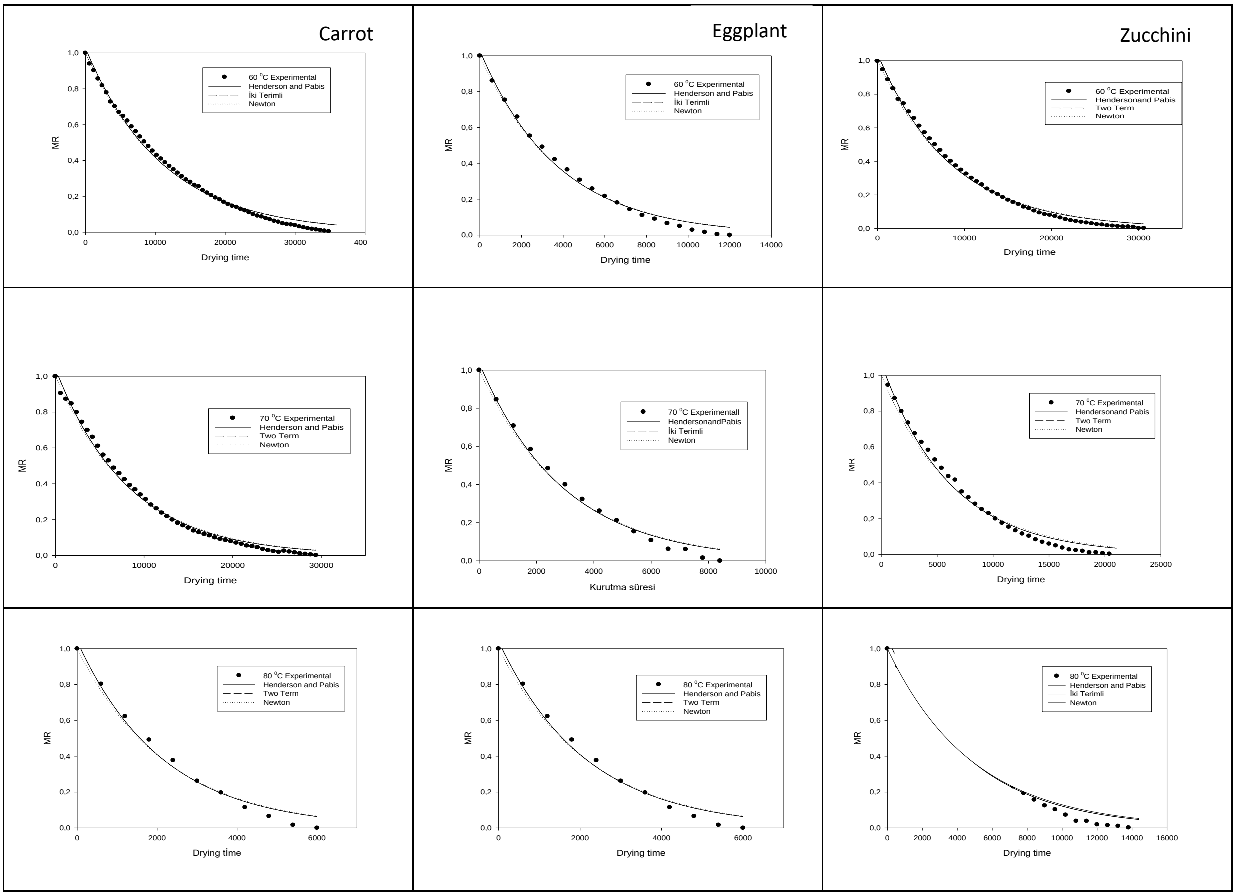

Figure 2. Comparisons of experimental and predicted thin layer model curves of carrot, eggplant and zucchini samples seen in columns respectively at different drying air temperatures.

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