MODELLING OF THE DRYING OF MILLED CARROT USING MICROWAVE AND LABORATORY OVEN

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Abstract
The effect of drying temperature and microwave power was carried out on the drying characteristics of milled carrot. The milled carrots were dried in laboratory oven (40 - 80 ^{O}C) and microwave drying system (180-900W) at constant sample thickness and air velocity of the system. Moisture content, moisture ratio, drying rate and drying time were used to examine the drying characteristics of the milled carrot and the dimensionless moisture ratio was fitted into the ten (10) thin-layer empirical model to properly predict the drying behaviour of milled carrot. In addition, the temperature and power dependence of the effective diffusivity (D_{eff}) coefficient was expressed by an Arrhenius type relationship and the activation energy (Ea) was determined. The initial moisture content of milled carrot was approximately 87.78% ± 0.35 (wet basis) and the result shows that the microwave drying system reduces the drying time of the milled carrot as its drying rate is higher than that of the oven dried sample. The Hii et al model was selected as the best thin layer mathematical model for predicting the drying characteristics of the milled carrot. The effective moisture diffusivity (D_{eff}) of milled carrot increased progressively from 100.49×10^{-10}(m^2/s) to 250.16×10^{-10} (m^2/s) as the power increased from 180W to 900W in the microwave drying system and this result is higher than that of the oven dried sample which decreases progressively from 69.01×10^{-10} (m^2/s) to 20.32×10^{-10} (m^2/s) as the temperature decreases. The activation energy ranges between 13.22 - 38.65 kJ/mol for microwave oven and 22.00 to 39.89 kJ/mol for laboratory oven.

Keywords: Milled carrot; Thin-layer drying; drying kinetics; Modelling; Effective diffusivity; Activation energy

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1. INTRODUCTION

Carrots are root vegetable also known as *Daucus carota*, a member of the *Umbelliferae* family and thus related to parsley, dill and celery. Like the rest of these vegetables, an umbrella like inflorescence called the umbel is being possessed by carrot plant (Chapman and Hall, 1997). Carrots are one of the top ten foods that consumers recognise as health benefits beyond basic nutrition" (Charles, 2003). This reputation comes with good reason, as carrots are rich in carotenoids (pro-vitamin A) which are used to make vitamin A during digestion, and vitamins B, C, D, and E. They are also high in folic acid, fibre and minerals like K and Na.

Drying is an energy intensive operation involving moisture removal from a product in order to reach the desired moisture content and this is due to heat alongside mass transfer which contributes to the involvement of the application of heat to vaporize moisture and removing water vapour after its complete separation from the food products. In a drying process, a large amount of energy is needed for sensible heating and phase change of water and the high energy consumption is as result of energy required for water removal via a phase change, as well as the low heat transfer efficiency occurring in the falling rate period of a (hot-air) drying process. Majorly, the main objective involved in drying agricultural products is the reduction of the moisture contents to a level which allow safe storage over an extended period. In addition it also brings about substantial reduction in weight and volume minimizing packaging, storage and transportation costs.

According to Klemes *et al.* (2008), more than 200 various dryers can be used to perform different functions. In addition the features for drying of pressure, air velocity, relative humidity and product retention time vary according to the material and method of drying. Also the total estimation of drying feed on about 10% to 15% of the total energy requirements of all food industries in developed countries (Keey, 1972; Klemes *et al.,* 2008). Thus, it is energy-intensive based. In summary, drying is arguably the most long standing, diverse, and conventional operation. Consequently, the engineering aspects of drying have essential consideration needed. According to Kudra and Mujumdar (2002), industrial institute prefers conventional technologies compared to novel technologies. The simplicity of dryer construction is one of the multiple reasons, ease of operations and as well as the status of familiarity (Araya-Farias and Ratti, 2009).

Numerous conditions affecting the drying of fruits and vegetables include air velocity, drying temperature, size and shape of the material, and the relative humidity. Amongst these conditions, the most influential in terms of drying fruits and vegetables are drying temperature and material thickness (Meisami-asl and Rafiee, 2009; Pandey *et al*., 2010; Kuma *et al*., 2012). It has been debated that the air velocity rate significantly affects the drying process of food and agricultural products (Yaldiz *et al*., 2001; Krokida *et al*., 2003). However, this is mostly carried out on crops such as rice, corn, potatoes, and so on. Drying of fruits and vegetables are being studied to indicate that the air velocity has little influence on the drying kinetics of most of them (Tzempelikos *et al*., 2014; Darıcı and Şen, 2015). Result which are similar are being taken and recorded by Yaldiz *et al*. (2001); Akpinar *et al*. (2003); Krokida *et al*. (2003); Menges and Ertekin (2006); Sacilik (2007); and Meisamiasl *et al*. (2010), being highlighted by the authors that the effect of air velocity could depend on the respective heat and mass transfer, which could have either internal or external resistance. Greater internal resistance exists at a lower air velocity (≤1.5m/s) than at a higher flow rate. Generally, this parameter can only have great influence at air velocity above 2.5m/s (El-Beltagy *et al*., 2007; Reyes *et al*., 2007; Perez and Schmalko, 2009 and Guan *et al*., 2013).

For industrial drying, Erbay and Icer (2010) after their analysis reported that higher drying rates can be achieved with a minimum drying time when drying at higher velocities and temperatures. However, the final quality of fruit and vegetable and the total energy demand might be undesirably affected when drying at a very high temperature (above 80 °C) (Shi *et al*., 2008; Chen *et al*., 2013) and higher velocity (above 2.5 m/s), Therefore, it is not advisable to dry at extremely high temperature and air velocity.

Surface area (size and shape) serves as important parameter in the drying of bio-material. It is harmless to dry most fruits and vegetables using the approach of thin-layer which means that the size of the material is reduced to a specific dimension that will allow distribution to be uniform of the drying air and temperature over the material. The technique which involves the kinetic model of drying was integrated into the surface area factor in term of size to reduce the effect of product shape on the drying process (Pandey *et al*., 2010). Furthermore, the relative humidity of the drying chamber often fluctuates due to the conditions of the ambient temperature and relative humidity of the environment, hence this has less influence on the entire drying process of fruits and vegetables (Aghbashlo *et al*., 2009; Sturm *et al*., 2012; Misha *et al*., 2013). In summary, during the period of drying process the air velocity and relative humidity are the least significant factors that affect the drying kinetics of fruits and vegetables.

In Africa especially in Nigeria agricultural activities from most time requires tenacious and laborious input by farmers. The effort of farmers may be lost due to poor storage mechanism and inadequate processing facilities. Drying is essential and one of the common methods for preservation of agricultural products among several other methods, offering dehydrated products to have extended shelf life. The mathematical modelling of drying processes and equipment is the most important aspect of drying technology. the principle of modelling is based on having a set of mathematical equations that can adequately characterize the system. The main purpose is to allow design engineers to choose the most suitable operating conditions and then size the drying equipment and drying chamber accordingly to meet desired operating conditions. The main particular solution of these equations must allow prediction of the process parameters as a function of time at any point in the drying systems (Gunhan *et al*., 2005). Also, there is limited information about the modelling of thin layer, drying of carrot as influenced by reduction of particle size. Therefore, this study aims at the modelling of thin layer drying of milled carrot which will help in optimization of its drying process with focus on promoting its local acceptability and industrialization.

2. MATERIALS AND METHODS

2.1. Materials and Sample Collection

The materials used for experimentation of the modelling of thin layer drying of milled carrot as functions of drying temperature and microwave power was carried out with the availability of some materials which include Carrot (*Daucus carota L*, *Umbelliferae* family *Apiaceae*), Weighing balance, Thermometer, Laboratory Oven, Microwave Dryer, Desiccator, etc. The Carrot (*Daucus carota*) used for this study were purchased from the local market in Akure south local government, Ondo state, prior to the commencement of the experimentation. The carrot of the same size, free of disease, and without any visible defects was selected, cleaned, sealed and stored in a refrigerator at about 4°C.

2.2. Drying Equipment

Drying studies were carried out with a digital laboratory dry oven (Searchtech Instrument, DGH-9053A) with technical feature of 220 V, 50 Hz and 500 W and microwave oven (Nexus, NX-805c) with the technical feature of 230 V, 50 Hz and 900 W. The laboratory oven consists of heating element designed to be trigged on from the switch on the control panel to pre-heat the oven to a certain air temperature before the agricultural product is introduce into the oven drying tray. Its fan is for the evenly distribution and circulation of hot air in the oven and the thermostat is to ensure the thermal stability during drying. For the microwave oven, it was equipped with a microwave output power controller and timer to estimate and control the time of processing. The oven has a fan for air flow in drying chamber and cooling of magnetron. The moisture from drying chamber was removed with this fan by passing it through the openings on the right side of the oven wall to the outer atmosphere.

2.3. Drying Experiment

The initial moisture contents of the carrot samples were determined in three replicates using standard oven dried method. About 50g of the sample was dried in an oven at 105 ± 2°C for about 24 hours. The experiments were replicated three times.

Prior to the drying experiments, the carrots were washed and cut into slices with the thickness of about 5mm and milled using electric blender. The dryer was put in operation about 1hr for laboratory oven and 5min for microwave drying system before each experiment in order to achieve desirable steady state conditions. Then, about 50g of fresh milled carrot in a thin layer was weighed using a balance with accuracy of 0.01g and placed in the drying system in replicates, the reduction in mass was monitored at 30 minutes interval for the laboratory oven and 30 seconds interval in the microwave drying system. The experiments were performed at air temperatures of 40, 50, 60, 70 and 80°C at constant air velocities for laboratory oven and microwave power of 900, 720, 540, 360 and 180 W in microwave drying system. The equilibrium moisture content of the carrot slices was determined using a dynamic method as the experiment was terminated as the mass loss of the sample ceased with time in accordance to the report of Kashaninejad *et al*. (2007).

2.4. Theoretical consideration

Moisture ratio content determination

Moisture ratio of samples during drying was determined using the following equation:

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \qquad (1)$$

As the M_e value is very small compared to M_o and M values, the M_e value can be neglected and the moisture ratio was simplified and it can be expressed as

$$MR = \frac{M_t}{M_0} \quad (2)$$

Where: M_t is moisture content at time t, M_e is equilibrium moisture content, M_o is the initial moisture content, and MR is the dimensionless moisture ratio.

Moisture content determination

The quantity of moisture present in a material can be expressed either on the wet basis or dry basis and expressed either as decimal or percentage. The moisture content on the wet basis is the weight of moisture present in a product per unit weight of the undried material represented as,

$$M_{wb} = \frac{w_o - w_d}{w_o} \, x \, 100\% \quad (3)$$

Where W_o is the wet weight at a particular time, W_d is the dry weight of sample and M_{wb} is the moisture content on wet basis.

Drying rates

Agricultural products that are mostly hygroscopic in nature always has some moisture as residue after the drying while the drying for non-hygroscopic material such as sand, dust ,stone ,textiles in a laundry ,paper etc can continue to moisture content which is up to zero. Due of hygroscopic products, moisture is trapped in a capillary which is being enclosed. The rate at which moisture flow is relatively proportional to its vapour pressure difference with the environment because of the crop resistance to moisture flow. The drying rate regimes for agricultural products are of two main types, namely the constant drying rate period and the falling drying rate period and drying rate is shown in equation 5.

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \quad (5)$$

2.5. Model Fitting

To select a suitable empirical thin layer mathematical model used in describing the drying behaviour of the milled carrot were presented in Table 1, the drying curves were fitted into different thin layer drying equations using non-linear regression approach on Microsoft excel (Solver tool pack). Statistical parameters such as the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were used as the criteria for selecting the best model. The goodness of fit was determined by the high R^2 value and low χ^2 and RMSE values.

2.6 Estimation of effective moisture diffusivity

The drying processes are governed by internal mass transfer resistance. Fick's second law for diffusion can be used for the determination of drying characteristics of biological materials in the falling rate period (Arslan and Ozcan 2010; Maskan et al. 2002). The general series solution of Fick's second law for spherical co-ordinates under the assumption of constant moisture diffusivity and temperature, and also the negligible shrinkage is given by Doymaz and Akgun (2005) in equation 6.

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (6)$$

where D_{eff} is the effective diffusivity (m^2/s); L is the half thickness of slab (m)

The linear solution of the equation is obtained by using a simple approach that assumes that only the first term in the series equation is significant (Tutuncu & Labuza, 1996). Then, Eq. (7) is obtained by taking the natural logarithm of both sides. It shows that the time to reach given moisture content will be directly proportional to the square of the half-thickness and inversely proportional to D_{eff}

$$\ln MR = ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (7)$$

Diffusivities are typically determined by plotting experimental drying data in terms of ln(MR) versus time in Eq. (7), and the plot gives a straight line with a slope of

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \quad (8)$$

Table 1. Some thin layer drying models

Model Name	Model Equation	REFERENCE
Newton	$MR = exp\ (-kt)$	Ayensu (1997); Togrul and pehlivan (2004)
Page	$MR = exp\ (-kt^n)$	Kaleemullah Kaleemullah and Kailappan (2006)
Modified Page	$MR = exp\ [-(kt)^n]$	Goyal *et al*. (2007); Ceylan *et al*. Sogi *et al* (2006); White *et al*. (1978)
Henderson and Pabis	$MR = aexp(-kt)$	Kashaninejad *et al*. (2007); Saeed *et al*. (2006); Ozdemir and Devres,(2000); Zhang and Litchfield (2015)
Logarithmic	$MR = a\ exp\ (-kt) + c$	Babalis *et. al*. (2006); Celma *et al*. (2007);
Two-term	$MR = a\ exp\ (-kt) + b\ exp\ (-gt)$	Lahsani *et. al*. (2004); Rahman *et al*. (1998); Wang *et. al*. (2007)., Henderson (1974)
Two-term exponential	$MR = a\ exp\ (-kt) + (1 + a)\ exp\ (-kat)$	Midili and Kucuk (2003); Sacilik *et. al*. (2006); Tarigan *et. al*. (2007)
Wang and Singh	$MR = 1 + at + bt^2$	Wang and singh (1978)
Approximation of diffusion	$MR = a\ exp\ (-kt) + (1 - a)\ exp\ (-kbt)$	Wang *et al*. (2007); Yaldiz and Ertein (2001); Togrul and pehlivan (2002)
Modified Henderson and Pabis	$MR = a\ exp(-kt) + b\ exp\ (-gt) + c\ exp\ (-ht)$	Karathanos (1999).
Verma *et al*	$MR = a\ exp(-kt) + (1 + a)\ exp(-gt)$	Doymaz, (2005); Karathanos, (1999); Yaldiz and Ertekin,(2001); Verma *et al*., (1985)
Midilli and Kucuk	$MR = a\ exp\ (-kt^n + bt)$	Midilli *et al*. (2002)
Hii *et al*. model	$MR = aexp(-kt^n) + cexp(-gt^n)$	Hii *et al*. (2008)
Verma *et al*. model	$MR = a\ exp(-kt) + (1 - a)\ exp(-gt)$	Akpinar (2006)
Modified Midilli *et al*.	$MR = a\ exp(-kt) + b$	Gan and Poh (2014)
Diamante *et al*. model	$ln\ (-ln\ MR) = a + b\ (ln\ t) + c\ (ln\ t)^2$	Diamante *et al*., (2010)
Thompson	$t = a\ ln(MR) + b[ln(MR)]^2$	Pardeshi (2009)
Peleg model	$MR = 1 - \frac{t}{(a + bt)}$	Da Silva *et al*. (2015)

3. RESULTS AND DISCUSSION

3.1. Analysis of the drying curves

The changes of the moisture ratio versus drying time, drying rate versus drying time, moisture content versus time and drying rate versus moisture content for the milled carrot samples laboratory oven and microwave drying system are given in Figure 1 and 2 respectively. The figure reveals that the moisture ratio continuously decreases with drying time for increasing temperature and microwave power, and no constant drying rate period exists. However, there was an initial increase in the rate of drying with time until about 10 – 12 min in the microwave drying system and gradually decreases in the later. This observation is in agreement with the findings of Gogus and Maskan (2001) and Kadi and Hamlat (2002) on drying of olive cake. In the laboratory oven, the rate of moisture loss was initially low and rapidly increases before it later reduces as the sample approaches equilibrium. More so, about two-thirds of the time might have been spent removing the last one-third of the moisture content due to the slow diffusion process and the rate of moisture loss was greater at higher temperature, and the total drying time was reduced substantially with the increase in air temperature. Nevertheless, for the microwave drying system, The drying time required to reduce the moisture content of milled carrot from 58% w.b. to about 1.1 % w.b. decreased from 97min to 27min as the microwave power increases from 180W to 900W (Figure 2) This indicated that the greater the power applied, the shorter of the drying time required for the. These results also were consistent with previous literatures (Ozkan *et al.*, 2007; Alibaz, 2007 and Dalali *et al.*, 2007). As the drying progressed, almost all of the drying rate in various microwave output power shows a decreasing trend which maybe as a result of decrease in the absorption of microwave power due to the loss of moisture. Besides, as the microwave output power increased, the drying rates also increased. The highest drying rate obtained in 900W was $0.4545 kg_{water}\ kg_{matter}^{-1} min^{-1}$, it was 31.34 times higher than those in 180W which was $0.0145 kg_{water}\ kg_{matter}^{-1} min^{-1}$. Generally, the drying rate decreased continuously with time and decreasing moisture content. As indicated in these curves, there was no constant drying rate period in the drying of selected fruits. All the drying process occurred during the falling rate-drying period. During the falling drying rate period, the predominant mechanism of mass transfer in the sample is that of internal mass transfer. The internal mass transfer was therefore by molecular (liquid) diffusion or vapour diffusion or by capillary forces in the interior (wet) region of the product and the water was evaporated as it reached the surface (negligible resistance to mass transfer). The most probable mechanism within all mechanisms governing moisture transfer was that of liquid diffusion.

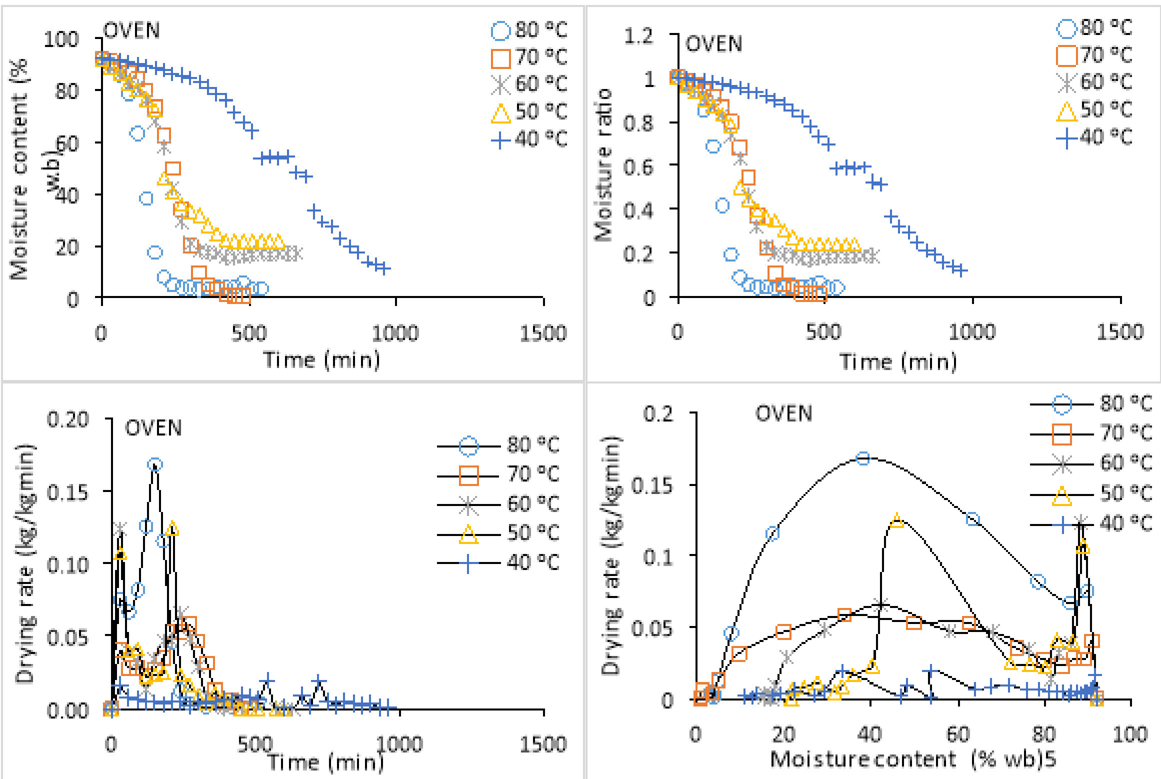

Fig. 1. Drying curve of milled carrot at different temperature for laboratory oven

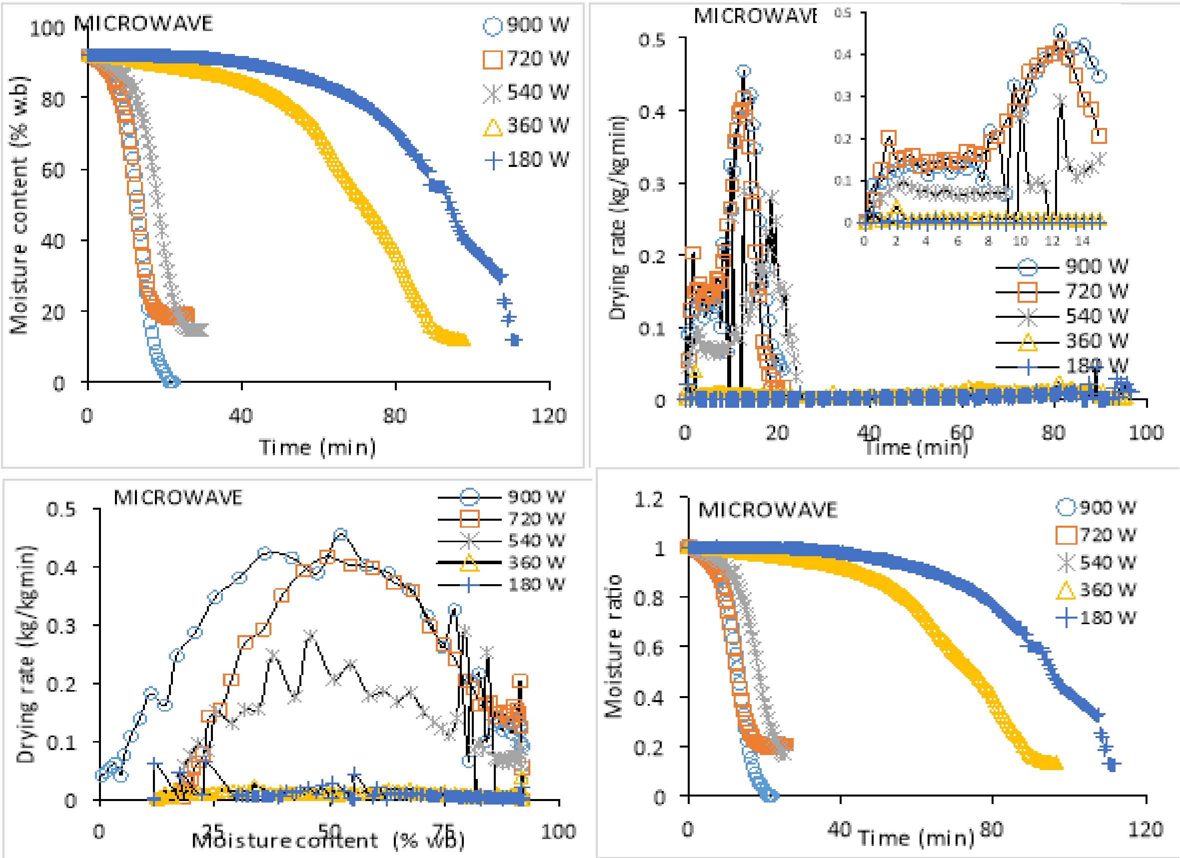

Fig 2. Drying curve of milled carrot at different power for microwave drying system

3.2. Fitting of the thin-layer drying curves

Selected ten (10) mathematical thin layer drying models were used for predicting the changes in the moisture ratio of milled carrot with the drying time at temperature 80, 70, 60, 50 and 40 °C in the laboratory oven and 180, 360, 540, 720 and 900W in microwave drying system. The obtained statistical parameters of the fitted data for the ten (10) models are presented in Table 4.1 and 4.2. Accordingly, all tested models could adequately describe the behaviour of drying milled carrot using a Laboratory oven and Microwave oven. The models revealed high values of R^2 for laboratory oven which varied between 0.9989 to 0.8973, 0.8407 to 0.9990, 0.8974 to 0.9305, 0.8636 to 0.9741 and 0.8431 to 0.9926 for temperature 80°C, 70°C, 60°C, 50°C and 40°C respectively. Also revealed high R^2 values for different powers of the Microwave drying system over which varied between 0.7934 to 0.9992, 0.8819 to 0.9976, 0.8160 to 0.9924, 0.7393 to 0.9815 and 0.7189 to 0.9430 for power 900W, 720W, 540W, 360W and 180W respectively. Nevertheless, Midili and Kucuk model and Hii *et al.* model averagely displayed the highest degree of accuracy ($0.930<R^2<0.999$) and the lowest residual values ($0.000<\chi^2<0.010$; $0.015<RMSE<0.089$ and $0.018<SEE<0.101$) for all the oven temperature and microwave power respectively. Consequently, the Midili and Kucuk model and Hii *et al.* model was selected as the best model among all the tested models that accurately express the thin-layer drying behaviour of milled carrot under the studied conditions. The constants of the best model for describing the thin-layer milled carrot drying curves are shown in Table 2 and 3 for laboratory oven and microwave drying system respectively. Figure 3 depicts the plots of the experimental and the predicted moisture ratio by the best model (Midili and Kucuk model and Hii *et al.* model) of milled carrot for laboratory oven and microwave oven respectively. From the plots, it is clear that the models gave an accurate prediction for the drying process of milled carrot under the tested settings.

Table 2. Model constant and goodness of fit parameter of the selected models for different temperature

Temperature	Model	Model constant	R^2	RMSE	SEE	X^2
80^0C	Newton	k = 0.385	0.9071	0.1332	0.1369	0.0187
	Henderson and Pabis	k = 0.449, a = 1.2029	0.9032	0.1166	0.1233	0.0000
	Page	k = 0.0437, n = 3.2447	0.9977	0.0344	0.0364	0.0043
	Logarithmic	k = 0.3969, a = 1.2457, c = -0.0581	0.9070	0.1127	0.1228	0.0253
	Two term	k = 0.7286, g = 1.5569, a = 2.6853, c = -1.7118	0.9661	0.0680	0.0766	0.0061
	Verma et al	k = -0.0009, g = 0.2979, a = -0.1255	0.8973	0.1266	0.1379	0.0131
	Diffusion approach	k = 0.9884, g = 1.0486, a = 34.0375	0.9700	0.0644	0.0702	0.0020
	Midili Kucuk	k = 0.0352, b = 0.0063, a = 0.9805, n = 3.516	0.9989	0.0125	0.0141	0.0161
	Wang and Smith	a = -0.2894, b = 0.0208	0.9333	0.1075	0.1137	0.0210
	Hii et al.	k = 0.0469, g = 0.0082, a = 0.9343, c = 0.0596, n = 3.2579	0.9969	0.0318	0.0370	0.0037
70^0C	Newton	k = 0.2148	0.8704	0.1911	0.1970	0.0388
	Henderson and Pabis	k = 0.2653, a = 1.2384	0.8407	0.1660	0.1767	0.0312
	Page	k = 0.0053, n = 3.4903	0.9981	0.0189	0.0201	0.0004
	Logarithmic	k = 0.0023, a = 69.6882, c = -68.554	0.9373	0.1001	0.1103	0.0122
	Two term model	k = 0.2864, g = 14.6379, a = 1.3402, c = -0.2513	0.8720	0.1508	0.1724	0.0297
	Verma et al	k = -0.0436, g = -0.0379, a = -23.8734	0.9293	0.1119	0.1233	0.0152
	Diffusion approach	k = 0.0002, g = -5.8533, a = 99.6849	0.9374	0.1215	0.1339	0.0179
	Midili Kucuk	k = 0.0041, b = 0.0023, a = 0.9789, n = 3.6693	0.9986	0.0156	0.0179	0.0003
	Wang and Smith	a = -0.0917, b = -0.0068	0.9302	0.1100	0.1172	0.0137
	Hii et al.	k = 0.0182, g = 0.0438, a = 1.4769, c = -0.4968, n = 2.8625	0.9986	0.0150	0.0178	0.0003
60^0C	Newton	k = 0.1121	0.9066	0.1101	0.1126	0.0127
	Henderson and Pabis	k = 2.1305, a = 0.1395	0.9079	0.0978	0.1023	0.0105
	Page	k = 0.1286, n = 0.9412	0.9246	0.0908	0.0951	0.0090
	Logarithmic	k = 0.1386, a = 1.0011, c = 0.0545	0.9064	0.0985	0.1056	0.0112
	Two term mdel	k = 0.1614, g = 0.0403, a = 0.8671, c = 0.1982	0.9076	0.0978	0.1076	0.0116
	Verma et al	k = 0.0237, g = 0.1344, a = 0.0974	0.9073	0.1149	0.1232	0.0152
	Diffusion approach	k = 0.1121, g = 1, a = 3.0345	0.9036	0.1073	0.1151	0.0133
	Midili Kucuk	k = 0.1266, b = 0.0016, a = 1.0457, n = 1.0047	0.9298	0.0915	0.1007	0.0101
	Wang and Smith	a = -0.0776, b = 0.0015	0.8974	0.1051	0.1100	0.0121
	Hii et al.	k = 0.0575, g = 0.0046, a = 0.6804, c = 0.3086, n = 1.723	0.9305	0.0897	0.1014	0.0103
50^0C	Newton	k = 0.2148	0.9326	0.0860	0.0881	0.0078
	Henderson and Pabis	k = 0.2653, a = 1.2384	0.9332	0.0754	0.0793	0.0063
	Page	k = 0.0053, n = 3.4903	0.9388	0.0770	0.0809	0.0065
	Logarithmic	k = 0.0023, a = 69.6882, c = -68.554	0.9113	0.0869	0.0938	0.0088
	Two term mdel	k = 0.2864, g = 14.6379, a = 1.3402, c = -0.2513	0.9330	0.0755	0.0839	0.0070
	Verma et al	k = -0.0436, g = -0.0379, a = -23.8734	0.8742	0.1051	0.1135	0.0129
	Diffusion approach	k = 0.0002, g = -5.8533, a = 99.6849	0.9319	0.0846	0.0913	0.0083

	Midili Kucuk	k = 0.0041, b = 0.0023, a = 0.9789, n = 3.6693	0.9432	0.0703	0.0781	0.0061
	Wang and Smith	a = -0.0917, b = -0.0068	0.8636	0.1108	0.1165	0.0136
	Hii et al.	k = 0.0182, g = 0.0438, a = 1.4769, c = -0.4968, n = 2.8625	0.9741	0.0470	0.0538	0.0029
40^0C	Newton	k = 0.1121	0.8698	0.1471	0.1494	0.0223
	Henderson and Pabis	k = 2.1305, a = 0.1395	0.8431	0.1221	0.1260	0.0159
	Page	k = 0.1286, n = 0.9412	0.9919	0.0276	0.0285	0.0008
	Logarithmic	k = 0.1386, a = 1.0011, c = 0.0545	0.9408	0.0738	0.0774	0.0060
	Two term mdel	k = 0.1614, g = 0.0403, a = 0.8671, c = 0.1982	0.9463	0.0736	0.0785	0.0062
	Verma et al	k = 0.0237, g = 0.1344, a = 0.0974	0.9799	0.0442	0.0463	0.0021
	Diffusion approach	k = 0.1121, g = 1, a = 3.0345	0.9512	0.0687	0.0721	0.0052
	Midili Kucuk	k = 0.1266, b = 0.0016, a = 1.0457, n = 1.0047	0.9882	0.0329	0.0351	0.0012
	Wang and Smith	a = -0.0776, b = 0.0015	0.9848	0.0377	0.0389	0.0015
	Hii et al.	k = 0.0575, g = 0.0046, a = 0.6804, c = 0.3086, n = 1.723	0.9918	0.0275	0.0299	0.0009

Table 3. Model constant and goodness of fit parameter of the selected models for different Microwave power

Power	Model	Model constant	R^2	RMSE	SEE	X^2
900 W	Newton	k = 0.0608	0.8332	0.2135	0.216	0.0466
	Henderson and Pabis	k = 0.0810, a = 1.2823	0.7934	0.1818	0.186	0
	Page	k = 0.000005, n = 4.620862	0.9992	0.0183	0.0187	0.0118
	Logarithmic	k = 0.0060, a = 10.062, c = -8.8375	0.9169	0.1121	0.116	0.0562
	Two term mdel	k = 0.0810, g = 0.0777, a = 1.2524, c = 0.0297	0.7935	0.1818	0.1904	0.0297
	Verma et al	k = -0.0349, g = -0.0322, a = -17.6156	0.9437	0.097	0.1004	0.0121
	Diffusion approach	k = 0.1827, g = 1.0558, a = 31.5412	0.9178	0.1178	0.1219	0.0335
	Midili Kucuk	k = 0.0000, b = 0.0041, a = 0.9543, n = 5.2244	0.9942	0.0346	0.0362	0.0274
	Wang and Smith	a = -0.0032, b = -0.0024	0.9505	0.087	0.089	0.0457
	Hii et al.	k = 0.000, g = 0.0140, a = 0.9580, c = 0.0455, n = 5.0789	0.9988	0.0152	0.0162	0.0439
720 W	Newton	k = 0.0551	0.8989	0.1455	0.1469	0.0216
	Henderson and Pabis	k = 0.0709, a = 1.2310	0.8818	0.1159	0.1182	0.0139
	Page	k = 0.0020, n = 2.2327	0.9577	0.0705	0.0719	0.0051
	Logarithmic	k = 0.0197, a = 2.7471, c = -1.5966	0.9156	0.0967	0.0996	0.0099
	Two term mdel	k = 0.0709, g = 0.0707, a = 1.2037, c = 0.0273	0.8818	0.1159	0.1207	0.0145
	Verma et al	k = -0.0104, g = -0.0003, a = -3.2354	0.9027	0.1115	0.1149	0.0132
	Diffusion approach	k = 0.1554, g = 1.0710, a = 21.9597	0.9597	0.0672	0.0692	0.0047
	Midili kucuk	k = 0.0001, b = 0.0088, a = 0.9639, n = 3.6409	0.9976	0.0161	0.0168	0.0002
	Wang and Smith	a = -0.0314, b = -0.0003	0.9009	0.1112	0.1134	0.0128
	Hii et al.	k = 0.0281, g = 0.1049, a = 1.6050, c = -0.6418, n = 1.4362	0.9703	0.0583	0.0614	0.0037
540 W	Newton	k = 0.037	0.8476	0.1761	0.1776	0.0315
	Henderson and Pabis	k = 0.0502, a = 1.2421	0.8159	0.146	0.1485	0.022
	Page	k = 0.0002, n = 2.8371	0.9822	0.0462	0.047	0.0022
	Logarithmic	k = 0.0044, a = 8.9304, c = -7.7363	0.9106	0.1	0.1026	0.0105
	Two term mdel	k = 0.0208, g = -0.0932, a = 1.1577, c = -0.0420	0.9266	0.0906	0.0938	0.0088
	Verma et al	k = -0.0265, g = -0.0244, a = -16.2475	0.9338	0.0881	0.0904	0.0081

	Diffusion approach	k = 0.1179, g = 1.0515, a = 31.8771	0.935	0.0874	0.0896	0.008
	Midili Kucuk	k = 0.0001, b = 0.0001, a = 1.0107, n = 3.0719	0.9855	0.0407	0.0421	0.0017
	Wang and Smith	a = -0.0031, b = -0.0011	0.9438	0.08	0.0814	0.0066
	Hii et al.	k = 0.0001, g = -0.0001, a = 1.0074, c = 0.0010, n = 3.2647	0.9924	0.0292	0.0305	0.0009
360 W	Newton	k = 0.0550	0.7706	0.1685	0.1689	0.0285
	Henderson and Pabis	k = 0.0709, a = 1.2310	0.7393	0.1452	0.146	0.0213
	Page	k = 0.0020, n = 2.2327	0.7572	0.1733	0.1742	0.0303
	Logarithmic	k = 0.0197, a = 2.7471, c = -1.5966	0.8298	0.1167	0.1176	0.0138
	Two term mdel	k = 0.0709, g = 0.0707, a = 1.2037, c = 0.0273	0.7562	0.1421	0.1436	0.0206
	Verma et al	k = -0.0104, g = -0.0003, a = -3.2354	0.9614	0.0557	0.0561	0.0031
	Diffusion approach	k = 0.1554, g = 1.0710, a = 21.9597	0.8779	0.1004	0.1012	0.0102
	Midili Kucuk	k = 0.0001, b = 0.0088, a = 0.9639, n = 3.6409	0.9451	0.0666	0.0673	0.0045
	Wang and Smith	a = -0.0314, b = -0.0003	0.9606	0.0636	0.0639	0.004
	Hii et al.	k = 0.0281, g = 0.1049, a = 1.6050, c = -0.6418, n = 1.4362	0.9800	0.0400	0.0406	0.0016
180 W	Newton	k = 0.0373	0.7371	0.1132	0.1135	0.0128
	Henderson and Pabis	k = 0.0502, a = 1.2421	0.7189	0.096	0.0964	0.0093
	Page	k = 0.0002, n = 2.8371	0.6805	0.1263	0.1269	0.0161
	Logarithmic	k = 0.0043, a = 8.9304, c = -7.7363	0.7727	0.0861	0.0867	0.0075
	Two term mdel	k = 0.0208, g = -0.0932, a = 1.157689, c = -0.0420	0.8531	0.0701	0.0707	0.005
	Verma et al	k = -0.0265, g = -0.0244, a = -16.2475	0.9429	0.0432	0.0435	0.0019
	Diffusion approach	k = 0.1179, g = 1.0515, a = 31.8771	0.8686	0.0658	0.0663	0.0044
	Midili Kucuk	k = 0.0001, b = 0.0001, a = 1.0107, n = 3.079	0.905	0.0558	0.0563	0.0031
	Wang and Smith	a = -0.0031, b = -0.0011	0.9356	0.0486	0.0488	0.0023
	Hii et al.	k = 0.0001, g = -0.0001, a = 1.0074, c = 0.0010, n = 3.2647	0.9370	0.0453	0.0458	0.0021

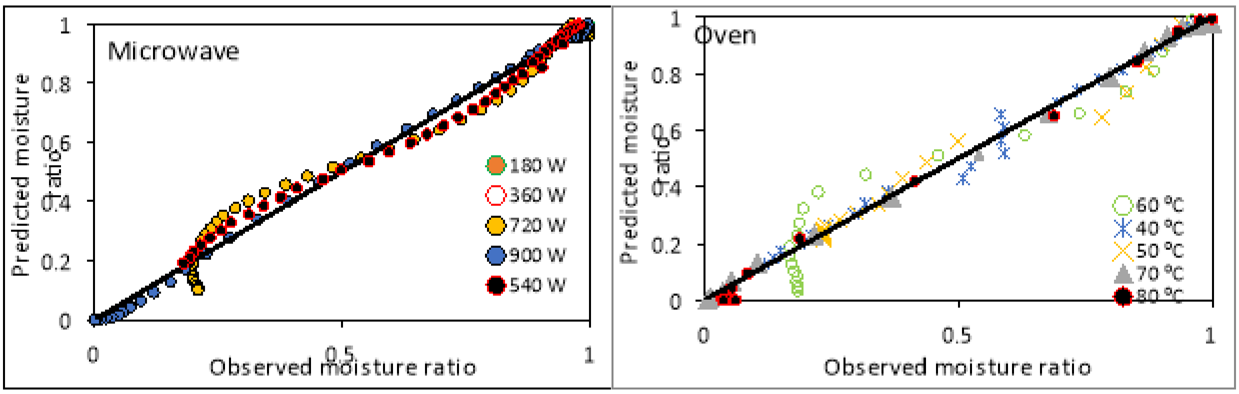

Fig. 3. The graph of the observed and predicted moisture ratio for the Hii *et al.* model

3.3. Effective moisture diffusivities (D_{eff})

The relationship of ln(MR) for the microwave oven at different power was determined and it was observed that the value of D_{eff} increased progressively from 25.16×10^{-9} (m^2/s) to 10.05×10^{-9}(m^2/s) as the power increased from 180W to 900W and the value also decreases progressively from 69.01×10^{-10} (m^2/s) to 20.32×10^{-10} (m^2/s) as the temperature decreases which shows that the rate of effective diffusivity increases with increase temperature of laboratory oven. The increase in power of

Table 4. Activation energy, Ea and Effective moisture diffusivity, D_{eff}

Laboratory oven					
Temperature (°C)	80	70	60	50	40
D_{eff} x 10^{10}	69.01	46.81	31.87	29.15	20.32
Activation Energy, Ea	22.00	24.55	38.39	39.89	35.99
Microwave drying system					
Power (W)	900	720	540	360	180
D_{eff} x 10^{10}	250.17	136.03	123.52	167.84	100.49
Activation Energy, Ea	13.22	12.97	19.65	28.42	38.65

microwave drying system or temperature of the laboratory oven makes the movement of water molecules more rapidly, which resulted in the higher absorption of microwave and the higher moisture diffusion due to the rise of water vapour pressure and this best explain the reason why higher power and temperature lead to the faster of the drying, The increase in D_{eff} with increase in temperature as observed is in agreement with the results of Akgun and Doymaz (2005).

3.4. Activation Energy (Ea)

The temperature dependence of the effective diffusivity may be represented by an Arrhenius relationship (Madamba *et al.*, 1996; Sanjuan *et al.*, 2003). The activation energy values (Ea) of dried milled carrot were calculated by use of effective moisture diffusivity, thermal diffusivity and drying rate constant obtained from the best model. The calculated Ea values ranges from 13.22 to 38.65 kJ/mol as shown in Table 4. According to the results, Ea shows a little inconsistencies with increasing microwave power between 540 to 900W this maybe because non isotropic behaviour of agricultural, the value of activation energy might not depend directly on the microwave power unlike the trend observed in laboratory oven as the value of activation energy decrease with decreasing temperature (22.00<Ea<39.89 kJ/mol).

4. CONCLUSIONS

In this study, modelling of thin layer drying kinetics of milled carrot was carried out. The drying time decreased with higher drying temperatures. The effective diffusivity values varied from 100.49×10^{-10}(m^2/s) to 250.17×10^{-10} (m^2/s) as the power increased from 180W to 900W. Also the value of the D_{eff} decreases progressively from 69.01×10^{-10} (m^2/s) to 20.32×10^{-10} (m^2/s) as the temperature decreases which shows that the rate of effective diffusivity increases with increase temperature of laboratory oven.

The temperature dependence of the effective diffusivity was described by an Arrhenius type equation and the experimental results did not exhibit the constant rate period The activation energy was found to be 13.22 to 38.65 kJ/mol for microwave oven and 22.00 to 39.89 kJ/mol kJ/mol for laboratory oven. The Hii *et al.* model could adequately describe their thin-layer drying behaviour for milled carrot. Statistical parameters such as x^2, MBE and RMSE have also confirmed the suitability of these models. The coefficients of the assumed models, which are the most important parameters in the moisture transfer, depend strongly on the temperature and microwave output power.

5. REFERENCES

[1]. Aghbashlo, M., Kianmehr, M. H., Khani, S. and Ghasemi M. (2009). Mathematical modelling of thin-layerdrying of carrot. International Agrophysics 23:313–7.

[2]. Akgun, N. A. and Doymaz, I. (2005). Modeling of olive cake thin-layer drying process. J. Food Eng., 68, 455–461.

[3]. Akpinar E. K., Bicer Y. and Yildiz C. (2003). Thin-layer drying of red pepper. Journal of Food Engineering 59(1):99–104.

[4]. Akpinar, E. K. (2006). Determination of suitable thin-layer drying curve model for some vegetables and fruits. Journal of Food Engineering 73:75–84.
[5]. Araya-Farias, M. and Ratti, C. (2009). Dehydration of foods: general concepts. In: Ratti C, editor. Advances in food dehydration. Boca Raton, FL: CRC Press. 1–36.
[6]. Ayensu, A. (1997). Dehydration of food crops using solar dryer with convection heat flow. Solar Energy, 59(4-6): 121-126
[7]. Babalis, S. J, Papanicolaou, E., Kyriakis, N., and Belessiotis, V.G. (2006). Evaluation of thin-layer drying models for describing drying kinetics of figs (*Ficus carica*). Journal of Food Engineering, 75(2): 205-214
[8]. Celma, A. R., Rojas, S., Lopez, F., Montero, I., and Miranda, T. (2007). Thin-layer drying behaviour of sludge of olive oil extraction. Journal of Food Engineering, 80: 1261-1271
[9]. Ceylan, I., Aktas, M. and Dogan, H. (2007). Mathematical modelling of drying characteristics of tropical fruits. Applied Thermal Engineering, 27: 1931-1936.
[10]. Charles, S. (2003). Encyclopedia of Food and Culture. New York:
[11]. Chen, J., Zhou, Y., Fang, S., Meng, Y., Kang, X., Xu, X. and Zuo, X. (2013). Mathematical modelling of hot air-drying kinetics of *momordica charantia* slices and its color change. Adv J Food Science Technology 5(9):1214–9.
[12]. Diamante, L, Durand, M, Savage, G. and Vanhanen, L. (2010). Effect of temperature on the drying characteristics, colour and ascorbic acid content of green and gold kiwifruits. International Food Resourses J 451:441–51.
[13]. Doymaz, I. (2005). Sun drying of figs: An experimental study. Journal of Food Engineering, 71; 403-407
[14]. El-Beltagy, A., Gamea, G. R. and Essa, A. H. A. (2007). Solar drying characteristics of strawberry. J Food Engr 78:456–64.
[15]. Erbay, Z. and Icier F. (2010). A review of thin-layer drying of foods: theory, modelling, and experimental results. Crit Rev Food Sci Nutr 50(5):441–64
[16]. Dalali, G., E. Demirhan and B. Ozbek (2007). Drying Technol. Vol. 25, .1703.
[17]. Darici, S. and Sen, S. (2015). Experimental investigation of convective drying kinetics of kiwi under different conditions. Heat Mass Transfer 51(8):1167–76.
[18]. Gan, P. L. and Poh, P. E. (2014). Investigation on the effect of shapes on the drying kinetics and sensory evaluation study of dried jackfruit. Intl J Sci Engr 7:193–8.
[19]. Gogus, F., & Maskan, M. (2001). Drying of olive pomace by a combined microwave-fan assisted convection oven. Nahrung Food, 45, 129–132.
[20]. Guan, Z., Wang, X., Li, M. and Jiang, X. (2013). Mathematical modelling on hot air drying of thin-layer fresh tilapia fillets. Polish J Food Nutr Sci 63(1):25–34.
[21]. Gunhan, T. V. Demir, E. Hancioglu, A. Hepbasli (2005 Mathematical modelling of drying of bay leaves Energy Convers. Manage., Volume 46, Issues 11–12, pp. 1667-1679
[22]. Henderson S. M. (1974). Progress in developing the thin layer drying equation. Transactions of the ASAE, 17, 1167–1172
[23]. Hii, C.L., Law, C.L. and Cloke, M. (2009). Modeling using a new thin-layer drying model and product quality of cocoa. J Food Engr 90(2):191–8
[24]. Kadam D .M. Goyal R. K. and Gupta M. K. (2011). Mathematical modeling of convective thin-layer drying of basil leaves. J Med Plants Res 5(19):4721–30
[25]. Kadi, H. and Hamlat, M. S. (2002). Studies on drying kinetics of olive foot cake. Grases y Aceites, 53, 226–228
[26]. Kaleemullah, S. and Kailappan, R. (2006). Modeling of thin- layer drying kinetics of red chilies. Journal of Food Engineering, 76 (4): 531-537
[27]. Karathanos, V. T. (1999). Determination of water content of dried fruits by drying kinetics. Journal of Food Engineering 39:337-344
[28]. Kashaninejad, M., mortazavi, A., Safekordi, A. and Tabil, L. G. (2007). Thin-layer drying characteristics and modeling of pistachio nuts. Journal of Food Engineering, 78:98-108
[29]. Keey, R. B. (1972). Drying principles and practice. Oxford: Pergamon Press. 1–18
[30]. Kiranoudis, C. T., Tsami, E., Maroulis, Z. B. and Marinos-Kouris, D. (1997). Drying kinetics of some fruits. Drying Technol 15(5):1399–418.
[31]. Klemes J., Smith R. and Kim J. K. (2008). Handbook of water and energy management in food processing. Boca Raton: Woodhead Publishing and CRC Press. 449–629.
[32]. Krokida, M. K, Karathanos, V. T, Maroulis, Z. B. and Marinos-Kouris, D. (2003). Drying kinetics of some vegetables. J Food Engr 59(4):391–403
[33]. Kudra T. and Mujumdar, A. S. (2002). Part I. General discussion: conventional and novel drying concepts. In: Kudra T, Mujumdar A. S, editors. Advanced drying technologies. New York: Marcel Dekker Inc. 1–26.
[34]. Kumar, C, Karim, A, Joardder M. U. H. and Miller, G. J. (2012). Modeling heat and mass transfer process during convection drying of fruit. The 4th International Conference on Computational Methods (ICCM2012), Gold Coast, Australia, 25–27, November 2012.
[35]. Madamba, P. S., Driscoll, R. H., and Buckle, K. A. (1996). The thin-layer drying characteristics of garlic slices. Journal of Food Engineering, 29, 75–97.
[36]. Meisami-asl, E. and Rafiee, S. (2009). Mathematical modelling of kinetics of thin layer

drying of Apples (Golab). Agric Engr Intl: CIGR J 6:1–10.
[37]. Menges, H. O. and Ertekin, C. (2006). Mathematical modeling of thin-layer drying of golden apples. J Food Engr 77(1):119–25.
[38]. Midilli, A., Kucuk, H. and Yapar, Z (2002). A Hii et al. model for single layer drying. Drying Technology, 20(7): 1503-1513
[39]. Misha S., Mat A. S., Ruslan M. H., Sopian K. and Salleh, E. (2013). The effect of drying air temperature and humidity on the drying kinetic of kenaf core. Appl Mech Mater 315:710–4.
[40]. Mujumdar, A. S. (2007). Handbook of Industrial Drying, 3rd Ed.; CRC Press: Boca Raton, FL
[41]. Ozdemir, M. and Devres, Y.O. (2000). The thin layer drying characteristics of hazel nuts during roasting. Journal of Food Engineering, 42(4): 225-233
[42]. Ozkan, I. A., B. Akbudak and N. Akbudak (2007). Advances in Drying. J. Food Eng. Vol. 78,.577. http://dx.doi.org/10.1016/j.jfoodeng.2005.10.026
[43]. Pandey, H., Sharma, H. K., Chauhan, R. C., Sarkar, B. C. and Bera, M. B. (2010). Experiments in food process engineering. New Delhi: CBS Publisher and Distributors PVT. 139–45.
[44]. Perez, N. E. and Schmalko, M. E. (2009). Convective drying of pumpkin: Influence of pre-treatment and drying temperature. Journal of Food Process Engineering 32(1):88–103.
[45]. Proietti, S. Rouphael, Y. Colla, G. Cardarelli, M. Agazio, M. D Zacchini, M. Rea, E. Moscatello, S. and Battistel, A. (2008). Fruit quality of mini-watermelon as affected by grafting and irrigation regimes. Journal of the science of Food and Agriculture. 88 (6). Pages 1107-1114
[46]. Rahman, M.S., Perera, C.O. and Theband, C. (1998). Desorption isotherm and heat pump drying kinetics of peas. Food Research international, 30: 485-491
[47]. Reyes A, Alvarez P. I. and Marquardt F. H. (2007). Drying of carrots in a fluidized bed. I. Effects of drying conditions and modeling. Drying Technology 20 (7):1463–83.
[48]. Sacilik K. (2007). Effect of drying methods on thin-layer drying characteristics of hull-less seed pumpkin (Cucurbita pepo L.). Journal of Food Engineering 79(1):23–30.
[49]. Saeed I. E., Sopian K., Abidin Z. Z. (2006). Drying characteristics of Roselle (1): mathematical modelling and drying experiments. Agricultural Engineering International: CIGR J X (1):1–25.
[50]. Sanjuan, N., Lozano, M., Garcia-Pascal P. and Mulet A. (2003). Dehydration kinetics of red pepper (Capsicum annuum L. var. Jaranda). J. Sci. Food Agric. 83, 697–701.
[51]. Shi, J., Pan, Z., McHugh, T. H., Wood, D., Hirschberg, E. and Olson, D. (2008). Drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation heating. LWT—Food Science Technology 41(10):1962–72
[52]. Sturm, B., Hofacker, W. C. and Hensel, O. (2012). Optimizing the drying parameters for hot-air–dried apples. Drying Technology 30(14):1570–82.
[53]. Tarigan, E., Prateepchaikul, G., Yamsaengsung, R., Sirichote, A. and Tekasakul, P. (2007). Drying characteristics of unshelled kernels of candle nuts. Journal of food Engineering, 79: 828-833.
[54]. Togrul, I.T. and Pehlivan, D. (2004). Modelling of thin layer drying kinetics of some fruits under open-air sun drying process. Journal of Food Engineering 65: 413-425.
[55]. Tzempelikos, D. A., Vouros, A. P., Bardakas, A. V., Filios, A.E. and Margaris, D.P. (2014). Case studies on the effect of the air-drying conditions on the convective drying of quinces. Case Stud Thermal Engr 3:79–85.
[56]. Verma, L.R., Bucklin, R. A, Endan, J. B. and Wratten, F. T. (1985). Effects of drying air parameters on Rice drying models. Transactions of the American Society Agricultural Engineering. 28:296-301
[57]. Wang, C.Y. and Singh, R.P. (1978). A single layer drying equation for rough rice. American society Agricultural engineering, paper No. 78-3001, St. Joseph, MI, USA.
[58]. Wang, Z., Sun, J., Liao, X., Chen, F Zhao, G., Wu, J. and Hu, X. (2007). Mathematical modelling on hot air drying of thin layer apple pomace. Food Research International, 40: 39-46
[59]. White, G. M., Bridges, T. C., Grewer, O. J. and Ross, I. J. (1978). Seed coat damage in thin layer drying of soyabeans as affected by drying conditions. American Society Agricultural Engineering, Paper No. 3052.St. Joseph (MI).
[60]. Yaldiz O., Ertekin C. and Uzun H. I. (2001). Mathematical modeling of thin-layer solar drying of sultana grapes. Energy 26 (5):457–65.
[61]. Yaldiz, O. and Ertekin, C. (2001). Thin layer solar drying of some vegetables. Drying Technology, 19: 583-596
[62]. Zhang, Q. and Litchfield, J. B. (2015). An optimization of intermittent corn drying in a laboratory scale thin layer dryer. Drying Technology, 9, 383–395.