THIN LAYER DRYING OF SOME SELECTED VEGETABLES IN A FORCED CONVECTION SOLAR DRYER WITH ENERGY BACKUP SYSTEM FOR CONTINUOUS DRYING OPERATION

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ABSTRACT
Vegetables (tomato, pepper and ginger) are high moisture agricultural products that normally begin to undergo deterioration immediately after harvest. Heavy losses of the products usually occur as a result. Farmers employ open air sun drying to control the losses and this has the disadvantages of exposing the products to rain and dust contamination, insect and rodent attack and poor quality outputs. Most of the solar dryers already developed have the inability to continue the drying process during off sunshine hours of the day. If drying process has not come to completion prior to sunset, the operation has to be broken to commence again when the sun rises the next day. During the break in drying, normally at night, certain biochemical reactions can occur and lead to the commencement of material deterioration. The novel continuous drying solar dryer was developed to address the above problem, and it was used to determine the drying characteristics of tomato, pepper and ginger in the temperature and relative humidity ranges of 17 - 60 ^oC and 10 - 76%, respectively. Each product was dried in thin layer and moisture loss was monitored with time. Fourteen popular thin layer-drying models were tested using the data obtained. Results showed that tomato, pepper and ginger dried from 95 to 6.3%, 88 to 18.2% and 84 to 19.8% moisture contents in 15, 16 and 12 hours, respectively. The products dried mainly in falling rate phase. The values of effective diffusivity for tomato, pepper and ginger in the dryer were 2.1885×10^{-9}, 2.3101×10^{-9} and 2.4317×10^{-9} m^2/s respectively. Aghbashlo et al. model with randomized residual plots, lowest RMSE and highest R^2 was the best model for predicting the drying behavior of tomato, pepper and ginger in the dryer.

KEYWORD: Drying, forced convection, drying rate, continuous drying solar dryer, fruits and vegetables, drying kinetics, drying models, drying time

1. INTRODUCTION

Tomato fruit (*Lycopersicon Esculentum*) is one of the most important vegetable/fruits found Worldwide that contribute to healthy well-being and balanced diet as they are rich in minerals, vitamins, essential amino acids, sugars and dietary fibers (Naika *et al.,* 2005). The fresh tomato fruit has the problem of short post-harvest life (Jayathunge *et al.*, 2012; Shahnawaz *et al.*, 2012). Pepper fruit (*Capsicum Annuum*) is produced in many parts of the World and it is used to spice up food (Boseland and Votava, 2000). When not in season, and where effective and efficient storage systems are not available, pepper can be dried to enhance storage (John, 2015). Ginger rhizome belongs to the *Zingiberaceae* family, an herbaceous perennial plant that is native to Southern Asia. It is extensively consumed as spice in foods and beverages because of its characteristic pungency and piquant flavor (Srinivasan, 2017). Ginger rhizome is a very important cash crop in Nigeria due to its oleoresin and ginger oil contents. Among other spices it is the one majorly grown on a commercial scale for export and highly valued in the international market for its aroma, pungency and high oleoresin content (Famurewa *et al.*, 2011). Ginger is also a medicinal plant that has been widely used all over the world for the treatment of a wide range of ailments including arthritis, cramps, rheumatism, sprains, sore throats, muscular aches, pains, constipation, vomiting, hypertension, indigestion, dementia, fever and infectious diseases (Ali *et al.*, 2008).

The short post-harvest life of the above vegetables is due to high moisture content and inadequate drying which result in heavy post-harvest losses due to deterioration. Different genera of fungi, bacteria, protista and even viruses are responsible for spoilage of food and agricultural products affecting taste, color and rendering them unsuitable for consumption (Naresh and Pratibha, 2021). To minimize post-harvest losses in these products, they are usually subjected to drying unit operation. Drying involves the removal of water from a hygroscopic material at medium to high moisture contents to a level considered safe for storage or commencement of other processing operations, by means of evaporation (Sokhansanj and Jayas, 2006).

The drying process normally adoptedby rural farmers in different parts of the developing World involves drying in the sun by spreading the products either on cemented floors or on trays and openly placing them under the sun. Farmers lose substantial percentage of the harvest of their products due to the open air drying practice. This is normally due to exposure of the products to rain, contamination by dust and debris, uncontrolled drying and attack by insects and rodents. In most cases drying cannot be concluded in a single day, and when the sun sets in the evening, deterioration of the products as a result of microbial and biochemical activities may occur. The exposure of products to direct sunlight which is undesirable and infestation by insects and attack by animals, coupled with the slow drying rate, in addition to the stoppage of drying during the off-sunshine hour are the major drawbacks of the traditional open air sun drying method and the conventional solar dryer system, respectively. To solve the above problems, a continuous drying solar dryer for agricultural and food products needs to be developed. Scalin (1997) recommended drying temperatures for fruits and vegetables to be between 37.7-54.4^{o}C. The optimum temperature for drying of fruit and vegetables is 60^{o}C according to Henneman (1994). The use of higher drying temperatures in the drying of fruits and vegetables, it may cause case hardening. Drying rates and final crop quality have been reported to be very much dependent on crop drying temperature (Jayaraman and Gupta, 2006).

The drying behaviour of different products have been expressed using mathematical models. These models have been used to describe drying processes, help their optimization, and assist in the effective design of dryers (Vega *et al.*, 2007). Empirical equations frequently used to model the drying kinetics of food include: Newton, Page, Henderson–Pabis, Page modified, Logarithmic, Two-terms exponential, Thomson, Diffusion approach, Verma, Wang and Singh, Henderson–Pabis modified models and others (Vega *et al.*, 2007; Meisami-asl *et al.*, 2010). Mohapatra *et al.* (2015) developed a natural convection grain dryer for drying paddy and other cereals by use of thermal energy effectively. Average drying temperature of paddy was between 50 to 58°C. Pangavhen *et al.* (2002) designed, constructed and tested a new convection solar dryer capable of producing average temperature between 36.5 and 55^{o}C, on the dehydration of grapes as well as most fruits and vegetables. It was reported that engineered solar dryers overcame the limitations of the open-air sun drying method (Itodo *et al.*, 2002). Awechie (1982) designed and constructed a solar box dryer and obtained a temperature of 180° for drying crops. Itodo and Fulani (2004) evaluated the performance of a direct active solar dryer using cassava marsh with centrifugal fan forcing the air through the dryer. Pembi (2000) developed a small-scale solar dryer with the aim of achieving effective method of tomato preservation and eliminating the drudgery and product deterioration associated with traditional methods of open sun drying of the product. None of the studies above addressed the problem of breakage in the drying process after sunset. A novel continuous drying solar dryer was conceptualized, developed, and used to address the problem. The objective of this study was to investigate the drying behaviour of tomato, pepper and ginger slices in the developed novel continuous drying solar dryer and determine the suitable model for predicting the thin layer drying kinetics of the products in the dryer.

2. MATERIALS AND METHODS

2.1 Material Procurement and Preparation

The bulk quantities of fresh tomato fruits (*Lycopersicon Esculentum*), pepper fruits (*Capsicum Annuum*) and ginger rhizome (*Zingiber Officinale*) used in this study, were purchased from Monday market, Maiduguri, Borno State, Nigeria. The fruits were sorted, washed and sliced to an approximate thickness of 2-3 mm each in line with the recommendations of FAO (1997). After that, the product weighing 150 g on an electronic balance, was placed on a tray and loaded into the drying chamber for drying to commence. Loading of trays was carried out in triplicates for each of the products.

2.2 Description and Operation of Novel Continuous Drying Solar Dryer

The continuous drying solar dryer, as shown in Figure 1, consists of two 250 W capacity solar panel system for capturing the solar radiation from the sun. The panels were mounted on the tool frame and inclined to the horizontal as such angle that will enable it to track the movement of the sun. An insulated cable transfers energy from the panels to the solar battery through a 30 A charge controller. The controller regulates the charging of the battery. The battery has a capacity of 200 A and, it is used for storing and releasing energy to the 45 W axial fan and 100 W heating element. The axial fan circulates the air from the plenum chamber to the drying chamber where the heating element supplies the heat to raise its temperature before it impinges on the drying product in the drying chamber. When the heated air comes in contact with the product, the vapour from the product is released into it for transport outside the dryer through the chimney.

The solar panels capture the insolation from the sun during the hours of the day with sunshine (morning, afternoon and evening), and during this period, the battery is charged while energy is still supplied to the axial fan and heating element for the drying operation. During the night period when the sun sets and energy supply from the panel stops, drying operation continues because the battery is triggered to release the stored energy that was accumulated during the daytime to maintain the working of the fan and heating element. The dryer continuous to operate throughout the night without stoppage, when there is no sunshine, until the sun rises the next day to continue the recharging of the system battery. If the products have not reached the equilibrium moisture content during the day, the dryer continues to operate during the night. Drying operation for the novel continuous drying solar dryer does not stop until the drying of product is completed and dynamic equilibrium moisture content is attained. The photograph of the continuous drying solar dryer is presented in Figure 2.

To operate the dryer, the mains of the inverter is switched on and the flow of energy starts from the solar panels through the charge controller to effect the charging of the solar battery. The energy (electric current) at the same time flows from the battery through the inverter to power the heating element and the blower (axial fan). The heating element provides the heat that raises the temperature of the air supplied by the fan into the drying chamber. The heated air comes in contact with the drying product, supplies the latent heat of vapourisation, receives the vapor from the product and transfers it out of the dryer through the chimney.

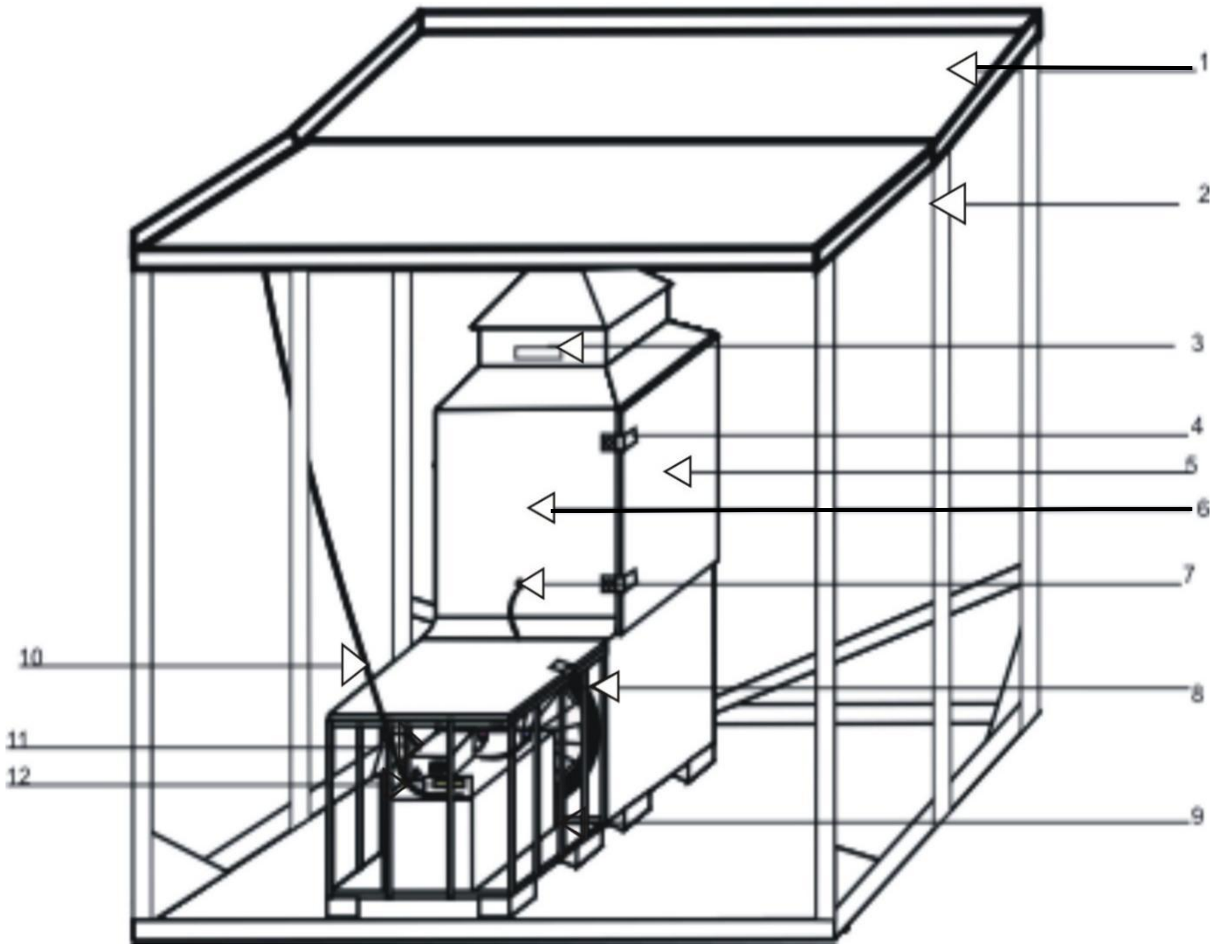

Figure 1**:** Continuous drying solar dryer showing the working components

Key: 1: Solar panel, 2: Tool frame (Angle iron), 3: Exhaust (air vent), 4: Door handle 5: Loading and unloading doorway, 6: Drying chamber with trays, 7: Heating element in plenum chamber 8: Axial fan, 9: Battery, 10: Copper wire, 11: Inverter, 12: Charge controller

Figure 2: Photo of the continuous drying solar dryer

At the commencement of drying run, the dryer is allowed to run empty with the door closed for 30 minutes to enable the drying chamber to acquire uniform condition of temperature and relative humidity. The door is then, opened and the product to be dried is placed on the drying trays and transferred into the drying chamber. The reduction of product moisture content with time is then monitored until the drying operation is completed and dynamic equilibrium moisture content is attained. The continual removal of moisture from the products results in the lowering of its moisture content indicating that drying is taking place.

2.3 Drying Experiment

The thin layer drying experiments for tomato, pepper and ginger were conducted in an open space when the drying system was fully exposed to solar radiation at Damboa Road Opposite Federal Road Safety Office, Maiduguri, Borno State, Nigeria in the month of October. Drying of the tomato, pepper and ginger slices was performed on trays in the continuous drying solar dryer. The dryer was allowed to run without load for 30 minutes to enable the drying chamber to acquire uniform condition of temperature and relative humidity and the weight of the product was measured using an electronic weighing balance with an accuracy of 0.01 g. Slices of the drying product were placed on the three drying trays in thin layers and loaded into the drying chamber with each tray having 150 g of the product, with the dryer still running on. The initial moisture content was 95% for tomato, 88% for pepper and 84% for ginger. The procedure described by Aviara and Igbeka (2016) was followed in conducting the drying tests with slight modification to suit the drying conditions. The drying of tomato fruits, pepper fruits and ginger rhizomes commenced at 6:00am. Weighing of samples was carried out periodically as follows: every 10 minutes for one hour, 20 minutes for two hours, followed by 30 minutes for three hours and lastly every hour until three consecutive readings gave identical values. Equilibrium is said to have been attained at this point and the drying operation is terminated. If drying is not completed by sunset, it is continued using the stored energy mode, and breakage of the drying process is not experienced. At the end of drying, the time taken is noted and the moisture content of the dried product is taken and termed dynamic equilibrium moisture content (EMC). The temperature and relative humidity during the drying process was respectively measured using a digital thermometer and hygrometer at the above regular time intervals.

2.4 Data and Analysis

The data obtained from the drying operation of tomato, pepper and ginger were subjected to Analysis of Variance (ANOVA) to determine the effects of tray position and time, tray position and temperature, tray position and relative humidity, temperature and time and relative humidity and time on the moisture content of the products during drying. SPSS for Windows version 20 was used to conduct the ANOVA.

2.5 Equilibrium Moisture Content, Drying Time and Drying Rate

The moisture content of each product at a given time during the drying process was estimated using the Equation by Kajuna *et al.* (2001) and Aviara and Igbeka (2016) given in Equation 1.

$$M_t = \frac{Mimi - Wl}{mi - Wl} \tag{1}$$

where:

M_t is the moisture content (%) at a given time t,
M_i is the initial moisture content of the product (%),
mi is the initial mass of the wet product, (g) and
Wl is the mass loss (g) at time t.

The time (min) taken from the start of drying to the attainment of dynamic EMC became the drying time and was recorded for each product. The equilibrium moisture content is the point at which the product is no longer gaining or losing moisture. Moisture content, temperature and relative humidity were then plotted against time to establish the drying curve.

The rate of drying is the amount of moisture lost per unit of the drying surface per unit time of the drying operation or the amount of evaporated moisture over time (Dhanushkodi *et al.*, 2014). The drying rate was computed using Equation 2.

$$\mathrm{dr} = \frac{mi - md}{t} \tag{2}$$

where:

mi *is* mass of product before drying (g),
md *is* mass of product at a given time (g),
t *is* the time interval (minutes).

Drying rate was plotted against drying time and moisture content to establish the drying rate phase.

2.6 Effective moisture diffusivity (D_e)

The effective diffusivity (*De*) of tomato, pepper and ginger, respectively, was estimated by applying the diffusion model for infinite slabs (Samimi *et al.*, 2016).

$$MR = \frac{8}{\pi^2}\sum\frac{1}{(2n-1)^2}exp\ \left[\frac{-(2n-1)^2\pi^2 Det_d}{4L^2}\right] \quad (3)$$

where:

D_e is the effective diffusivity (m^2/s),
t_d is the drying time (s),
L is the half thickness of the slice (m) and
n is a positive integer.

When L is small and t is large, the first term of the expansion in Equation 3 is considered (Samimi *et al.*, 2016), and then stated as follows:

$$MR = \frac{8}{\pi^2}exp\ \left[\frac{-\pi^2 Det_d}{4L^2}\right] \quad (4)$$

A logarithmic transformation of Equation 4 yields a linear equation of the form

$$\text{Ln}\ (MR) = A + Bt \quad (5)$$

where A and B are constants, and

$$B = \frac{\pi^2 De}{4L^2} \quad (6)$$

Ln(MR) was plotted against t and the constant B in Equation 5 was obtained from the slope and used in Equation 6 to compute the values of D_e.

2.7 Modelling the thin layer drying process

The moisture content obtained at a given time was converted to moisture ratio, which is the dimensionless parameter that normalizes the drying curves and is expressed as given in Equation 7.

$$MR = \frac{Mt - Me}{Mi - Me} \quad (7)$$

where:

MR is the dimensionless moisture ratio,
Mt is the moisture content at a given time (%),
*M*e is the equilibrium moisture content (%), and
M_i is the initial moisture content (%).

The thin layer drying models presented in Table 1 were fitted to the drying data that was obtained for tomato, pepper and ginger, using linearization by logarithmic transformation and nonlinear regression procedure in Statistics 10 statistical package. Fitting was carried out using dimensionless moisture ratio as a function of time for the drying of the products and the model parameters were evaluated. The observed and predicted moisture ratios were compared and statistically analyzed to determine the best-fitting equation. The goodness of fit of each model was evaluated using coefficient of determination and standard error of estimate, calculated by the procedure, and residual plots. Coefficient of determination is expressed as R^2 and defined as

$$R^2 = \left(1 - \frac{\sum \left(\mathrm{MR_{obs}} - \mathrm{MR_{pred}}\right)^2}{\sum \left(\mathrm{MR_{obs}} - \mathrm{MR_{mean}}\right)^2}\right) \tag{8}$$

The standard error of estimate, *SE*, is defined as

$$SE = \sqrt{\frac{\sum_1^N \left(MR_{obs} - MR_{pred}\right)^2}{N}} \tag{9}$$

where:

MR_{obs} is the observed moisture ratio,
$\mathrm{MR_{pred}}$ is the predicted moisture ratio,
N is the number of observations in each set and
$\mathrm{MR_{mean}}$ is the mean of the observed moisture ratio values.

A model is regarded as being acceptable if the residuals are uniformly scattered around the horizontal value of zero, showing no systematic tendency towards a clear pattern in which case the residual plots is said to be randomized. One model is regarded as being better than another if it produces a higher coefficient of determination and a lower standard error of estimate (Ajibola, 1989). The moisture ratios predicted by the best-fitting model for the drying run of each product were then plotted alongside the measured values against time. The reliability of the model for describing the drying curves of tomato, pepper and ginger was evaluated by comparing the predicted moisture ratios with the measured values (Onuoha *et al.*, 2013). This was carried out by plotting the predicted moisture ratios against the measured moisture ratios. A model is regarded as being reliable if the predicted moisture ratios fall near the line y = x (Syarief *et al.*, 1984).

Table 1: Selected thin layer drying models

Model	MR	Equation	Reference
Aghbashlo *et al.*	MR	$exp(-kt/1+ct)$	Aghbashlo *et al.,* 2009
Diffusion Approach	MR	$a\ exp(-kt) + (1-a)exp(-kgt)$	Akpinar and Bicer, 2006
Henderson and Pabis	MR	$a\ exp(-kt)$	Akpinar *et al.,* 2003
Hii *et al.*	MR	$a\ exp(-kt^n) + c\ exp\ (-gt^n)$	Hii *et al.,* 2008
Logarithmic	MR	$a\ exp(-kt) + c$	Yaldiz *et al.,* 2001
Midilli and Kucuk	MR	$a\ exp(-kt^n) + bt$	Midilli and Kucuk, 2003
Modified Henderson and Pabis	MR	$a\ exp(-kt) + exp(-gt) + c\ exp(-ht)$	Hamdami *et al.,* 2006
Modified Hii *et al.*	MR	$a\ exp(-kt^m) + c\ exp\ (-gt^n)$	Aviara and Igbeka, 2016
Newton	MR	$exp(-kt)$	Muhidong *et al.*, 1992
Page	MR	$exp(-kt^n)$	Karathanos and Belessiotis, 1999
Two term exponential	MR	$a\ exp(-kt) + (1-a)\ exp(-kat)$	Hii *et al.,* 2008
Two term model	MR	$a\ exp(-kt) + c\ exp(-gt)$	Yaldiz et al., 2001
Verma *et al.*	MR	$a\ exp(-kt) + (1-a)\ exp(-gt)$	Verma et al., 1985
Wang and Singh	MR	$1 + at + bt^2$	Wang and Singh, 1978

3. RESULTS AND DISCUSSION

The drying behaviour of tomato, pepper and ginger in the novel continuous drying solar dryer is respectively presented as follows.

3.1 Temperature, Relative Humidity and Moisture Content of products in trays with time During Drying

Table 2 shows the temperature, relative humidity and moisture content of tomato, pepper and ginger in the drying trays at different times during the drying operation. From the Table, it can be seen that tray 1 was the first to attained equilibrium for each of the products. Trays 2 and 3 then followed after. This may have been due to the fact that the drying air always had to come in contact with the products in tray 1 before reaching the other trays because of its position. However, the results of ANOVA of moisture content with tray and time presented in Tables 3, 4 and 5 show that the position of the tray did not have significant effect on moisture content of the products. Moisture content was not significantly different with tray. Only time had significant effect on the moisture content at 1% level of significance. Even the interaction between tray and time did not have significant effect on moisture content and for this reason, the average of the moisture content of the three trays at a given time was obtained and used as the moisture content of the product in the drying chamber at the given time. Similar results were obtained on the variation of temperature and relative humidity with tray position and time.

Table 2: Temperature, Relative Humidity and Moisture Content of products in Drying Trays at different times during the drying operation.

	TOMATO									PEPPER									GINGER								
	TRAY 1			TRAY 2			TRAY 3			TRAY 1			TRAY 2			TRAY 3			TRAY 1			TRAY 2			TRAY 3		
TIME	TEMP.	R.H %	MC	TEMP.	R.H %	MC	TEMP.	R.H %	MC	TEMP	R.H %	MC	TEMP.	R.H %	MC	TEMP	R.H %	MC	TEMP.	R.H %	MC	TEMP.	R.H %	MC	TEMP.	R.H %	MC
6:00:00 AM	21.6	76	0.950	17.2	72	0.95	17.5	75	0.95	22.9	64	0.88	19.1	63	0.88	19	64	0.88	23.1	70	0.84	18.1	76	0.84	17	81	0.84
6:10:00 AM	33.4	56	0.949	18.1	78	0.949	17.9	77	0.949	34	39	0.8776	19.5	63	0.8759	19.4	64	0.8759	24.5	65	0.831	18.9	77	0.8367	18.9	83	0.8367
6:20:00 AM	36.3	49	0.947	19.1	74	0.9479	18.3	77	0.9486	42	34	0.875	19.9	65	0.8741	19.3	65	0.875	25.4	57	0.8273	19.3	77	0.8356	18.7	83	0.8356
6:30:00 AM	38.4	48	0.946	19.9	67	0.9476	18.7	76	0.9476	42.9	30	0.8723	20.2	66	0.8723	19.5	67	0.8732	26.3	50	0.8235	20.1	76	0.8345	19	82	0.8345
6:40:00 AM	42.1	46	0.944	20.5	65	0.9468	19.2	72	0.9472	43.7	33	0.8696	20.5	66	0.8696	19.8	67	0.8714	26.9	44	0.8182	20.7	76	0.8333	19.6	80	0.8322
6:50:00 AM	45.5	28	0.943	21.1	63	0.9457	19.7	70	0.946	40	36	0.8657	20.8	66	0.8676	20.3	64	0.8696	27.6	42	0.814	21	70	0.8286	19.8	77	0.8298
7:00:00 AM	47.7	26	0.942	21.5	61	0.9449	20.1	69	0.9457	42.7	36	0.8626	21.1	65	0.8657	20.5	64	0.8686	29.2	41	0.808	21.2	68	0.8248	20	76	0.8286
7:20:00 AM	48.3	26	0.939	22.4	60	0.9427	21.9	69	0.9436	42.6	27	0.8571	22	66	0.8615	21.3	64	0.8657	35.8	36	0.7966	22.3	66	0.8209	20.8	75	0.8235
7:40:00 AM	49.1	28	0.935	23.3	59	0.9409	21.7	67	0.9419	51.3	15	0.8487	23.3	65	0.8571	23	62	0.8615	32.3	34	0.7838	23.6	59	0.814	22.2	72	0.8195
8:00:00 AM	50.3	18	0.931	25	57	0.938	23.3	63	0.939	53.6	10	0.8407	24.8	60	0.85	25	61	0.856	31.4	32	0.7647	25.4	53	0.8065	23.8	68	0.8125
8:20:00 AM	51.4	13	0.926	27	52	0.9353	25.4	58	0.937	54.4	10	0.8302	27	51	0.8435	26.5	57	0.8512	40.1	30	0.7419	27.6	44	0.7949	25.9	56	0.8017
8:40:00 AM	52.7	12	0.921	30.5	43	0.9318	27.2	53	0.9324	55.6	10	0.8125	28.6	45	0.8349	27	44	0.8421	44.8	23	0.7108	28.5	44	0.7818	28	49	0.7931
9:00:00 AM	53	10	0.915	30.5	42	0.9279	28.7	47	0.9272	55.6	10	0.8022	29.5	44	0.8235	29	42	0.8333	47.1	20	0.6712	30.2	39	0.7692	28.7	47	0.7624
9:30:00 AM	53.1	10	0.903	32.2	42	0.9211	30.6	39	0.9211	59.9	10	0.775	31.1	41	0.8043	30.8	36	0.8163	48.3	16	0.619	32.2	33	0.7447	30.7	44	0.7526
10:00:00 AM	53.3	10	0.883	33.1	34	0.9118	31.2	36	0.9096	49.4	10	0.7391	32.8	37	0.7831	33.4	34	0.7955	48.7	10	0.5472	33.8	30	0.7143	33.3	36	0.7209
10:30:00 AM	53.7	10	0.864	34	35	0.9	34.3	33	0.8973	49.8	10	0.7097	34.5	31	0.7353	34.7	30	0.7805	49.9	10	0.4667	35.7	24	0.6842	34.3	37	0.6842
11:00:00 AM	56	10	0.833	36.1	25	0.8864	35.1	28	0.8828	57.9	10	0.6842	35.5	30	0.7353	34.9	28	0.7429	54.6	10	0.3846	37.5	22	0.6471	36.2	32	0.6418
11:30:00 AM	57.2	10	0.797	37.6	23	0.8684	37.1	21	0.8611	54.8	10	0.625	37.9	21	0.6949	35.2	20	0.7049	54.5	10	0.2941	38.2	20	0.5862	37.2	31	0.5714
12:00:00 PM	58.5	10	0.758	39.4	18	0.85	38.8	19	0.8333	57.2	10	0.561	39.1	18	0.6667	38.1	19	0.6786	55.9	10	0.25	40.5	16	0.5556	38.8	26	0.5385
1:00:00 PM	59.1	10	0.659	42.6	13	0.7727	42.2	14	0.7414	55.3	10	0.4	42.5	10	0.6471	40.7	19	0.5714	57.6	10	0.2258	43.4	10	0.4286	42	17	0.4286
2:00:00 PM	60	10	0.375	44.7	13	0.6875	43	13	0.6053	57.1	10	0.3333	44.8	10	0.4857	44.6	19	0.4706	58.6	10	0.1724	44.7	10	0.3143	43.6	12	0.3333
3:00:00 PM	58	10	0.167	45.8	12	0.5833	45.4	11	0.375	51.9	10	0.28	44	10	0.3793	40.8	15	0.3793	52.1	10	0.1429	44	12	0.25	43.9	10	0.25
4:00:00 PM	57	10	0.063	40.4	12	0.375	40.3	11	0.25	53.6	10	0.1818	41.2	12	0.3333	40.7	12	0.3077	51	10	0.1429	41.1	14	0.2258	40.6	12	0.2258
5:00:00 PM	56	10	0.063	39.1	11	0.25	38.6	11	0.25	50.6	10	0.1818	39.6	12	0.28	38.2	12	0.25	49.1	10	0.1429	38.1	14	0.2258	37.3	14	0.2258
6:00:00 PM	56	10	0.063	37.2	13	0.1667	37.2	12	0.1667	50.6	10	0.1818	36.8	12	0.25	36.1	13	0.2174				37.7	15	0.2258	37.2	16	0.2258
7:00:00 PM				34.8	19	0.0625	36.9	12	0.0625				35	13	0.2174	34.5	14	0.2174									
8:00:00 PM				33.3	23	0.0625	32.8	24	0.0625				33.1	18	0.1818	32.4	16	0.1818									
9:00:00 PM				33	25	0.0625	32.5	26	0.0625				31.2	21	0.1818	31.1	21	0.1818									
10:00:00 PM													30.5	24	0.1818	30	21	0.1818									

Table 3: ANOVA of moisture content with tray (TR) and time (TI) for tomato

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	6.416[a]	14	.458	1085.381	.000
Intercept	43.471	1	43.471	102949.124	.000
TR	.000	2	.000	.506	.605
TI	6.416	4	1.604	3798.577	.000
TR * TI	4.587E-006	8	5.733E-007	.001	1.000
Error	.025	60	.000		
Total	49.912	75			
Corrected Total	6.442	74			

a. R Squared = 0.996 (Adjusted R Squared = 0.995)

Table 4: ANOVA of moisture content with (TR) and time (TI) for pepper

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	4.167[a]	14	.298	1531.255	.000
Intercept	34.388	1	34.388	176894.117	.000
TR	.000	2	8.041E-005	.414	.663
TI	4.167	4	1.042	5358.769	.000
TI * TR	.000	8	4.065E-005	.209	.988
Error	.012	60	.000		
Total	38.567	75			
Corrected Total	4.179	74			

a. R Squared = 0.997 (Adjusted R Squared = 0.997)

Table 5: ANOVA of moisture content with (TR) and time (TI) for ginger

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	4.167[a]	14	.298	1531.255	.000
Intercept	34.388	1	34.388	176894.117	.000
TI	4.167	4	1.042	5358.769	.000
TR	.000	2	8.041E-005	.414	.663
TI * TR	.000	8	4.065E-005	.209	.988
Error	.012	60	.000		
Total	38.567	75			
Corrected Total	4.179	74			

a. R Squared = 0.997 (Adjusted R Squared = 0.997)

The average values of moisture content, temperature and relative humidity in the trays with time were used to plot the product drying curves (Figure 3a, b and c).

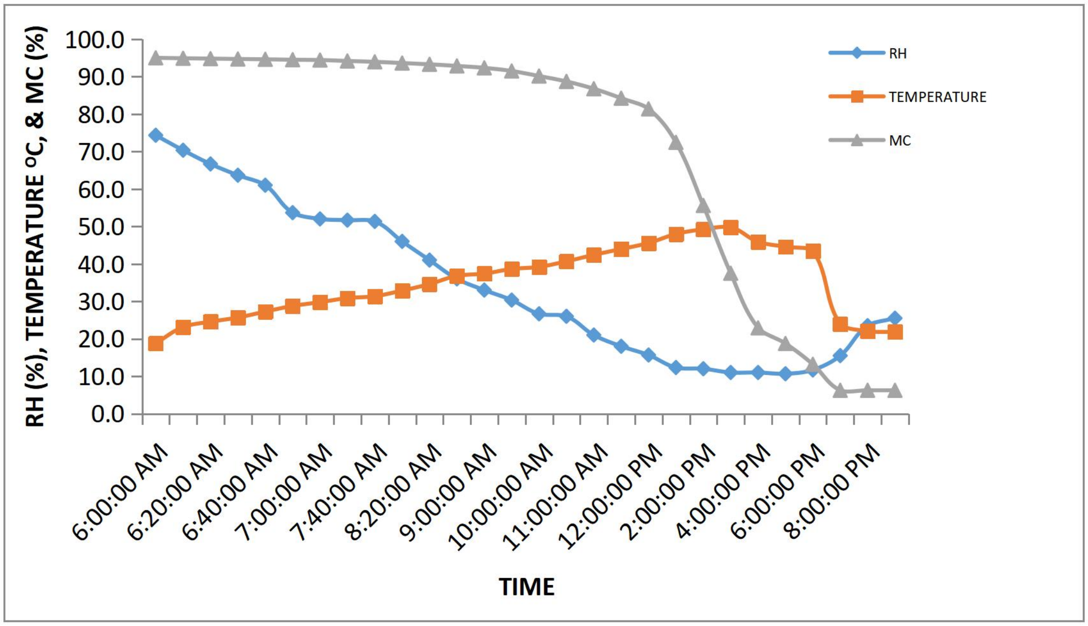

Figure 3a: Variation of relative humidity, temperature and moisture content with time for tomato

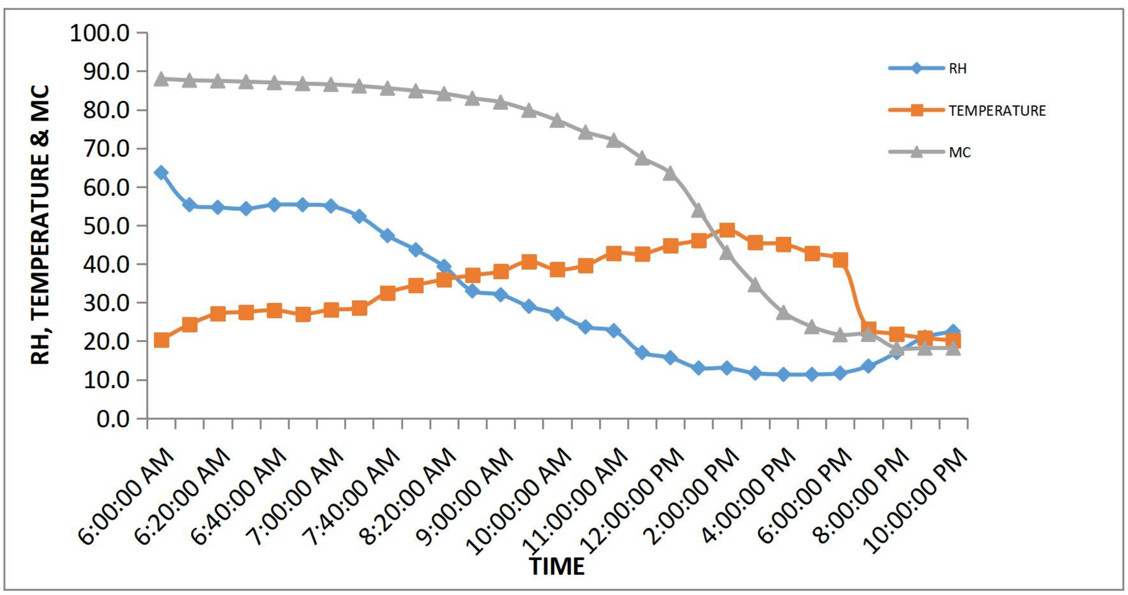

Figure 3b: Variation of relative humidity, temperature and moisture content with time for pepper

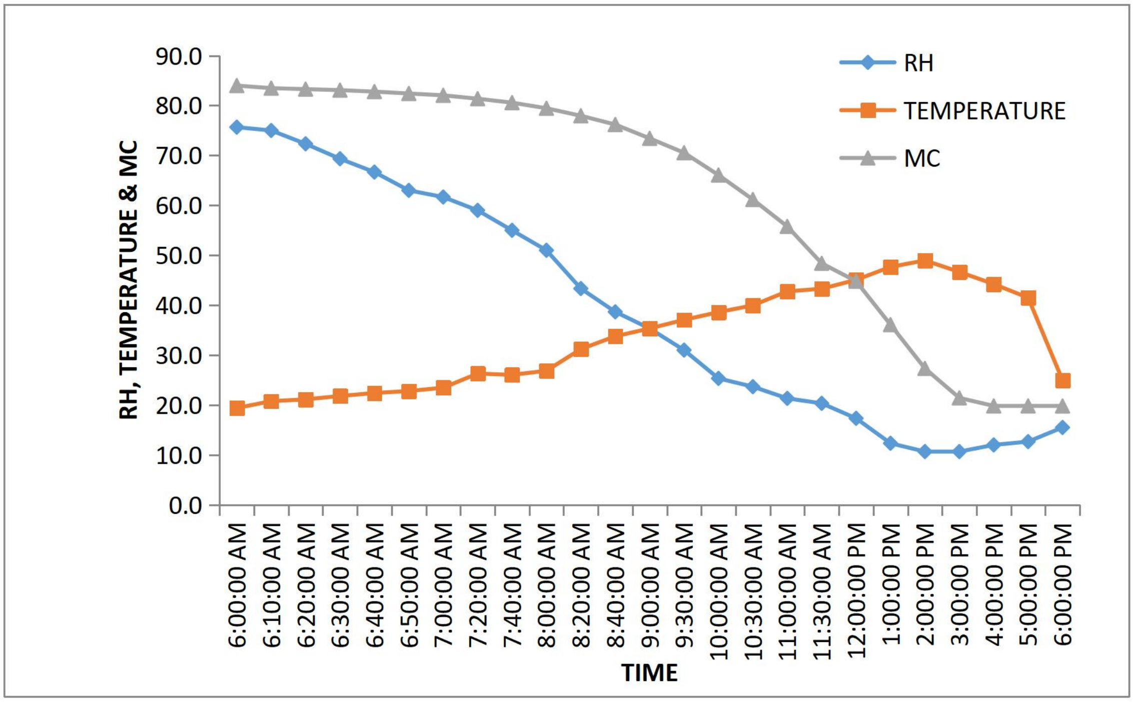

Figure 3c: Variation of relative humidity, temperature and moisture content with time for ginger

The ANOVA of moisture content with temperature and time for tomato fruit presented in Table 6 reveals that temperature and time as well as their interaction had significant effect on the moisture content of the product at 1% level of the significance. Similarly, results were obtained in the ANOVA of moisture content with temperature and time for pepper fruit and ginger rhizomes. The ANOVA of moisture content with relative humidity and time for tomato (Table 7) shows that both parameters had significant effect on the product moisture content at 1% level of significance. Pepper fruit and ginger rhizome exhibited similar ANOVA results as that of tomato that is presented in Table 7.

Table 6: ANOVA of moisture content of tomato with temperature (T) and time (T) during drying

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	6.441[a]	24	.268	28112.504	.000
Intercept	43.471	1	43.471	4553485.756	.000
T	.013	4	.003	335.103	.000
TI	6.416	4	1.604	168012.760	.000
TE * TI	.012	16	.001	81.791	.000
Error	.000	50	9.547E-006		
Total	49.912	75			
Corrected Total	6.442	74			

a. R Squared = 1.000 (Adjusted R Squared = 1.000)

Table 7: ANOVA of moisture content of tomato with relative humidity (RH) and time (TI) during drying

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	6.435[a]	24	.268	8996.896	.000
Intercept	43.437	1	43.437	1457621.445	.000
RH	.014	4	.003	113.276	.000
TI	6.408	4	1.602	53760.205	.000
RH * TI	.013	16	.001	26.974	.000
Error	.001	50	2.980E-005		
Total	49.873	75			
Corrected Total	6.436	74			

a. R Squared = 1.000 (Adjusted R Squared = 1.000)

3.2 Drying Curves of Tomato, Pepper and Ginger

The variation of moisture content, temperature and relative humidity with time for tomato during drying in the novel continuous drying solar dryer is shown in the drying curve presented in Figure 3a. It can be seen that from the commencement of drying at 6.00 am with the product at 95% initial moisture content to 12 noon when the product attained the moisture content of 81.4%, moisture removal was slow, and this may have been due to the environmental temperature at the early hours of the day which was low. From 12.00 noon on, the rate of moisture removal began to occur at a higher rate presenting a steep slope down to 22.92% at 4.00 pm and then gradually declining to 6% at 9.00 pm. The moisture content decreased with time until moisture equilibrium was attained, and this is in agreement with the findings of Yassen *et al.* (2014). From Figure 3a, it can be seen that the temperature was initially low with a value of 18.8 ^{o}C at 6.00 am. It increased steeply to its peak at 49.73^{o}C by 3.00 pm. This was maintained until 7.00 pm when the temperature began to decline and it gradually reached 21.9 ^{o}C at 9.00 pm as a result of the setting of the sun and draining of the energy stored in the battery. The Figure also shows that the relative humidity was initially high with the value of 74.3% at 6.00 am. This was so because the relative humidity in the morning hours is usually high (Yelmen *et al.*, 2019).

The relative humidity decreased steeply until it reached 10.7% at 5.00 pm. It then started to rise until it reached 25.5% at 9.00 pm. The Figure equally shows that temperature and relative humidity crossed twice during the drying of tomato. The first point occurred at 8.40 am and the second point was at 8.00 pm. The points of crossing could be termed the inflexion point of temperature and relative humidity in line with the report of Yelmen *et al.* (2019). The above results indicate that moisture content of the product decreased significantly with increase with time and temperature and decrease in relative humidity at 1% level of significance. The variation of moisture content with time for pepper and ginger is respectively, presented in Figure 3b and 3c. Moisture content in each of these products also gradually decreased with time from 6.00 am to 12.00 noon for pepper and 6.00 to 9.30 am for ginger. It thereafter decreased steeply until the drying process terminated. Temperature also increased with time to a maximum value, which was maintained for a period of time after which it began to decrease. In pepper, temperature crossed the decreasing relative humidity twice, while in ginger the crossing was once during the drying operation. The implication of the above is that in the dryer, moisture content of drying products decreases significantly with increase in time and temperature and decrease in relative humidity at 1% level of significance. If the stored energy released after sun set is maintained until the sun rises the next day, the temperature will likely remain high with time and the relative humidity would likely be low, so that only a single point of crossing will be obtained between them. If the battery capacity is not adequate to maintain energy supply until the next sun rise, the temperature will begin to decrease after a time in the night. The relative humidity will begin to increase and a second point of crossing with temperature will occur.

3.3 Drying Time, Dynamic EMC, Drying Rate and Effective Diffusivity

The time (min) taken from the start of drying to the attainment of dynamic EMC became the drying time and was recorded for each product. For tomato, pepper and ginger at initial moisture content of 95, 88 and 84%, respectively, dried in the novel continuous drying solar dryer, the drying time was 15, 16 and 12 hours, respectively. The dynamic Equilibrium moisture contents obtained were 6.3% (tomato), 18.2% (pepper) and 19.8% (ginger). The changes in drying rates with time for the products are shown in Figure 4. It was observed that drying rate decreased continuously with time and there was no defined constant rate period. The results are in good agreement to the earlier observations (Kaymak-Ertekin, 2002; Passamai and Saravia, 1997).

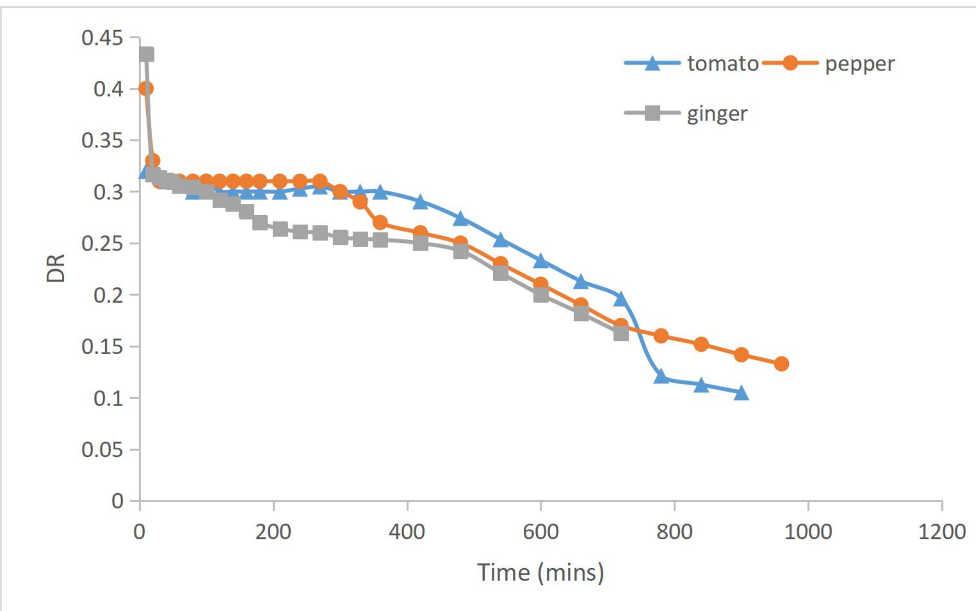

Figure 4: Drying rate variation with time for tomato, pepper and ginger

The variation in the drying rate of tomato, pepper and ginger with moisture content is shown in Figure 5. The Figure shows that the drying rate of each product decreased continuously with decrease in moisture content as reported by Akpinar *et al.* (2003) for red pepper. There was no defined constant rate phase in the drying period as the drying occurred mainly in the falling rate phase. In the falling rate phase, the material was no longer saturated with water as drying may have been controlled by diffusion of moisture from the interior to the surface of the product (Arumuganathan *et al.*, 2009). More than one falling rate period or step was observed. During the first falling rate phase, the drying rate had a steep slope as the movement of water was mostly by trans membrane transport along the cell pathway (Phongsomboon and Intipunya, 2009), so the drying rate was high with a steep slope as the products were saturated and could easily give away moisture. During the second falling rate phase, the material surface was no longer saturated with water and drying rate was controlled by the diffusion of moisture from the interior of the solid to the surface. In this rate phase, the movement of water was mostly in symplastic transport mechanism, and the drying rate was lower (Phongsomboon and Intipunya, 2009).

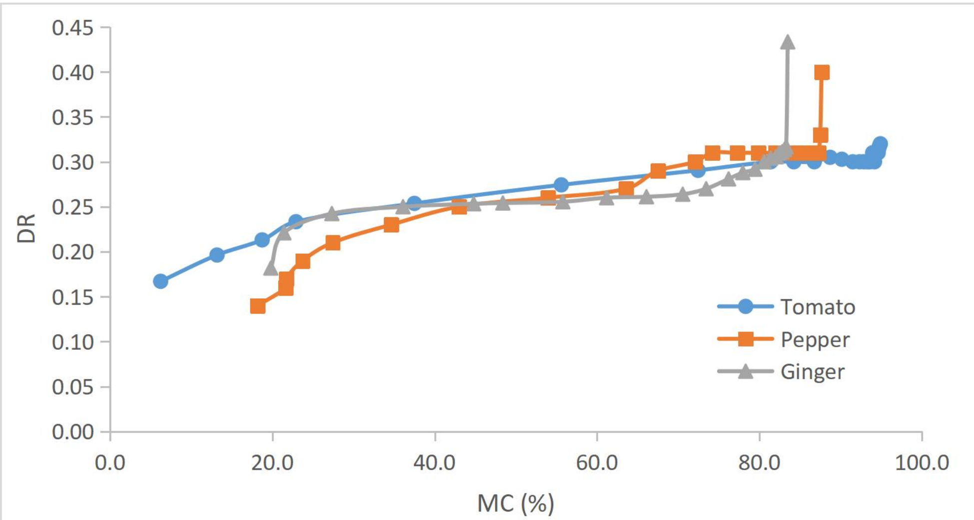

Figure 5: Drying rate against Moisture content for tomato, pepper and ginger

The effective diffusivity of tomato, pepper and ginger slices in the continuous drying solar dryer was found to be 2.1885 x 10^{-9}, 2.3101 x 10^{-9} and 2.4317 10^{-9} m^2/s, respectively. The effective diffusivity values of the products were within the range of 10^{-11} to 10^{-9} m^2/s generally considered acceptable for agricultural and food products (Madamba *et al.*, 1996).

3.4 Drying model evaluation

The parameter estimates and comparison criteria for the thin layer drying models tested on tomato, pepper and ginger drying kinetics are presented in Tables 8, 9 and 10 respectively.

Table 8 shows that in the temperature range of 17.2 ^{o}C minimum to 60 ^{o}C maximum for tomato, and out of the fourteen models evaluated, the Hii *et al.* and Page models failed to predict the drying kinetics of the product, while the Midilli and Kucuk, and Modified Hii *et al*. models (with patterned residual plots), gave unacceptable predictions of the drying behaviour of the product in the novel continuous drying solar dryer. Of the remaining ten models that gave acceptable predictions (with randomized residual plots), the Aghbashlo *et al.* model with the lowest standard error of estimate and highest R^2 was considered and taken as the best model for expressing the drying behaviour of tomato slices in the continuous drying solar dryer.

Table 8: Parameter estimates and comparison criteria for selecting the thin layer drying models for tomato fruit at temperature range of 17.2°C minimum to 60°C maximum

S/N	Model name	Coefficient constant	R2	S.E	Nature of residual plots
1	Aghbashlo et al.	k= 1.93886E-03 c= -1.38889E-03	0.999	3.07E-03	Randomized
2	Diffusion Approach	k= 3.33769E-03 g= 1.000000 a= 1.000000	0.9491	0.1585	Randomized
3	Henderson and Pabis	k= 3.72366E-03 a= 1.087944	0.9631	0.1148	Randomized
4	Hii et al.	Failed	Failed	Failed	Failed
5	Logarithmic	k= 2.07984E-03 c= -0.395488 a= 1.441157	0.9876	0.0387	Randomized
6	Midilli and Kucuk	k = -0.609859 a = 0.890570 b = -1.52721E-03 n = -0.612590	0.9512	0.1519	Patterned
7	Modified Henderson and Pabis	k= 3.72366E-03 a= 0.362648 c= 0.362648 c= 0.362648 g= 3.72366E-03 h= 3.72366E-03	0.9631	0.1148	Randomized
8	Modified Hii et al.	k= -5.286197 a= -11.83873 c= 12.02515 m= -1.219713 g= -2.361589 n= -0.819194	0.546	1.4137	Patterned
9	Newton	k= 3.33769E-03	0.9491	0.1585	Randomized
10	Page	Failed	Failed	Failed	Failed
11	Two term exponential	k= 0.221368 a= 1.000010	0.9491	0.1585	Randomized
12	Two term model	k= 3.72366E-03 a= 0.543972 c= 0.543972 g= 3.72366E-03	0.9631	0.1148	Randomized
13	Verma et al.	k= 7.26466E-03 a= 24.12745 g= 7.56901E-03	0.9927	0.0226	Randomized
14	Wang and Singh	a= -2.52559E-03 b= 1.48535E-06	0.9887	0.035	Randomized

Table 9: Parameter estimates and comparison criteria for selecting the thin layer drying models for pepper fruit at temperature range of 19°C minimum to 59.9°C maximum

S/N	Model name	Coefficient constant	R2	S.E	Nature of residual plots
1	Aghbashlo et al.	k= 2.17586E-03 c= -1.28205E-03	0.9981	6.28E-03	Randomized
2	Diffusion Approach	k= 3.49783E-03 a = 1.000000 g= 1.000000	0.9609	0.1296	Randomized
3	Henderson and Pabis	k= 3.85861E-03 a= 1.079692	0.9715	0.0944	Randomized
4	Hii et al.	Failed	Failed	Failed	Failed
5	Logarithmic	k= 2.59019E-03 c= -0.232230 a= 1.278225	0.9877	0.0409	Randomized
6	Midilli and Kucuk	K= -0.904359 a= 0.835083 b= -1.36303E-03 n= -0.618220	0.9284	0.2374	Patterned
7	Modified Henderson and Pabis	K=3.85861E-03 a= 0.359897 c= 0.359897 g= 3.85861E-03 b= 0.359897 h= 3.85861E-03	0.9715	0.0944	Randomized
8	Modified Hii et al.	K = -4.735680, g= -2.110293 c = 14.08039 a = -13.93070 m= -1.224234 n= -0.819422	0.5694	1.4282	Patterned
9	Newton	k= 3.49871E-03	0.9609	0.1296	Randomized
10	Page	k= 2.01464E-04 n= 1.513647	0.9974	9.31E-03	Randomized
11	Two term exponential	K= 3.49871E-03, a= 1.000008	0.9609	0.1296	Randomized
12	Two term model	k= 3.85861E-03, a= 0.539846 c= 0.539846, g= 3.85861E-03	0.9715	0.0944	Randomized
13	Verma et al.	k= 7.32446E-03 a= 18.07135 g= 7.71960E-03	0.9954	0.0154	Randomized
14	Wang and Singh	a= -2.69409E-03 b= 1.78537E-06	0.992	0.0267	Randomized

Table 10: Parameter estimates and comparison criteria for selecting the thin layer drying models for ginger rhizome at temperature range of 17°C minimum to 58.6°C maximum

S/N	Model name	Coefficient constant	R2	S.E	Nature of residual plots
1	Aghbashlo et al.	k=2.29789E-03, c= -1.71160E-03	0.9972	7.18E-03	Randomized
2	Diffusion Approach	k= 3.99939E-03, a= 1.000000 g= 1.000000	0.944	0.1418	Randomized
3	Henderson and Pabis	k= 4.47506E-03, a= 1.089351	0.9596	0.1023	Randomized
4	Hii et al.	Failed	Failed	Failed	Failed
5	Logarithmic	k= 2.14318E-03, c= -0.568193, a= 1.610483 K= 0.276465, a= 1.043518	0.9875	0.0316	Randomized
6	Midilli and Kucuk	b= -5.34069E-04, n= 0.101821, K= 0.563738, a= 0.363117	0.9631	0.0934	Randomized
7	Modified Henderson and Pabis	c= 0.363117, g= 4.47506E-03, b= 0.363117, h 0.563738	0.9596	0.1023	Randomized
8	Modified Hii et al.	k= -5.962792 a= -15.35665 c= 15.60025 g= -2.502213 m= -1.366592, n= -0.942215	0.5237	1.2064	Patterned
9	Newton	k=3.99939E-03	0.944	0.1418	Randomized
10	Page	Failed	Failed	Failed	Failed
11	Two term exponential	K= 3.99939E-03, a= 1.000007	0.944	0.1418	Randomized
12	Two term model	k=4.47506E-03, a= 0.544676 c= 0.544676, g= 4.47506E-03	0.9596	0.1023	Randomized
13	Verma et al.	K= 8.71973E-03, a= 15.69228, g= 9.30320E-03	0.9928	0.0183	Randomized
14	Wang and Singh	a= -0.501117, b= 0.249441	0.987	0.0329	Randomized

From Table 9, it can be seen that in the temperature range of 19 °C minimum to 59.9 °C maximum for pepper, out of the fourteen models evaluated, only the Hii *et al.* model failed, while the Midilli and Kucuk and Modified Hii *et al.* (with patterned residual plots), gave unacceptable predictions of the drying behaviour of the product in the novel continuous drying solar dryer. Among the remaining eleven models that gave acceptable predictions, the Aghbashlo *et al.* model proved the best for describing the drying behaviour of pepper in the dryer and it was selected as the best.

Table 10 shows that in the temperature range of 17 °C minimum to 58.6 °C maximum for ginger, and out of the fourteen models evaluated, the Hii *et al.* and Pages models failed, while the Modified Hii *et al.* only (with patterned residual plots), gave unacceptable prediction of the drying behaviour of the product in the novel continuous drying solar dryer. Of the remaining eleven models that gave acceptable predictions (with randomized residual plots), the Aghbashlo *et al.* model again had the highest R^2, and lowest standard error of estimate and it was considered the best model for describing the drying kinetics of ginger slices in the dryer.

The variation of the predicted and observed moisture ratios with time for tomato, pepper and ginger, presented in Figure 6, indicates that the moisture ratios in the products decreased with time. The Figure also shows that the Aghbashlo *et al.* model closely predicted the observed moisture ratios of the products.

The Aghbashlo *et al.* model expression for the drying kinetics of tomato, pepper and ginger slices in the novel continuous drying solar dryer are presented in Equations 10, 11 and 12 respectively.

Tomato: $MR=\exp(0.00193886*t/(1-0.00138889*t))$, $R^2=0.9990$ (10)

Pepper: $MR=\exp(0.00217586*t/(1-0.00128205*t))$, $R^2=0.9981$ (11)

Ginger: $MR=\exp(0.00229789*t/(1-0.00171160*t))$, $R^2=0.9972$ (12)

Figure 7 shows the plots of the predicted versus the observed moisture ratios for tomato, pepper and ginger respectfully. The Figure shows that the predicted moisture ratio of tomato, pepper and ginger banded around a straight line with high value of R^2, indicating that the Aghbashlo *et al.* model tracked the drying curves well through the drying periods. The data points banded close to each other demonstrating the suitability of the model for describing the thin layer drying behaviour of tomato, pepper and ginger.

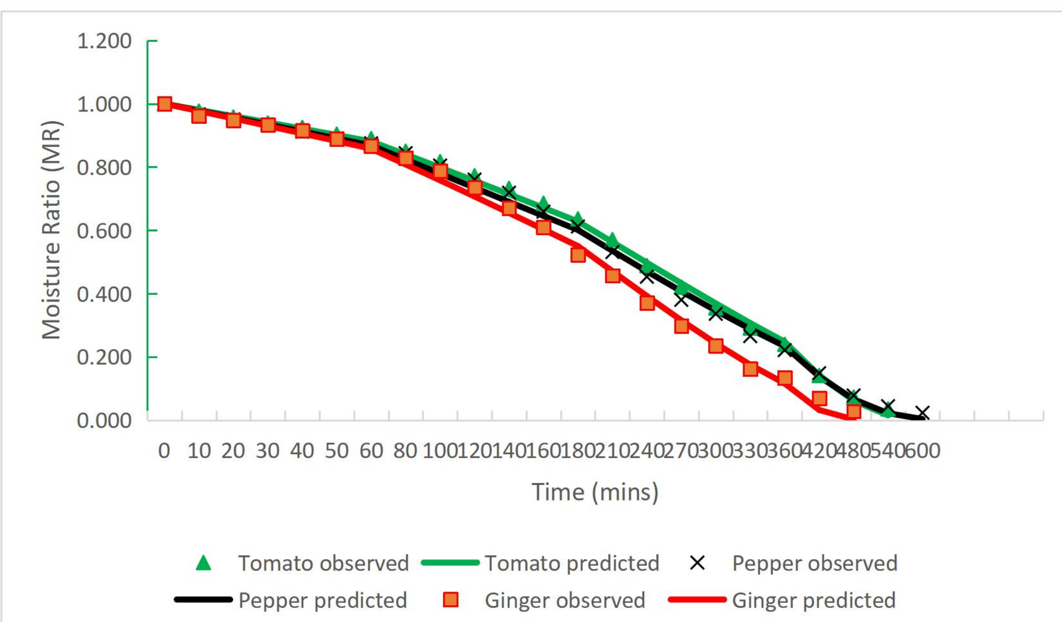

Figure 6: Variation of predicted and observed moisture ratios with time for tomato, pepper and ginger slices

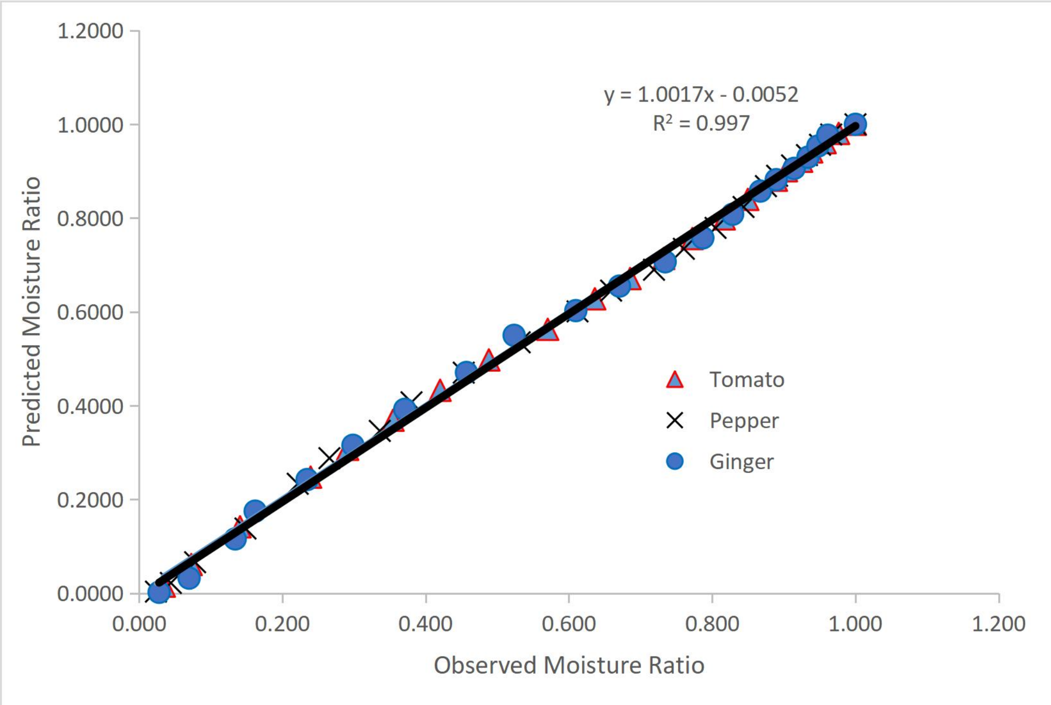

Figure 7: Plot of predicted moisture ratio versus observed moisture ratio for tomato, pepper and ginger

4. CONCLUSION

From the study, the following conclusions were drawn.
The continuous drying solar dryer reduced the moisture content of tomato, pepper and ginger without stoppage in the drying process. It continued to operate even in the absence solar radiant energy during the night until each product reached the dynamic equilibrium moisture content. Moisture content of all the products in the dryer, decreased with increase in time and temperature, and decreased with decrease in relative humidity. Tray position did not have significant effect on moisture removal from products in the dryer and drying process occurred only in the falling rate phase, and in more than one falling rate period. Moisture removal from the slices was governed by diffusion phenomenon and tomato, pepper and ginger slices were dried in 15, 16 and 12 hours respectively with their moisture content reduced from 95 to 6.3% (tomato), 88 to 18.2% (pepper) and 84 to 19.8% (ginger) in thin layer. The effective diffusivity values for the products were within the acceptable range. Aghbashlo *et al.* model proved to be the best among fourteen models tested for predicting the moisture ratio of the products at any time during the drying process for tomato, pepper and ginger slices.

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