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DRYING OF CARROT SLICES USING FLUIDIZED BED DRYER AND MICROWAVE-ASSISTED FLUIDIZED BED DRYER

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Abstract

The physical and biochemical effects of dried vegetables and fruits by several different drying technologies are influenced. In this paper, the drying of carrot slices (300gm weight, half-circle shape with 2mm thickness and 10mm radius) using the fluidized bed dryer and microwave-assisted fluidized bed dryer at controlled inlet air temperatures (43, 50 and 60 °C) with a crosshead speed 16.5 m/s were investigated. For thin-layer drying processes, a dryer test rig was installed, with moisture ratio (MR) values (Four different models, i.e. Newton, Henderson and Pabis, Logarithmic and Midilli et al.) compared for every drying period. The drying rate was significantly influenced by the drying techniques and temperatures. The results show that the higher drying levels of carrot slices at a higher temperature and a decrease in the drying time for microwave-assisted fluidized bed drying with a 600 W microwave capacity, were observed. Drying time was reduced to 30 % when the fluidized bed dryer was replaced by the microwave –assisted fluidized bed dryer. The results show that the statistical model of Logarithmic gave the best fit with root-mean-square error in the range of 0.9 *–11.4% and with higher coefficient of determination (R2)* value ranged from 0.894 to 0.995.

Keywords: Carrot slices, Fluidized bed drying, Microwave-assisted fluidized bed drying, Mathematical models.

1. Introduction

The residues created during production and selling of fresh fruit, vegetables and other items are a third of global food products that are missing or wasted, While these residues should be disposed-off to prevent environmental problems, their drying processing into by-products is one of the best ways to recover their value. Preserving high moisture content food is done by drying. Through minimizing the moisture content to an acceptable level and decrease the microbiological spoilage and chemical reactions inside the food material. Also, by food drying transportation and packaging will be at a lower cost since drying reduce the weight and volume of the products [1].
Reducing the moisture content by drying will reduce the water activity in the food material, which will prevent the food from spoilage. Food shelf life determined by knowing the water activity which is the main factor, typically most of the bacteria are unable to grow under 0.91 water activity, water activity also affects the activity of enzymes and vitamins that are the reason for food taste and aroma [2].
Food drying is a problematic operation since it has undesirable changes in the quality of the food material and that depend on the preparation part of food material before drying and on the drying process that used [3].
During drying there are two processes happen at the same time which they are heat transfer from

the surroundings to the food material surface leading to evaporate the moisture on the food surface and then transferring the heat to internal part of the food by conduction, the second process are the mass transfer of the moisture particles from inner to the surface of the food and then evaporating due to the heating process from the surface to the ambient. Choosing the type of dryer to depend on the heat and mass transfer process [4].

One of the most used methods for drying is the fluidized bed dryer especially for drying the products with granular shapes as foodstuff, chemicals, pharmaceutical, etc. the advantage of this drying process is the high heat and mass transfer, uniform distribution of heat around the food material, the high amount of mass transfer removal rate, easy material transportation in and out of the operation, and low maintenance cost. In general, fluidized bed, dryer considers an economical drying process comparing to other drying methods [5].

Because of low thermal conductivity of food material heat transfer inside the food material is limited, which will affect the overall drying process, to deal with this and to achieve fast and efficient drying the using of microwave drying increased in the food drying process. Comparing microwave drying with the other drying process, it’s clear that microwave drying is rapid, uniform and energy-efficient, but it can’t compete with conventional drying process due to high cost [6].

Microwave heating creates gradient partial pressure difference between surface and internal part of the food material leading the moisture transfer from interior to surface, and this pressure difference is a result of microwave heating which penetrate through the food material [7].

Heat and mass transfer in apple cubes investigated in microwave-assisted fluidized bed dryer by Askari et al. [8], apple were washed and sliced (10*10*10 mm) and with constant air velocity about (21 m/s) and variation of temperatures at (50,60 and 70 °C), it was clear that microwave power enhanced the drying rate reduced drying time.

Niamnuy and Devahastin [9] introduced an industrial-scale fluidized bed dryer to dry out chopped coconut pieces (50 Kg) per batch under the effect of temperature variation from (120 to 65 °C) and air velocity from (3.85 to 5.94 m/s), they found out that the colour of the product mostly affected by inlet air temperature while the quantity of surface oil affected by air velocity.

Wang and Chen [10] discussed heat and mass transfer in batch fluidized bed dryer of apple particles, they took inlet air velocity between (0.5 to 10 m/s) and temperature between (40 to 100 °C), it turned out when increasing the gas velocity will be increasing the drying rate, and also it can be dried much faster using higher temperature.

Souraki and Mowla [11] discussed the effects of microwave power and inlet air temperature and velocity on drying behaviors of garlic in an inert medium. They find out that the early stages of drying the garlic reach its equilibrium value; the internal resistance against mass transfer controls the drying rate of this product.

Reyes et al. [12] investigated tunnel dryer, fluidized bed dryer and microwave fluidized bed dryer of potato slices, at (40 and 60 °C) temperature, air velocity of (1 and 2 m/s), they found out applying microwave to fluidized bed dryer reduced the time required for drying, a and about 70% decrease in drying time while using fluidized bed dryer rather than tunnel dryer.

Souraki and Mowla [13] investigated small foodstuff particle drying in fluidized bed dryer with inert energy carriers, using microwave with four power set (360, 540, 720 and 900 W), temperature of (30,50 and 70 °C), air velocity of (5.2, 4 and 6.3 m/s), it shows out that by increasing any of the three-factor it leads to decrease the time required for drying.

Swasdisevi et al. [14] investigated the effect of air velocity of (10.36, 1.2, 0.95 m/s) and inlet air temperature of (32 °C) on drying of chopped spring onion and the found out that the inlet
air temperature and its velocity have the main effect on the drying rate, decreasing the speed by increasing them as long as keeping the temperature lower than (53 °C) to maintain the quality of the product.

Kumar et al. [15] investigated the effect of different inlet air velocity (9, 10.5, 12 m/s) and different inlet air temperature (60, 67.5, 75 °C) on drying time required to dry beetroot with and without microwave assistance. They found out that microwave assistance offered 2 to 3 times reduction in the drying time with lower moisture content in the final product.
Goksu et al. [16] studied the effect of inlet air temperature of (50,60 and 70 °C) and an air velocity of (2.3 m/s) with the variation of power level (2.1 and 3.5 W/g) on microwave-assisted fluidized bed dryer of macaroni beads; the result was a decreasing in the time required for drying by increasing the temperature and the power.
Ranjbaran and Zare [17] investigated the performance of microwave-assisted fluidized bed dryer of soybeans at different drying condition which included microwave power of (0, 0.89, 1.6, 3.2, 4.3 and 5.3 W/g) and inlet air temperature of (30, 40, 50 and 60 °C) with inlet air velocity of (1.2, 1.85 and 2.2 m/s) it has found out that by increasing the inlet air temperature we decrease the time required for drying and applying more power will increase the drying rate.
The main goal of this paper is to design, build and investigate the food drying processes using fluidized bed dryer and microwave-assisted fluidized bed dryer and determine the optimal experimental conditions (type of dryer, drying temperature and air velocity) at different power that minimize drying time and improve the quality of dehydrated carrot slices, and to evaluate four models (*Newton, Henderson and Pabis, Logarithmic and Midilli et al.*) to fit the drying curves of carrot slices.

2. Materials and methods

2.1. Material
Fresh carrot with an initial moisture content of (87%-90%) [18] purchased from local grocery shop at Erbil Iraq, before drying the sample been washed and cleaned then dried, the carrot has sliced into half-circle shape with a thickness of 2 mm and radius of 10 mm pieces.

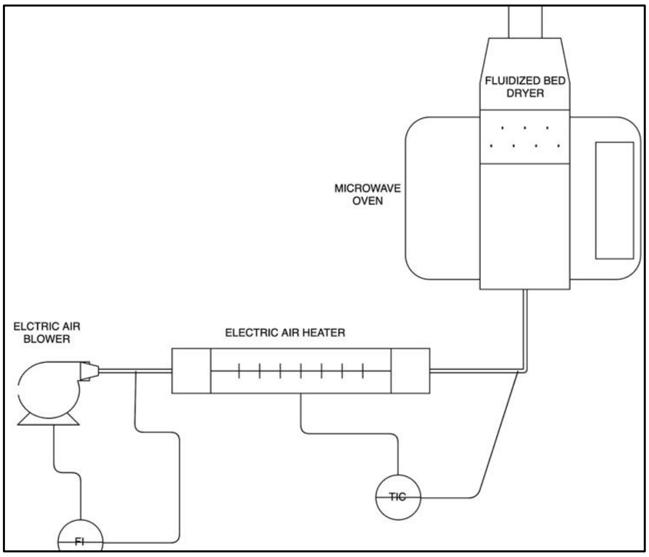
2.2. Drying equipment and procedure
In this experiment, an air blower (electric blower) with a controlled valve and velocity meter type (Tack life anemometer DA03) with an accuracy of (0.1 m/s) at the range of (0.8-30 m/s), has been used to measure the air velocity. The air is heated by an electric heater, which was designed and constructed using aluminum tube of (90 mm) diameter, have five electric heaters (400W) each fitted inside it controlled with a TIC controller type (XH-W1219) connected to a temperature sensor type (NTC10K).
The fluidization process take place in an acrylic PMMA clear tube pipe with inner diameter of (90 mm) and wall thickness of (0.5 mm) and (0.5 m) long fitted inside a Samsung microwave oven model type (MS23F301EAS) with maximum power output of (800 W) at (2450 MHz) frequency used to provide the required power to the experiment. Figure 1 shows a schematic diagram of the drying installed equipment. The operation is taking place by allowing the air to flow from the air blower through the air heater into the fluidized bed dryer over the carrot slice, each time (300 gm) of the sliced carrot weighted using mechanical balance model (Tylor 3720).

2.3. Methodology
The variable operation condition in this experiment are the inlet air temperature, inlet air velocity and assisted microwave oven power the range of these variables shown in table 1.

Table 1: operating conditions

Variables	Material
	carrot
Inlet air temperature (°C)	43, 50, 60
Inlet air velocity (m / s)	16.5
Assisted Microwave power (W)	600

Figure 1: Schematic diagram of the drying process



2.4. Mathematical modelling and statistical analysis

The moisture ratio of the carrot slice calculated using the following equation

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

Where MR is the dimensionless moisture ratio; M, M_0 and M_e are respectively the moisture content at any time, initial moisture content and equilibrium moisture content, this equation was simplified by Pala et al. [19] to the following one

$$MR = \frac{M}{M_0} \qquad (2)$$

Nonlinear regression analysis performed by fitting four drying model shown in table.2. [20] to the experimental data to determine the goodness of fitting these models to the experimental data namely; coefficient of determination (R^2) and root mean square error (RMES) the higher (R^2) value and lower (RMES) value is the best fitting. Akoy [21]

Table 2: Mathematical drying models

No.	Model Name	Model
1	Newton	$MR = \exp(-kt)$
2	Henderson and Pabis	$MR = a.exp(-kt)$
3	Logarithmic	$MR = a.\exp(-kt) + c$
4	Midili et al	$MR = a.\exp(-kt^n) + b.t$

3. Results and discussion

3.1. Fluidized bed drying

Table 3 represents the moisture content of the carrot slice at a different time under different air temperature with fixed air velocity. It was obvious that the time required for drying the carrot slice decreased by increasing the inlet air temperature since the increased temperature resulting in an increase in the evaporation rate of the moisture from the carrot slice surface to the ambient air surrounding. Moreover, figure 2 shows a faster drying rate at a higher air temperature as well.

Table 3: Fluidized bed dryer test results

Fluidized Bed Dryer at 16.5 m/s air velocity			
Time / min	Temperature ^{o}C		
	43	50	60
	Moisture contents %		
0	90	90	90
10	87	86	85
20	83	81	78
30	79	73	68
40	75	65	57
50	70	57	40
60	65	45	25
70	57	33	14
80	54	25	9
90	45	21	0

Table 4: Microwave-assisted fluidized bed dryer test results

Fluidized Bed Dryer at 16.5 m/s air velocity and 600 W microwave power			
Time / min	Temperature ^oC		
	43	50	60
	Moisture contents %		
0	90	90	90
10	86	85	83
20	82	79	75
30	76	71	63
40	71	57	54
50	65	54	38
60	57	40	29
70	50	30	14
80	40	21	0
90	40	14	0

3.2. Microwave-assisted fluidized bed drying

Table 4 shows the moisture content of the carrot slice at a different temperature under a fixed airflow rate with microwave assisting as an additional heat source, from figure 3 besides the effect of air temperature which affects the drying time, the impact of microwave contributing is also very clear on the drying rate, comparing it with figure 2. This decrease in the drying rate is caused by the microwave energy which elevated the internal temperature of the carrot slice inner higher than the air temperature surrounding it leading to increase in vapor pressure which is the driving force inside the particle to the surface then evaporating it to ambient air.

Figure 2: Moisture content Vs Time at 16.5m/s

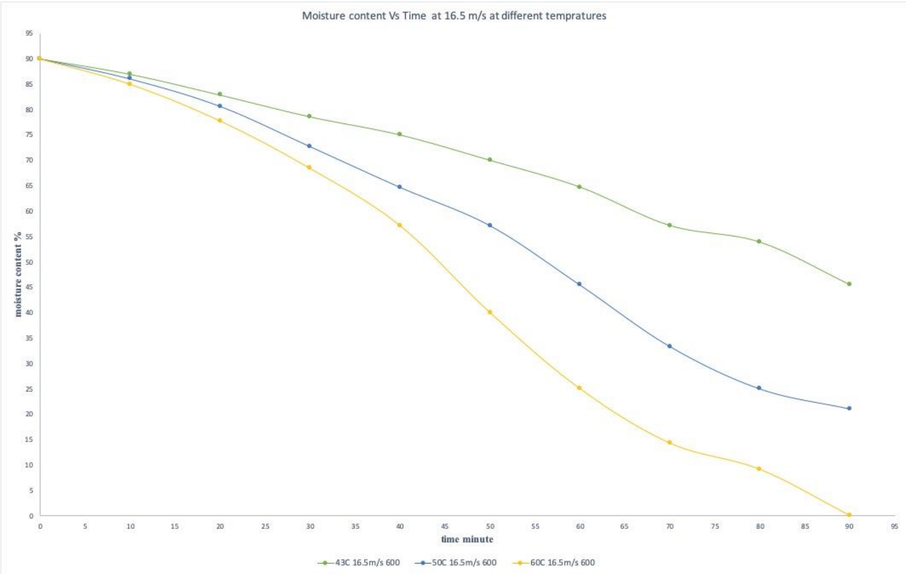
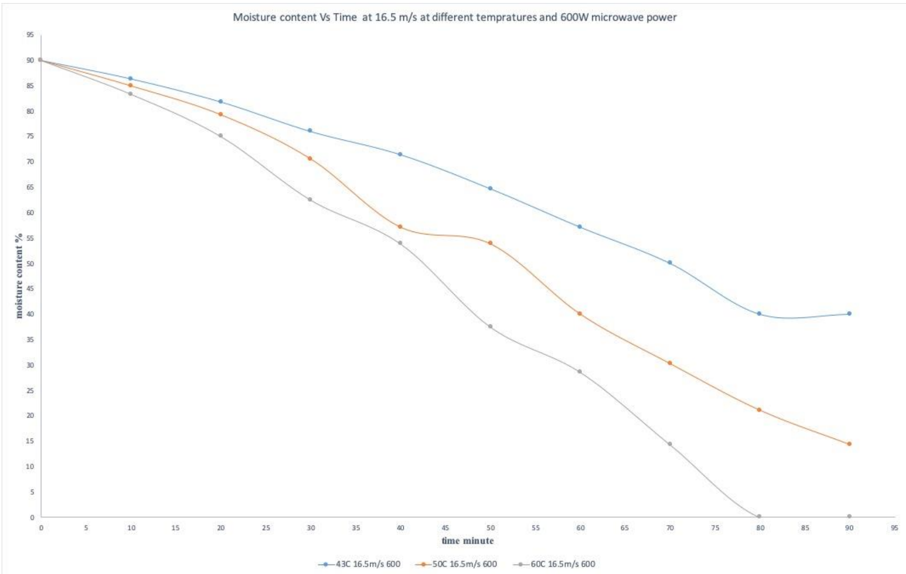


Figure 3: Moisture content Vs Time at 16.5m/s



3.3. Modelling the drying data

By applying four drying model to the experimental data, then using nonlinear regression analysis to calculate the coefficient of determination (R2) and root mean square error (RMES) of each drying model as shown in table 5 and table 6. In all models for fluidized bed dryer and microwave-assisted fluidized bed dryer experiments, the R2 value ranged from 0.894 to 0.995, and the RSME value ranged from 0.114 to 0.009; it's very clear from the results that logarithmic model fits the experimental data the best since it has both higher R2 and lower RMSE value comparing with the other models, all the constant and coefficient of the logarithmic model equation listed in table 5 and table 6. By comparing the experimental MR vs time with the other drying models through figures 3 to 8, it shows how exactly dose the model fitting the experimental data, especially the logarithmic drying model.

Table 5: Mathematical model applied to experimental data for

MODEL	TEMPERATURE	R2	RMSE	Drying model constants				
				K	A	C	B	N
NEWTON	43	0.9457	0.036562	0.00604064				
	50	0.8975	0.086054	0.0117075				
	60	0.8644	0.129277	0.0180248				
HENDERSON AND PABIS	43	0.9629	0.030227	0.00675928	1.04224			
	50	0.9275	0.072355	0.0135606	1.1027			
	60	0.894	0.114281	0.0207536	1.14141			
LOGARITHMIC	43	0.9963	0.009533	-0.00779318	-0.48296	1.48614		
	50	0.9913	0.0250412	-0.00568765	-1.25506	2.28385		
	60	0.9851	0.0427903	-0.00185829	-5.9977	7.0471		
MIDILI ET AL.	43	0.9944	0.0117705	-0.0148375	0.995408		-0.0084985	0.635684
	50	0.995	0.018951	-0.0363107	0.995993		-0.0188674	0.63961
	60	0.9894	0.036072	-0.0728702	0.999897		-0.0129178	0.0943184

Table 6: Mathematical model applied to experimental data for fluidized bed dryer with 600W microwave power

MODEL	TEMPERATURE	R2	RMSE	Drying model constants				
				K	A	C	B	N
NEWTON	43	0.9366	0.0491391	0.00796521				
	50	0.9083	0.086224	0.013509				
	60	0.8735	0.125467	0.0192093				
HENDERSON AND PABIS	43	0.9563	0.0408037	0.00897409	1.0578			
	50	0.9323	0.074093	0.0153649	1.09928			
	60	0.8976	0.1128679	0.0217856	1.12968			
LOGARITHMIC	43	0.9893	0.020218	-0.00499152	-1.07315	2.08626		
	50	0.9925	0.024662	-0.00358972	-2.33142	3.35475		
	60	0.9893	0.036445	-0.00135208	-8.49529	9.53003		
MIDILI ET AL.	43	0.9909	0.0185932	-0.0177726	0.997146		-0.011605	0.679482
	50	0.9947	0.020697	-0.0317427	0.997134		-0.0205047	0.684625
	60	0.9914	0.032628	-0.0626507	0.999998		-0.011262	0.0201721

Figure 2: Drying model fit to experimental data at 43-degree temperature and 16.5m/s air velocity

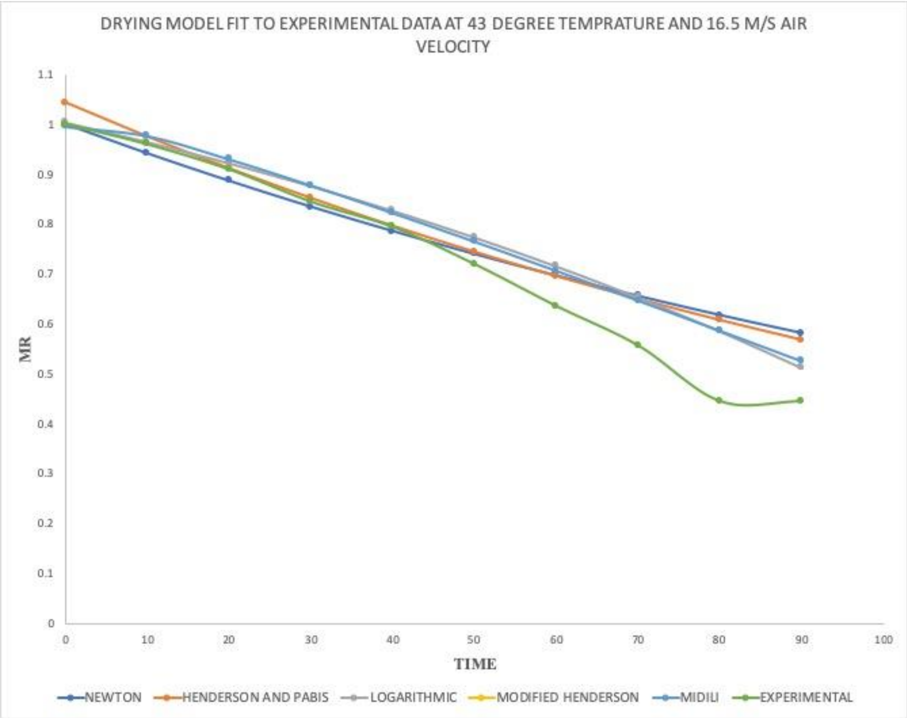


Figure 3: Drying model fit to experimental data at 50-degree temperature and 16.5m/s air velocity

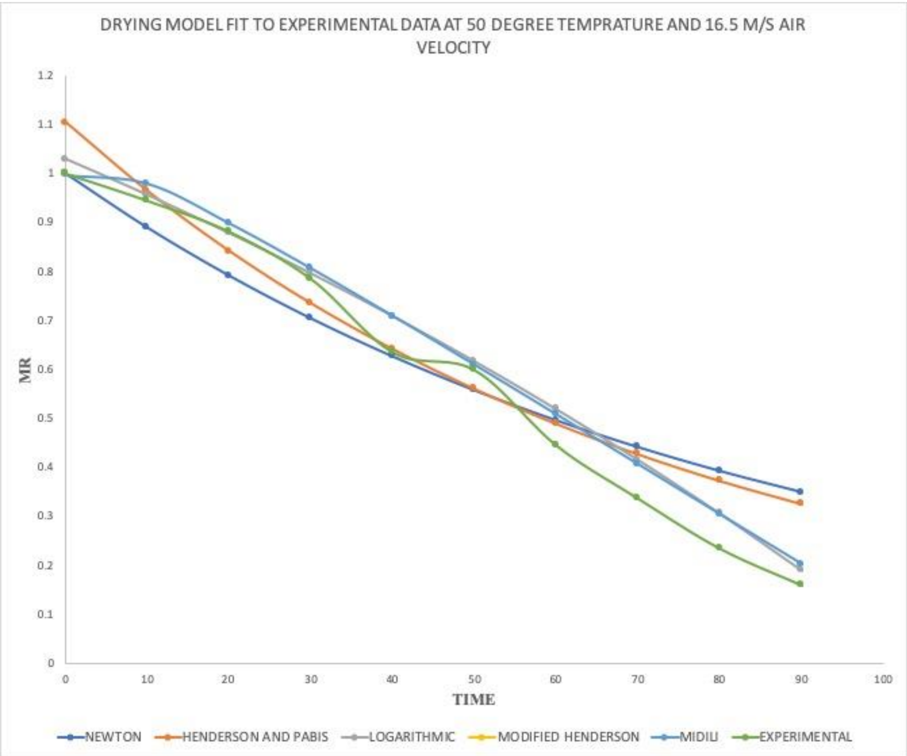


Figure 4: Drying model fit to experimental data at 60-degree temperature and 16.5m/s air velocity

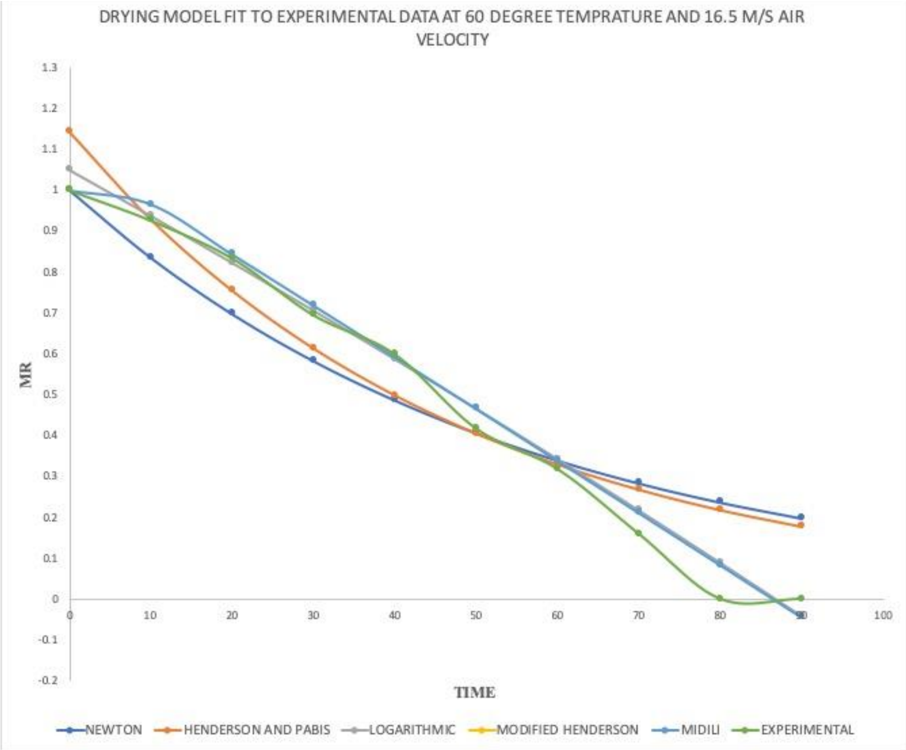


Figure 7: Drying model fit to experimental data at 43-degree temperature, 600W microwave power and 16.5m/s air velocity

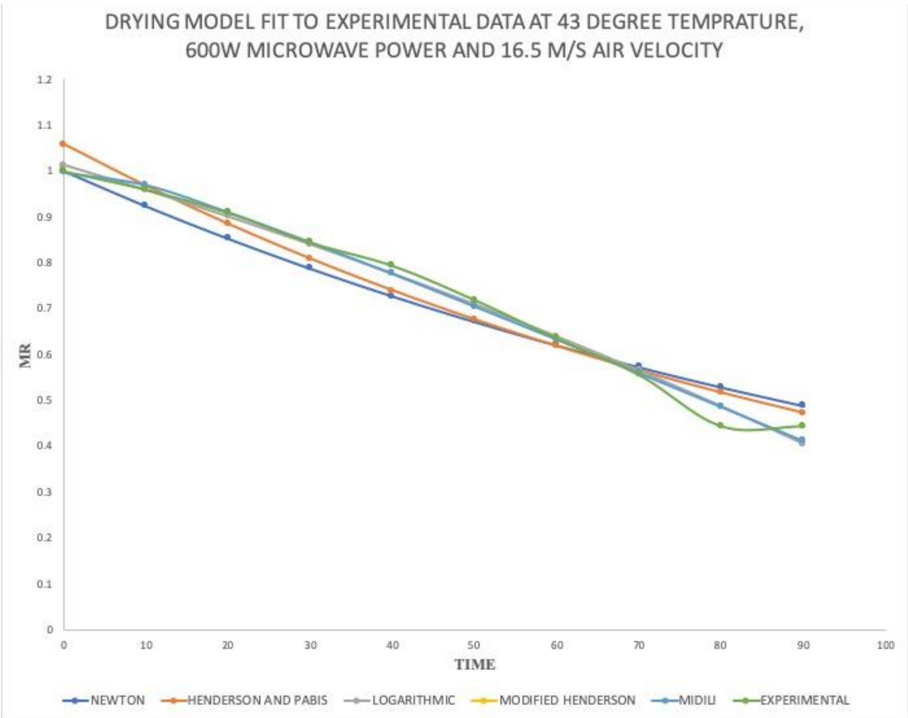


Figure 8: Drying model fit to experimental data at 50-degree temperature, 600W microwave power and 16.5 m/s air velocity

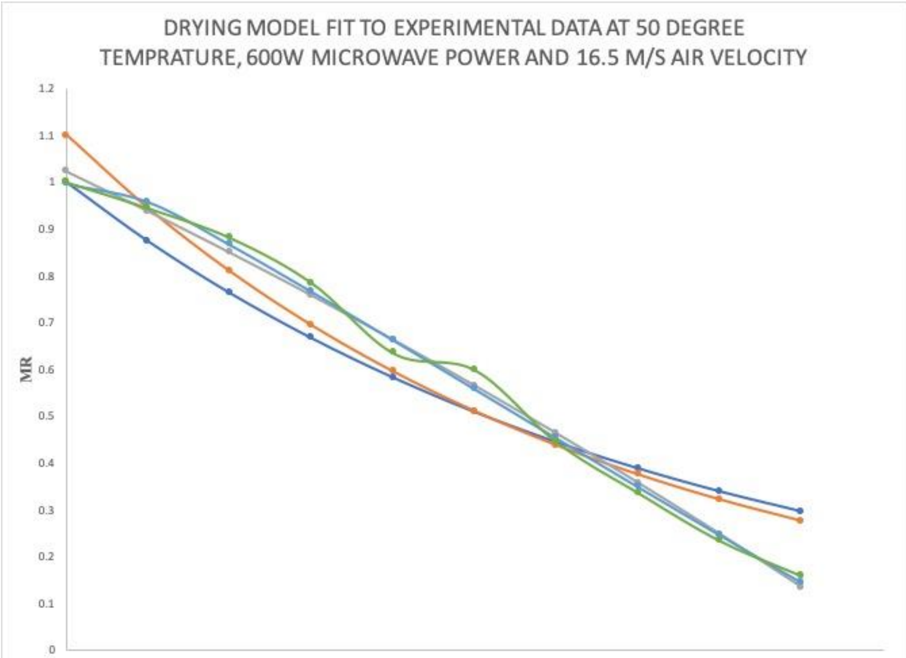
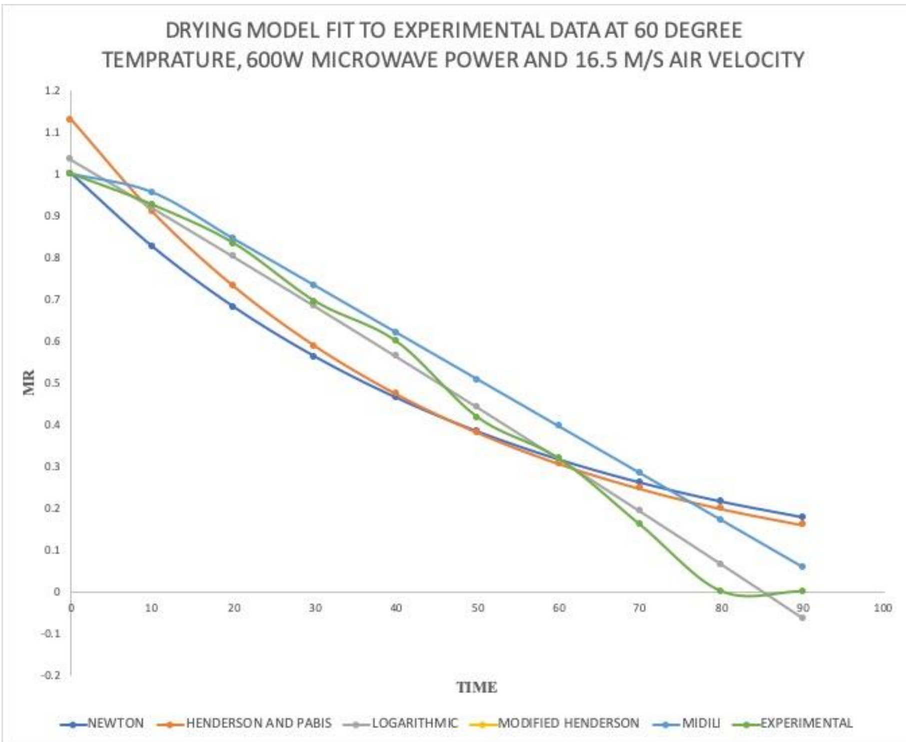


Figure 5: Drying model fit to experimental data at 60-degree temperature, 600W microwave power and 16.5m/s air velocity



4. conclusion

The following conclusion, based on the result of the investigation, were obtained.

1- Drying by hot air in fluidized bed dryer was high at the start, but with moisture decreasing, the warm air effect decreases.
2- Drying time decreased with increasing the air temperature since it causes a higher rate of evaporation on the surface.
3- Using the microwave power increased the drying rate remarkably and decreased the time required for the process as a result of the internal energy generated due to the microwave power leading to raise the temperature more than the air temperature which it considers as the driving force for moisture to move internally to the surface.
4- By using nonlinear regression analysis to fit four drying model to the experimental data it visible that logarithmic drying model satisfies the highest R^2 and lowest RMSE value, and therefore it is the best fit representing the drying of carrot slice in fluidized and microwave-assisted fluidized bed dryer.

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