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Dehydration kinetics and mathematical modeling of carrot, onion and garlic in convective hot air drying

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Abstract
Drying of carrot, onions and garlic by convective hot air drying is done. The drying kinetics were investigated at 55 °C temperature. The air velocity inside the dryer was 2-3 m/s. The drying process completed within 11.5 hrs for carrot, 18 hrs for onion and 15.5 hrs for garlic. Fitting of the experimental data to different thin layer drying models for carrot, onion and garlic i.e. Newton, Page, Henderson and Pabis, Two term, Wang and Sing, Thompson and Midilli *et al.* models. Among all the models, Midilli *et al.* is the most suitable model fitted to the experimental data for all investigated drying techniques. The Midilli *et al* has highest R^2 values in all carrot, onion and garlic. The effective moisture diffusivites observed are 1.724×10^{-8} m^2/s, 4.03×10^{-9} m^2/s and 3.855×10^{-9} m^2/s for carrot, onion and garlic at 55 °C respectively.

Keywords: Drying, drying models

1. Introduction
Dehydration is the most precious method for preservation of fruits and vegetables. Dehydration is the best option to preserve the fruits and vegetable during abundant production. Drying, in which the water content are decreased, is an important method of preservation and production of a wide variety of products. The most common methods widely used for drying are open air sun drying and solar drying. But their disadvantages include inability to handle the large quantities and to achieve consistent quality standards, contamination problems, long drying times, low energy efficiency and high costs, which is not desirable for the food industry.
Drying is one of the oldest methods of food preservation, and it represents a very important aspect of food processing. The advantage of dried foods is that they have decreased moisture content, which reduces thermodynamic water activity, thus preventing the growth of microorganisms that causes the spoilage reaction (Vega - Galvez *et al*. 2009) [34]. Besides, drying helps to achieve longer shelf life, lighter weight, lesser storage space, and lower packing and transportation costs (Arabhosseini *et al.*, 2009) [1].
Hot air drying is widely applied in food industry. Compared with natural drying methods, hot-air drying is less influenced by climatic conditions, reducing the drying cycle, and maintaining the hygienic condition (Fang *et al.*, 2009) [12]. Drying is a complex process including simultaneously coupled transient heat, mass, and momentum transfers (Cui *et al.*, 2004). Drying kinetics is often used to describe the drying mechanisms of heat and mass transports, and it is also essential for equipment design, process optimization, and product quality improvement.
Carrot (*Daucus carota* L.), one of the most popular root vegetables grown throughout the whole world which is rich in bioactive compounds like carotenoids, vitamins, and minerals (Mestry *et al.*, 2011) [19]. The production of carrot in the year 2016-17 is 1.37 million metric tons in India (NHB: HSD, 2017). It has significant health promoting properties such as antioxidant, anti-inflammatory, anti-cancer, and being a precursor of Vitamin A (Sharma *et al.*, 2012) [30]. Usually, carrot is cooked and dried for the use in instant soups or meals or consumed as raw materials (Sumnu *et al*., 2005) [31].
Onion (*Allium cepa* L.) is considered to be one of the most important crops in all countries. It is the round in shape edible bulb. Red, white and gold onions represent the most common varieties of this species. It is widely used as seasoning in foods. Onion is a strong flavoured vegetable used in a wide variety of ways, and its characteristic flavour (pungency) or aroma, biological compounds and medicinal uses are mainly due to their high organo-sulphur compounds (Mesery and Mwithiga, 2012) [14].

Production of onion in India in the year 2016-2017 was 21.56 million metric tons (NHB: HSD, 2017). It is commonly used in the world food preparations especially in the tropical countries. It has special qualities, which add to taste and flavour to food and hence it is mainly used in India for cuisine and culinary preparations. It is widely used in salads, stew and as flavouring in all cooked vegetables (Sargar *et al*., 2017) [27].
Garlic (*Allium sativum* L.) is a herbaceous plant recognized for its numerous medicinal and culinary properties, used in diverse food preparations for its characteristic flavour and odour (Block *et al*., 1993) [2]. It is usually used without any preprocessing operation. More recently, it has been used in its dried form, as an ingredient of precooked foods and instant convenience foods including sauces, gravies and soups, which led to a sharp increase in the demand of dried garlic. Its main chemical constituents are allicin, carbohydrates, phosphoric and sulfuric acids, proteins and mineral salts (Rahman and Lowe, 2006) [26]. Dehydrated garlic powder is of high commercial value and is used as a seasoning or standard ingredient in food preparations and formulations (Pezzutti and Crapiste, 1997) [24]. Longer shelf life, product diversity and volume reduction are the reasons for the popularity of dried fruits and vegetables, and this could be expanded further with improvements in product quality and process applications (Prakash *et al*., 2004) [25].
Mathematical models, which describe the drying phenomena, could be useful for design and operation of equipments and controlling the process easily (Sharma *et al*., 2005) [29]. Kinetic model studies were usually based on convective drying systems in literature (Demiray and Tulek, 2014) [8].
Sufer *et al.*, 2016 studied Lewis, Page, Modified page, Henderson and Pabis, Logirithmic, Two term, Midilli *et al*., Wang and Sing, Weibull, Parabolic, Cubic, Sigmoid and Thompson models for onion drying. Among that Midilli *et al*., Sigmoid and cubic was best fitted for the convective drying of onion at 50, 60 and 70 °C. Doymaz, 2004 [9] studied the Page and Henderson and Pabis models for convective drying of carrot at 50, 60, 65 and 70 °C. The Page model was best fitted for the data. Demiray and Tulek, 2014 [8] studied the Page, Lewis, Henderson and Pabis, Logarithmic and Modified page model for convective drying of garlic at 55, 65 and 75 °C the Page and Modified page models was best fitted for drying of garlic.
The present study was done because onion and garlic have generally used as culinary and seasoning purpose dehydrated powders are more useful in formulations of dried mixes. Also dried carrot is used in instant soup mixes. In the present investigation it is planned to study the drying kinetics of carrot, onion and garlic.

2. Material and Methods

The carrot, onion and garlic were procured from the local market of Roha (Maharashtra), India.

2.1 Moisture content

The moisture content of carrot, onion and garlic was determined as per AOAC, 2010. Initial moisture content of carrot, onion and garlic was determined by the hot air oven method at 105 °C ±1 °C for 24 hours. The final weight of carrot, onion and garlic were recorded after 24 hours. The moisture content of the carrot, onion and garlic was determined by following formula (Chakraverty, 1994) [4].

$$\text{Moisture content (db)\%} = \frac{W_1 - W_2}{W_2} \text{x} 100 \qquad \ldots (1)$$

Where,
W_1= Weight of sample before drying, g
W_2= Weight of sample after drying, g

2.2 Convective hot air drying

Convective hot air drying of carrot, onion and garlic was performed at Department of Post Harvest Engineering, Post Graduate Institute of Post Harvest Management, Killa-Roha. The drying was carried out in the convective hot air dryer (Make M/s. Aditi Associates, India; Model: ATD-124) having capacity of 5 kW.
There were nine numbers of trays placed inside the convective hot air dryer. The size of the tray was 81cm x 41cm x 3.4 cm. The carrot cubes of size 0.5 cm, onion slices of thickness 2.40 mm and garlic cloves were spread on the tray in single layer. The temperature of the drying was 55 °C. The air velocity inside the dryer was 2-3 m/s. The weight loss with respect to the time was recorded from trays at different location in the convective hot air dryer. The moisture content with respect to time was calculated from drying data. The drying data includes initial moisture content, average moisture content with respect to time, drying rates with respect to moisture content, moisture ratios with respect to time of carrot, onion and garlic were recorded. Three replications were taken for each experiment.

2.3 Moisture ratio

The moisture ratio of carrot, onion and garlic was calculated using following formula (Chakraverty, 2005) [3].

$$\text{Moistureratio} = \frac{\text{M} - \text{Me}}{\text{Mo} - \text{Me}} \qquad \ldots (2)$$

Where,
MR = Moisture ratio
M =Moisture content at any time θ, % (db)
M_e = Equilibrium Moisture Content, % (db)
M_0 = Initial moisture content, % (db)

2.4 Drying model

Moisture Content (% db) versus drying time (min) and drying rate (g of water/ 100g bone dry material/min) with respect to moisture content was determined for drying of carrot, onion and garlic. Moisture ratio versus drying time (min) was also determined from the experimental data.

Table 1: Mathematical models tested with the moisture ratio of carrot, onion and garlic.

Sr. No.	Model	Equation	Reference
1	Newton	$MR = \exp(-kt)$	Westerman *et al.*, 1973 [37]
2	Page	$MR = \exp(-kt^n)$	Zhang and Litchfield, 1991 [38]
3	Henderson and pabis	$MR = a\exp(-kt)$	Henderson and pabis,1961 [15]
4	Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Henderson 1974 [16]
5	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh 1978 [35]
6	Thompson	$t = a \ln(MR) + b \ln(MR)^2$	Thompson, Peart and Foster 1968 [32]
7	Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	Midilli *et al*. 2002 [20]

Various mathematical models listed in Table 1 were tested on the experimental data on moisture ratio versus drying time in minutes of carrot, onion and garlic with convective hot air drying. The moisture ratio determines the unaccomplished moisture change, defined as the ratio of the free water still to be removed, at time t over the initial total free water (Henderson and Pabis, 1961) [15].
The root mean square error was for the best fit of the model was determines for higher R^2 values and lower MSE.

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{n}(\mathrm{MR}_{exp} - \mathrm{MR}_{pre})^2\right]^{1/2} \qquad \ldots (3)$$

Where,
MR_{exp}= experimental moisture ratio
MR_{pre}= predicted moisture.
N and n are the number of observations and the number of constants respectively (Togrul and Pehlivan, 2004) [33].

2.5 Correlation regression coefficient and error analysis
The goodness of fit of the tested mathematical models to the experimental data was evaluated with the correlation coefficient (r^2), chi-square (χ^2) and the equation (3). The higher the r^2 value and lower the chi-square (χ^2) equation (4) and lower value of RMSE values, the better is the goodness of fit (Ozdemir *et al*, 1999; Ertekin and Yaldiz., 2004; Wang *et al.*, 2007) [23, 10, 36]. According to Wang *et al* (2007) [36] reduced chi-square (χ^2) and root mean square error (RMSE) can be calculated as follows

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{exp,i} - \mathrm{MR}_{pre,i})^2}{N - Z} \qquad \ldots (4)$$

Where,
$MR_{exp,i}$ = is the i^{th} experimental moisture ratio,
$MR_{pre,i}$= is the i^{th} predicted moisture ratio,
N = is the number of observation, and
z = is the number of constant.
The non-linear regression analysis was performed by using the statistical software SAS 6.5.

2.6 Effective moisture diffusivity
The effective moisture diffusivity was calculated by using the simplified Fick's second law of diffusion model (Doymaz, 2004) [9] as given in Eq (5).

$$\frac{\partial M}{\partial t} = D_{eff} . \nabla^2 M \qquad \ldots (5)$$

Where,
M = moisture content (kg water/kg dry matter);
t = the time (s);
D_{eff}= the effective moisture diffusivity, (m^2/s);
∇^2= the differential operator.

The solution of Fick's second law in slab geometry, with the assumption that moisture migration was caused by diffusion, negligible shrinkage, constant diffusion coefficient and temperature was given by Crank (1975) [6] as follows:

$$\mathrm{MR} = \frac{8}{\pi^2}\sum_{i=1}^{n}\frac{1}{(2n-1)^2}\exp\left(\frac{-(2n-1)^2\pi^2 D_{eff}\, t}{4H^2}\right) \qquad \ldots (6)$$

Where,
H=is the half thickness of the slab m;
n = 1, 2, 3 … the number of terms taken into consideration.

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

The diffusivities are typically determined by plotting the experimental drying data in the terms of ln (MR) vs drying time (t) in equation (7), because the plot gives a straight line with the slope as follows:

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

Where,
L= half thickness

3. Results and Discussion
3.1 Convective hot air drying of carrot, onion and garlic
Fig.1. shows moisture content (db) % with respect to time (min) of carrot, onion and garlic dried by convective hot air dryer. The carrot were dried from average initial moisture content of 1207.26% (db) to 8.00% (db) onion from 708.56% (db) to 8.46% (db) and garlic from 187.74% (db) to 6.26% (db) at 55 °C. It took around 11.5 hrs, 18 hrs and 15.5 hrs time to dry the carrot, onion and garlic at 55 °C respectively as the time increases drying took place in falling rate periods. Fig. 2 shows the drying rate (g water removed/100 g of bone dry material; /min) with respect to moisture content % (db) of carrot, onion and garlic dried by convective hot air drying at 55 °C. The initial drying rate of carrot was 0.575g of water removed / 100 g of bone dry matter per minute and decreases up to the 0.101 g of water removed / 100 g of bone dry matter per minute at 55 °C. The initial drying rate of onion was 0.091 g of water removed / 100 g of bone dry matter per minute and decreases up to the 0.009g of water removed / 100 g of bone dry matter per minute at 55 °C. The initial drying rate of garlic was 0.219 g of water removed / 100 g of bone dry matter per minute and decreases up to the 0.023g of water removed / 100 g of bone dry matter per minute at 55 °C. Similar results were obtained as theinitial drying rate of carrot was in the range of 0.322 to 0.636g of water removed / 100 g of bone dry matter per minute (Chen *et al.* 2017) [5] also similar behaviour of decreasing drying rate was observed for convective drying of carrot slices (Doymaz, 2004) [9] microwave drying of onion (Sharma *et al.*, 2005) [29] microwave-convective drying of garlic (Sharma and Prasad, 2001) [28] hot air drying of garlic (Fante *et al.*, 2013) [13].

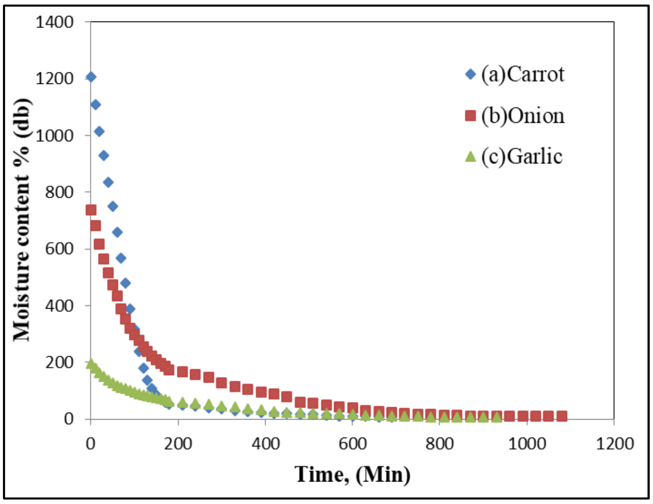

Fig 1: Moisture content % (db) verses time (Min) of (a)Carrot; (b) Onion; (c) Garlic dried by convective hot air drying at 55 °C

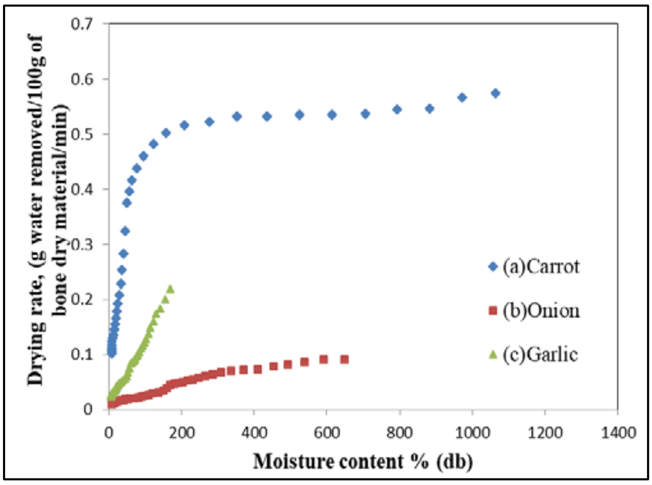

Fig 2: Drying rate (g water removed/100 g of bone dry material/min) versus moisture content % (db) of (a) Carrot; (b) Onion; (c) Garlic dried by convective air drying method at 55 °C drying temperature.

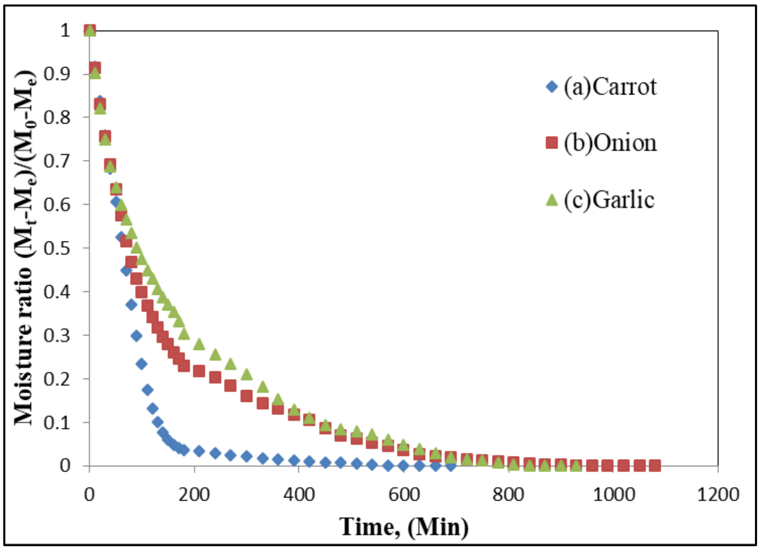

Fig 3: Decrease in moisture ratio with respect to time in min for (a) Carrot; (b) Onion; (c) Garlic dried by convective air drying method at 55 °C drying temperature.

Fig. 3 shows decrease in moisture ratio with respect to time in minute. During the drying experiment moisture ratio of carrot decreases from 1 to $6.21{\times}10^{-7}$ for onion it decreases from 1 to $7.6{\times}10^{-8}$and for garlic it decreases from 1 to $1.95{\times}10^{-7}$ at the drying temperature of 55 °C. The similar trend was observed in microwave oven dried carrot slices (Mohamad *et al.*, 2013) also in hot air drying of carrot (Prakash *et al.*, 2004) [25] hot air drying of garlic (Fante *et al.*, 2013) [13] hot air drying of onion (Mesery and Mwithiga, 2012) [14].

3.2 Evaluation of thin layer-drying model of carrot, onion and garlic dried by convective hot air drying at 55 °C drying temperature

Table 2, 3 and 4 shows the model parameters of various model fitted to the experimental data for Newton model, Page model, Henderson and Pabis, Two term, Logarithmic, Wang and Sing, Thompson and Midilli *et al.* models etc at 55 °C by convective hot air drying of carrot, onion and garlic respectively. Among the models fitted to the experimental data of carrot, onion and garlic at 55 °C the Midilli *et al.* model was well fitted to the experimental data with highest R^2 values 0.997;with lowest MSE2.672×10^{-4} and chi square (χ^2) 8.552×10^{-3} for carrot. For onion the highest R^2 values 0.995;with lowest MSE $3.680\times10^{-4}$and chi square (χ^2) $1.656\times10^{-2}$and for garlic the highest R^2 values 0.999;with lowest MSE 4.725×10^{-5} and chi square (χ^2) 1.890×10^{-3}.Non-linear regression analysis was done according to the seven thin layer models for moisture ratio data. Table 1, 2 and 3shows the statistical regression results of the different models, including the drying model coefficients and comparison criteria used to evaluate goodness of the fit including the R^2,$\chi^2$and RMSE of carrot, onion and garlic at 55 °C temperature. In all cases R^2values for the models were greater than 0.202, 0.840 and 0.902 indicating a good fit for carrot, onion and garlic respectively.

Table 2: Model parameters, R^2, RMSE and Chi square values of carrot dried by convective hot air drying at 55 °C.

Sr. No	Model name	Model Parameters	R^2	MSE	χ^2
1	Newton	k= 1.328×10^{-2}	0.977	2.436×10^{-3}	8.526×10^{-2}
2	Page	k=1.768×10^{-3} n=1.454	0.996	4.825×10^{-4}	1.640×10^{-2}
3	Henderson and Pabis	a=1.093 k=1.448×10^{-2}	0.979	1.890×10^{-3}	6.427×10^{-2}
4	Midilli *et al.*	a=0.966, k=1.033×10^{-3}, n=1.570 b=4.070×10^{-5}	0.997	2.672×10^{-4}	8.552×10^{-3}
5	Logarithmic	a=0.806, k=10.712, c=0.193	0.202	7.320×10^{-2}	2.488

Table 3: Model parameters, R^2, RMSE and Chi square values of onion dried by convective hot air drying at 55 °C.

Sr. No	Model name	Model Parameters	R^2	MSE	χ^2
1	Newton	k= 8.386×10^{-3}	0.991	9.470×10^{-4}	4.545×10^{-2}
2	Page	k=2.013×10^{-2}, n=0.826	0.994	4.103×10^{-4}	1.928×10^{-2}
3	Henderson and Pabis	a=0.958, k=8.408×10^{-3}	0.990	8.634×10^{-4}	4.058×10^{-2}
4	Wang and Sing	a=-0.003.435746, b=2.552×10^{-6}	0.840	3.567×10^{-2}	1.676
5	Midilli *et al.*	a=1.039, k=2.429×10^{-2}, n=0.796, b=4.606×10^{-6}	0.995	3.680×10^{-4}	1.656×10^{-2}

Table 4: Model parameters, R^2, RMSE and Chi square values of garlic dried by convective hot air drying at 55 °C.

Sr. No	Model name	Model Parameters	R^2	MSE	χ^2
1	Newton	k= 7.750×10^{-3}	0.992	1.266×10^{-3}	5.447×10^{-2}
2	Page	k=2.192×10^{-2}, n=0.786	0.999	7.127×10^{-5}	2.993×10^{-3}
3	Henderson and Pabis	a=0.911, k=6.832×10^{-3}	0.991	6.960×10^{-4}	2.923×10^{-2}
4	Two term	a=0.825, k_0=5.598×10^{-3}, b=0.129, k_1=3.726×10^{-3}	0.997	5.822×10^{-4}	2.328×10^{-2}
5	Wang and Sing	a=-0.003.741869, b=3.130×10^{-6}	0.902	2.318×10^{-2}	0.973
6	Thompson	a=-0.003.741869, b=3.130×10^{-6}	0.902	2.318×10^{-2}	0.973
7	Midilli *et al.*	a=1.013, k=2.562×10^{-2}, n=0.755, b=-0.00001.5309	0.999	4.725×10^{-5}	1.890×10^{-3}

3.3 Effective moisture diffusivity of carrot, onion and garlic dried by convective hot air drying:

Fig. 4 shows Ln (MR) versus time (minute) for convective hot air drying of carrot, onion and garlic dried at 55 °C. The graph shows the straight line curve. The straight line equation y= mx+c where the m is the slope of line. Effective diffusivity (D_{eff}) at time for carrot, onion and garlic which was calculated by Eq.(5). The diffusivity value were 1.724×10^{-8}m^2/s, 4.03×10^{-9} m^2/s and 3.855×10^{-9} m^2/s for carrot, onion and garlic respectively at 55 °C temperature. The effective diffusivity used to explain the mechanism of moisture movement during drying and complexity of the process (Kashaninejad *et al*., 2007; Falade and Solademi, 2010) [17, 11].

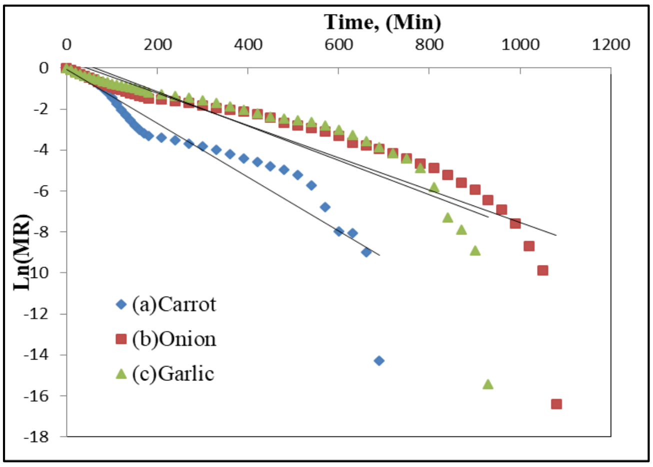

Fig 4: Ln (MR) versus time (minute) for convective hot air drying of (a)Carrot; (b) Onion; (c) Garlic dried by convective hot air drying at 55 °C

Similar results have been observed the values of D_{eff} obtained from this study lie within in general range 10^{-12}–10^{-8} m^2/s for drying of food materials (Zogas *et al.* 1996) [39]. Similar results are found to correspond well with those existing in the literature, it is also in agreement with studies of (Doymaz, 2004) [9] of carrot drying which in range of 0.776× 10^{-9}–9.335 ×10^{-9} m^2/sand 1.257×10^{-9} to 2.200×10^{-9} m^2/sfor carrot slices during convective drying (Kaya *et al.*, 2009). Mota *et al.*, 2010 [21] was observed for onion it is in the range of 3.33×10^{-9}m^2/s to 8.55×10^{-9}m^2/s also effective moisture diffusivity of garlic samples was found in the range between 2.221 ×10^{-10} and 4.214 ×10^{-10} m^2 s^{-1}.

4. Conclusion

The drying of carrot, onion and garlic occurred in falling rate period it took around11.5 hrs, 18 hrs and 15.5 hrs time respectively to dry the carrot from 1207.26%(db) to 8.00% (db), onion from 708.56% (db) to 8.46% (db) and garlic from 187.74% (db) to 6.26% (db). The experimental data of moisture ratio with respect to time of carrot, onion and garlic were fitted with the Midilli *et al.* model which betterly describes than the other models i.e. Newton, Page, Henderson and Pabis, Two term, Wang and Singh, Thompsons model for all carrot, onion and garlic. The effective moisture diffusivity for carrot was 1.724×10^{-8} m^2/s, for onion it was 4.03×10^{-9} m^2/s and for garlic it was 3.855×10^{-9} m^2/s.

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