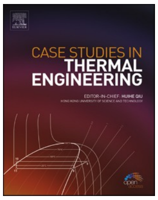
Case Studies in Thermal Engineering 15 (2019) 100542

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: http://www.elsevier.com/locate/csite



Modelling of moisture diffusivity during solar drying of locust beans with thermal storage material under forced and natural convection mode

Clement A. Komolafe [a,*], John O. Ojediran [b], Faith O. Ajao [b], Oluwasogo A. Dada [c], Yemisi T. Afolabi [c], Iyiola O. Oluwaleye [d], Adewumi S. Alake [b]

[a] *Department of Mechanical Engineering, College of Engineering, Landmark University, P.M.B. 1001, Omu Aran, Nigeria*
[b] *Department of Agricultural and Biosystems Engineering, College of Engineering, Landmark University, P.M.B. 1001, Omu Aran, Nigeria*
[c] *Industrial Chemistry Programme, Department of Physical Sciences, College of Pure and Applied Sciences, Landmark University, P.M.B. 1001, Omu Aran, Nigeria*
[d] *Department of Mechanical Engineering, Ekiti State University, P.M.B. 5363, Ado Ekiti, Nigeria*

ARTICLE INFO

Keywords:
Modelling
Moisture diffusivity
Solar drying
Locust beans
Thermal storage material
Forced and natural convection

ABSTRACT

This study investigated the modelling of moisture diffusivity of processed locust beans under forced and natural convection mode using solar drying with thermal storage materials (gravel). The experimental data obtained were fitted into eleven existing thin layer models and the best model choice was based on a comparison of statistical parameters including determination coefficient (R^2), reduced chi-square (χ^2), root mean square error (RMSE), square error sum (SSE) and normalised root mean square error (NRMSE) between the experimental and predicted data. The results showed that the Lewis model gave the best description of solar drying of locust beans under forced and natural convection mode. Thus, this model may be adjudged to represent the drying characteristics of locust beans in a thin layer within the experimental range of study. The obtained moisture diffusivity values were 2.73496 and 1.82331 $\times 10^{-11}$ m^2/s for the solar drying of locust beans under forced and natural convection mode respectively. The predicted Arrhenius constant and activation energy values were respectively 2.54 $\times 10^{-11}$ m^2/s and 21.65 kJ/mol.

1. Introduction

The locally processed seeds of African locust beans (*Parkia biglobosa*) known as dawadawa and iru in the northern and southern part of Nigeria respectively are highly nutritious food condiment in our daily meal, mostly soups, and stews. Apart from being a food condiment, the processed beans also contribute to the calorie and protein intake [1]. This processed condiment is highly perishable in nature, thus storing it for use at a later date is necessary. In many rural areas, the hygienic ways of preserving agricultural products seem to be impossible due to non-availability of electricity and/or the inability to purchase a refrigerator. Drying is a complex thermal techniques, the most important among other post-harvest steps, during which unstable heat and mass transfer happen concurrently [2]. Traditionally, most agricultural crops that are being dried in the open sun for storage purpose are usually of low quality due to resultant effects of associated shortcomings such as insect infestation, exposure of the product to rain and dust, etc [3]. One viable

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* Corresponding author.
E-mail addresses: komolafe.adekunle@lmu.edu.ng, clemkunle@yahoo.co.uk (C.A. Komolafe).

https://doi.org/10.1016/j.csite.2019.100542
Received 31 July 2019; Received in revised form 28 September 2019; Accepted 29 September 2019

Nomenclature

a,b, c,g,h,k,n,t	coefficients and constants
D	Arrhenius constant (m^2/s)
D_{eff}	effective diffusivity (m^2/s)
DR	drying rate (g H2O/g wet solid h)
E	activation energy (kJ/mol)
i	number of terms
L	half thickness of slab (mm)
m	number of model constants
M	moisture content (%)
MR	moisture ratio (dimensionless)
N	number of observations
NRMSE	normalised root mean square error
R	Universal gas constant (8.314 J/mol.K)
R^2	coefficient of determination
RMSE	root mean square error
SSE	sum of square error
T	temperature (K)
t	time
W	weight of sample (g)

Subscripts

bd	bone dried
cal	calculated
e	equilibrium
exp	expected
f	final
m	moisture
n	positive integer
o	initial

Greek letter

$\chi2$	reduced chi square

technique of preserving these products is drying using solar energy without appreciable loss of the nutrients. In respect of better quality products, several authors have recommended solar drying as a reliable option to open-sun drying and it is not as expensive as electricity or fossil-fuel powered dryers. However, the use of solar dryer integrated with thermal storage materials in order to eliminate intermittent effects, weather dependency and reabsorption of moisture have been proposed by several researchers [4]. Incorporating thermal storage material will also increase the operation periods of the solar dryer. Three different types of thermal storage materials (sensible, latent heat and thermophysical) have been identified. Thermal energy is stored in sensible heat storage (SHS) by increasing the temperature of a solid or liquid. SHS system uses the material's heat capacity and temperature shift during the loading and discharge phase. SHS is primarily used for low-grade heat such as solar energy or waste heat from power generation plants and for short- and long-term building storage industrial thermal procedures. The only drawback is their small heat capacity, which can render the storage device unrealistically large [5]. The prevalent benefit of sensible heat storage is its low cost compared with the elevated price of latent heat storage [6]. Latent heat storage (LHS) is based on heat absorption or release when a storage material changes from one physical condition to another. Change in phase occurs in solid or liquid or gas or vice versa [7,8]. During melting/solidification or gasification/liquefaction procedures, phase change materials (PCMs) can store/release a big quantity of heat when re-forming their phase structures. The primary drawback of latent heat storage, however, is its low thermal conductivity [5]. In reversible chemical reactions, thermochemical energy can be stored as reaction heat. The response in the forward direction in this storage mode is endothermic (thermal storage), whereas the inverse action is exothermic [9]. Thermochemical structures depend on the energy absorbed and released in a totally reversible chemical reaction when breaking and reforming molecular bonds. The heat stored in this situation relies on the quantity of storage material, the endothermal heat response and the magnitude of the transformation [10]. When breaking/forming certain chemical boundaries during endothermal/exothermal responses, special chemicals can absorb/release a big quantity of thermal energy. The storage technique using chemical heat was developed on the basis of such features. Suitable materials for the storage of chemical heat can be organic or inorganic, provided that their reversible chemical reactions require the absorption/release of a big quantity of heat [5]. The use of sensible storage materials such as bricks, granite, sand, etc. had been reported for solar drying of cocoa beans and other food crops [4,11,12]; latent heat (phase change materials PCM) for seeded grape [13] and thermophysical (desiccant) for peas and pineapple [14].

Several methods of processing and preserving (boiling, dehulling, separating, fermentation, salting, drying, etc.) of locust have

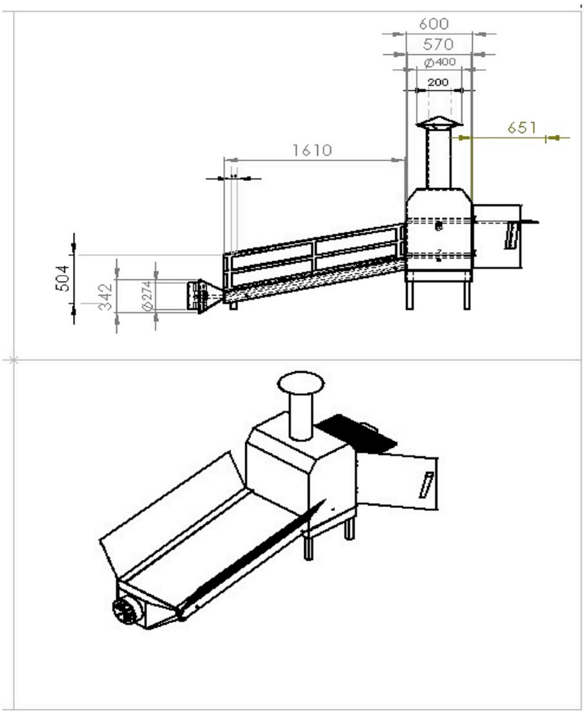

Fig. 1. Schematic diagram of the forced convection type.

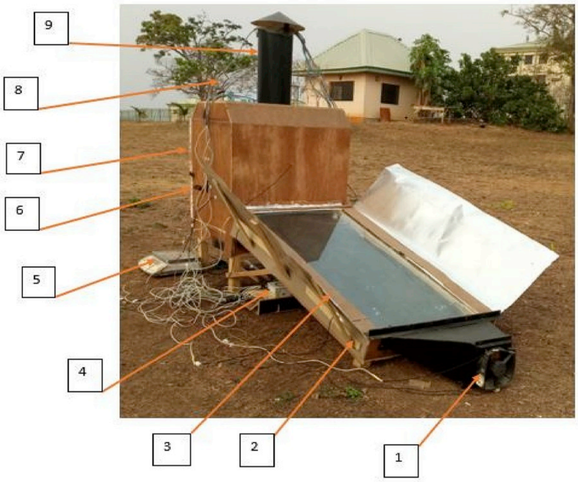

Fig. 2. Experimental set-up of the forced convection solar drying system indicating the position of the temperature and humidity sensors 1. Blower 2. Solar collector 3. Reflector 4. Data acquisition system 5. Weighing balance. 6. Thermostat 7. Drying chamber 8. Temperature and humidity sensors 9. Chimney.

been reported [1,15–19]. Limited literature is available on, drying of processed locust beans [15,17]. However, no research appears to have been done on modelling of solar drying of processed locust beans under forced and natural convection mode with thermal storage material. The selection of thermal storage material (gravel) was based mainly on the density and specific heat of the item material. The greater the product, the better the material, given it is possible to maintain the operating temperature [11]. The aim of this research was, therefore, to determine the diffusivity of moisture, activation energy and mathematical modelling of solar drying of processed locust beans under forced (active) and natural convection (passive) mode with thermal storage material.

2. Materials and methods

2.1. Experimental set-up

A 4 kg capacity solar drying system was locally made and tested under active (forced) and passive (natural) mode. The experimental set-up for both modes consists majorly of drying chamber, stainless drying tray, thermal storage material platform, thermostat, and a data logging system. The active type, incorporated with a blower is schematically shown in Fig. 1.

The components of the data acquisition system include Atmel ATmega 328P type micro-controller, real-time clock module, power bank unit and SD card mounting module. Temperature and humidity sensors DS18B20 and DHT22 were connected and strategically positioned as shown in Fig. 2 to measure –55 to +125 °C with ±0.5 °C precision and 0–100% humidity measurements with 2–5% precision. The data logging system was programmed to record data at the interval of one hourly. Solar radiation data, air velocity, ambient temperature, and relative humidity the experiment were collected from a nearby Campbell weather station within the campus.

2.2. Sample preparation and drying procedure

Sample of well-processed locust beans, free from the dirt was obtained from the local market at Omu Aran, Nigeria. Thereafter, the processed sample was taken to the Teaching and Research Farm, Landmark University, Omu Aran where the drying experiments took place. The beans were spread on a pre-weighted clean stainless steel tray (570 x 570 x 20 mm) in the drying chamber.

The solar drying process took place between 9:00 and 18:00 h. The fan was switched off during the night and air vent was also shut to avoid the influx of moist air. However, the locust beans were left to temper overnight for the redistribution of moisture from the inner part to the outer layer. The drying air temperature was monitored with a thermostat pre-set to turn off at 60 °C (The temperature above which was considered detrimental to cocoa beans quality [22]). As the drying process continues, the mass of the sample was measured on a digital weighing balance (Control S.R.L Aosta 6 Cernusco, Italy; Model No: D0630/30 Max: 30 kg, S/N 13237130091) every 2 h until a constant weight was obtained. The moisture content based on loss in weight on a wet basis was determined using Eqn. (1) (AOAC, 2000). The Association of Official Analytical Chemists (AOAC) standard was adopted to determine the equilibrium moisture content using A&D company N92 moisture analyser (MX-50, 0.01/Max 51 g S/N: 1028873) at 105 °C. Thermo-anemometers (Lutron AM4201A type) with a range of 0.40 to 45 m/s were positioned to measure the velocity of the air at inlet, outlet and within the drying chamber of the dryer. In addition, data were collected from the weather station generated by Campbell Scientific Ltd. (Data Logger Model No: 18728) situated a few meters from the solar dryer for other vital parameters such as ambient air, relative humidity and solar radiation, etc.

2.3. Drying characteristics

The procedure applied in determining the drying characteristics of processed locust had been presented by Refs. [2,3] for fish and cocoa beans respectively.

The moisture content (M_{ct}) was determined based on AOAC standard [20] as:

$$M_{ct} = \frac{W_{o-} W_{bd}}{W_o} \quad (1)$$

where M_{ct} is the moisture content (% w.b.); W_o is the initial weight of the sample (g) and W_{bd} the bone dried weight of the sample (g).

The moisture ratio (MR) of the locust beans was calculated according to Dinani et al. [21] using:

$$MR = \frac{M_{ct} - M_e}{M_o - M_e} \quad (2)$$

where M_o, M_e, and M_{ct} are the initial moisture content, equilibrium moisture content and the moisture content measured at time t, respectively. The M_e is considered negligible when compared to M_{ct} or M_o for long drying time. Therefore, Eqn. (2) is simplified as:

$$MR = \frac{M_{ct}}{M_o} \quad (3)$$

The drying rate (DR) of locust beans in relation to the law of diffusion for the unsteady state can be determined using Eqn. (4) [22,23]:

$$DR = \frac{M_{ct} - M_{t+dt}}{dt} \quad (4)$$

where M_{t+dt} is the moisture content (g water/g wet solid) at $t + dt$, and dt is time difference (hr).

2.4. Moisture diffusivity

The experimental data were fitted to determine the moisture diffusivity by using Fick's second law of diffusion:

Table 1
Considered thin layer models applied to the drying curves of processed locust beans.

Model No	Model Name	Model equation	References
1	Lewis	$MR = \exp(-kt)$	El-beltagy et al. [33]
2	Page	$MR = \exp(-kt^n)$	Senadeera et al. [34]
3	Henderson and Pabis	$MR = a \exp(-kt)$	Akpinar et al. [35]
4	Wang and Singh	$MR = 1 + at + bt^2$	Yaldiz et al. [36]
5	Logarithmic	$MR = a \exp(-kt) + c$	Sacilik et al. [37]; Kaleta et al. [38]
6	Midilli et al.	$MR = a \exp(-kt^n) + bt$	Midilli et al. [39]; Akpinar and Bicer [40]
7	Two term exponential	$MR = a \exp(-kt) + (1-a)\exp(-kat)$	Togrul and Pehlivan [41]
8	Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	Karathanos [42]
9	Verma et al.	$MR = a \exp(-kt) + (1-a)\exp(-gt)$	Verma et al. [43]
10	Peleg	$MR = 1 - t/(a+bt)$	Peleg [44] and Planinic et al. [45]
11	Hii et al.	$MR = a\exp(-kt^n) + c\exp(-gt^n)$	Hii et al. [28]

$$\frac{\partial M}{\partial t} = \nabla^2 D_{eff} M \tag{5}$$

Assume a slab geometry, the analytical solution of Eqn. (5) was given by Crank [24] as:

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

where L is the samples half-thickness (m), t is the time (s), n is a positive integer and D_{eff} is effective diffusivity.

Linearizing Eqn. (6) [25,26] yields:

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

The slope of the curve from the plot of ln (MR) versus drying time was used to determine the effective diffusivity as follows:

$$D_{eff} = slope \ \times \ \frac{4L^2}{\pi^2} \tag{8}$$

The activation energy (E) for diffusion was determined using the Arrhenius equation:

$$D_{eff} = D \ exp\left(-\frac{E}{RT}\right) \tag{9}$$

where D is the Arrhenius equation pre-exponential factor (m^2/s), E is activation energy (J/mol), R is universal gas constant (8.314 J/mol/K), T is absolute temperature (K).

The obtained Arrhenius pre-exponential factor and the activation energy was done using Microsoft Excel SOLVER tool.

2.5. *Mathematical modelling*

Table 1 presents eleven existing models drawn from the second law of Fick and the cooling law of Newton for the modelling of the drying curves of processed locust beans. Accurate simulation of the drying curves of different kinds of agricultural products have been reported: Boughali et al. [27] for tomato slices; Doymaz [22] for green apple; Dinani et al. [21] for mushroom slices; Fernando and Amarasinghe [23] for coconut coir pith; Hii [28] for cocoa beans; and Clement et al. [25] for cocoa beans. The validation and fittings of the equations to the experimental data in order to determine statistical parameters which includes coefficient of determination (R^2), reduced chi-square ($_\chi{}^2$), root mean square error (RMSE), sum of square error (SSE) and normalised root mean square error (NRMSE) were performed respectively using non-linear regression analysis curve fitting solver in Excel (2016 version) according to the relations (Eqns. (10)–(14)).

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,\ i} - MR_{cal,\ i}\right) \cdot \sum_{i=1}^{N}\left(MR_{cal,\ i} - MR_{exp,\ i}\right)}{\left[\sum_{i=1}^{N}\left(MR_{exp,\ i} - MR_{cal,\ i}\right)^2\right] \cdot \left[\sum_{i=1}^{N}\left(MR_{cal,\ i} - MR_{exp,\ i}\right)^2\right]} \tag{10}$$

$$x^2 = \frac{\sum_{i=1}^{N}\left(MR_{cal,i} - MR_{exp,i}\right)^2}{N - m} \tag{11}$$

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}\left(MR_{cal,\ i} - MR_{exp,i}\right)^2\right)^{\frac{1}{2}} \tag{12}$$

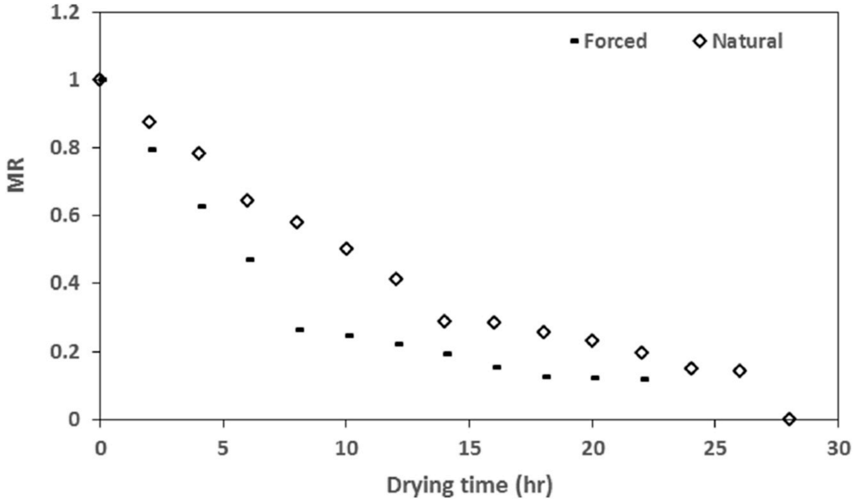

Fig. 3. The plot of moisture ratio versus drying time.

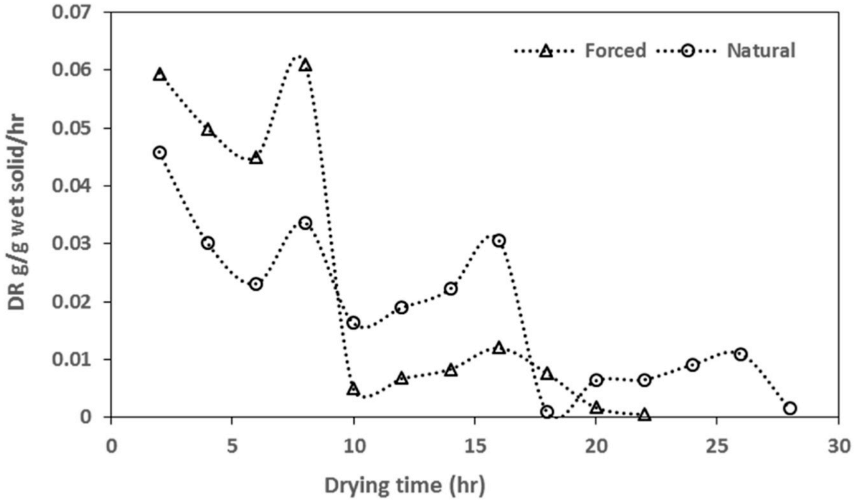

Fig. 4. Variation of drying rate with drying time.

$$\mathrm{SSE} = \sum_{i=1}^{N} \left(\mathrm{MR}_{\mathrm{cal},\,i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2 \tag{13}$$

$$\mathrm{NRMSE} = \frac{\left(\frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{cal},\,i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2\right)^{\frac{1}{2}}}{\max\left(\mathrm{MR}_{\mathrm{cal},\,i}\right) - \min\left(\mathrm{MR}_{\mathrm{cal},\,i}\right)} \tag{14}$$

Higher R^2 values and lower $_{\chi}{}^2$, RMSE, SSE and NRMSE values were selected as the fitness criteria (Dinani et al. [21]; Goyalde et al. [29]; Doymaz [26]; Balbay et al. [30]; Zarein et al. [31]; and Demir and Sacilik [32].

3. Results and discussion

3.1. Drying kinetics

Figs. 3 and 4 show the outcomes of variability in the moisture ratio and drying rate during solar drying of processed locust beans. It is evident that with an increase in drying time, the moisture ratio and the drying rate decreased. The period of constant rate, however, was absent. The drying behaviour, although non-monotonic, occurred throughout the drying processes in the order of the falling-rate period [2,3,46]. Similar drying behaviour have been reported [26,47,48] for figs, green apple and apple slices respectively. This result

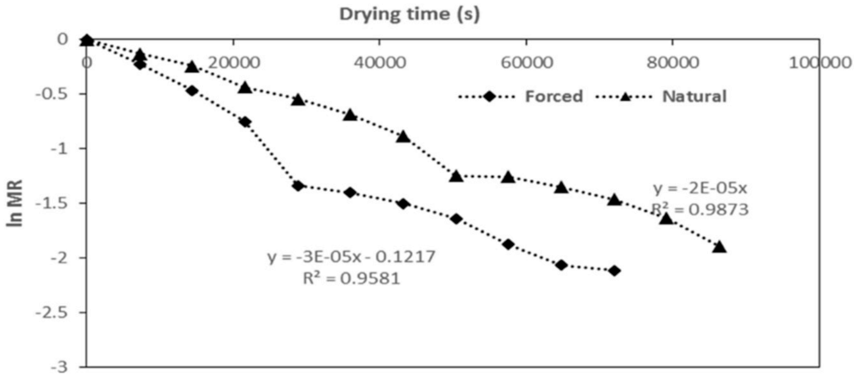

Fig. 5. Variation of the logarithm of moisture ratio with drying time.

Table 2
Calculated moisture diffusivity, D_{eff} (m^2/s).

S/N	Mode	D_{eff} (m^2/s)
1.	Forced Convection	2.73496E-11
2.	Natural Convection	1.82331E-11

Table 3
Statistical analysis from the considered thin layer models under forced convection solar drying mode.

Model No	Model Name	Coefficients and constants	R^2	χ^2	RMSE	SSE	NRMSE
1	Lewis	k = 0.1265	**0.9717912**	**0.005486354**	**0.070916554**	**0.060349892**	**0.1219213**
2	Page	k = 0.006324, n = 2.092805	0.8429111	0.014223562	0.108954056	0.142451836	0.2211164
3	Henderson and Pabis	a = 1.1538, k = 0.0967,	0.9632677	0.008926116	0.086246335	0.089261164	0.1669652
4	Wang and Singh	a = -0.06146, b = 0.000875	0.8895909	0.011533437	0.098036713	0.115334365	0.1694422
5	Logarithmic	a = 1.2185, k = 0.0967, c = - 0.056	0.9632679	0.010001494	0.086609008	0.090013443	0.142874
6	Midili et al.	a = 0.999309, k = 0.006509, b = 0.000171, n = 2.075	0.8421855	0.017831157	0.142284021	0.142284021	0.1882002
7	Two_term Exp.	a = 0.7813, k = 0.1033	0.9628455	0.009329159	0.088171988	0.093291594	0.1455081
8	Modified Henderson	a = 0.32342, k = 0.096706, b = 0.249194, g = 0.096, c = 0.2491, h = 0.096	0.9632681	0.017187665	0.092702925	0.103125989	0.1513343
9	Verma et al	a = 1.2321, k = 0.1024, g = 1.3306	0.8495101	0.011213561	0.091706981	0.100922045	0.1475102
10	Peleg	a = 8.8248, b = 0.6541	0.9579338	0.007250073	0.077728551	0.072500732	0.1312572
11	Hii et al.	a = 0.946056, k = 0.006232, c = 0.052639, n = 2.098119, g = 1.270623	0.8421584	0.020323141	0.108744737	0.141905014	0.1836326

is an indication that diffusion was the important physical phenomenon in the samples that governs the transfer of internal mass. Similar findings for separate agricultural products dried under varying circumstances have been recorded [46,49]. To reduce the moisture content from 58.4% and 58.3%–7.06% and 7.10% respectively, it took 22 and 28 h for the processed locust beans dried under forced and natural convection modes. The maximum and average solar radiation, relative humidity, drying chamber temperature, ambient temperature, and ambient air velocity for the active were 774 and 325.5 W/m; 97.8 and 34.10%; 54.6 and 33.25 °C, 32.8 and 26.0 °C; 5.75 and 1.65 m/s respectively, while that for the passive mode were 806 and 301.25 W/m; 95.4 and 32.5%; 52.9 and 30.1 °C, 31.5 and 25.5 °C; 4.25 and 2.25 m/s respectively. Fig. 5 shows the variation of the logaritm of moisture ratio with drying time. The mass flow rate within the drying chamber for the active and passive mode ranged between 0.015 and 0.044 kg/s, and 0.01 and 0.012 kg/s respectively.

3.2. Moisture diffusivity and activation energy

The calculated moisture diffusivities for the dried locust beans under active and passive convection mode were 2.73496 and 1.82331 $\times 10^{-11}$ m^2/s as shown in Table 2. It can be seen that in forced convection mode the moisture diffusivity value acquired was higher than in natural convection mode. The higher value in the forced convection mode can be ascribed to an rise in drying chamber temperature [2,3]. However, both moisture diffusivities from this study aligned within the 10^{-12} to 10^{-8} reported for drying of food materials [50] and other agricultural products [2,3,28,51,52]. The obtained Arrhenius and energy activation values were respectively 2.54 $\times 10^{-11}$ and 21.65 kJ/mol. Similar values have been reported [2,3,51].

Table 4
Statistical analysis from the considered thin layer models under natural convection solar drying mode.

Model No	Model Name	Coefficients and constants	R^2	χ^2	RMSE	SSE	NRMSE
1	Lewis	k = 0.086	0.993287	0.000279	0.01613832	0.00391	0.032624
2	Page	k = 0.019, n = 1.6609	0.9845613	0.001473214	0.035745697	0.019166	0.0722618
3	Henderson and Pabis	a = 1.0983, k = 0.0966,	0.9888067	0.000625795	0.023288531	0.008135	0.0372548
4	Wang and Singh	a = -0.0612, b = 0.00090	0.9871186	0.000702235	0.024669898	0.009129	0.0330788
5	Logarithmic	a = 1.1624, k = 0.0966, c = - 0.0581	0.9888065	0.000663299	0.023035612	0.00796	0.142874
6	Midili et al.	a = 0.9769, k = 0.0152, b = - 0.0001, n = 1.7471	0.982231	0.001721323	0.035467274	0.018869	0.0644697
7	Two_term Exp.	a = 0.8697, k = 0.0992	0.9889086	0.000633512	0.023431682	0.008236	0.0331522
8	Modified Henderson	a = 0.3032, k = 0.0966, b = 0.2285, g = 0.0966, c = 0.2285, h = 0.0966	0.9888065	0.001083902	0.025501788	0.009755	0.0340254
9	Verma et al	a = 1.1447, k = 0.1003, g = 1.1177	0.9792085	0.000800997	0.025313977	0.009612	0.03435
10	Peleg	a = 8.9949, b = 0.7427	0.9887441	0.000456714	0.019895203	0.005937	0.0355599
11	Hii et al.	a = 0.9461, k = 0.0062, c = 0.0526, n = 2.098119, g = 1.270623	0.9702797	0.00059435	0.019895203	0.005937	0.0355599

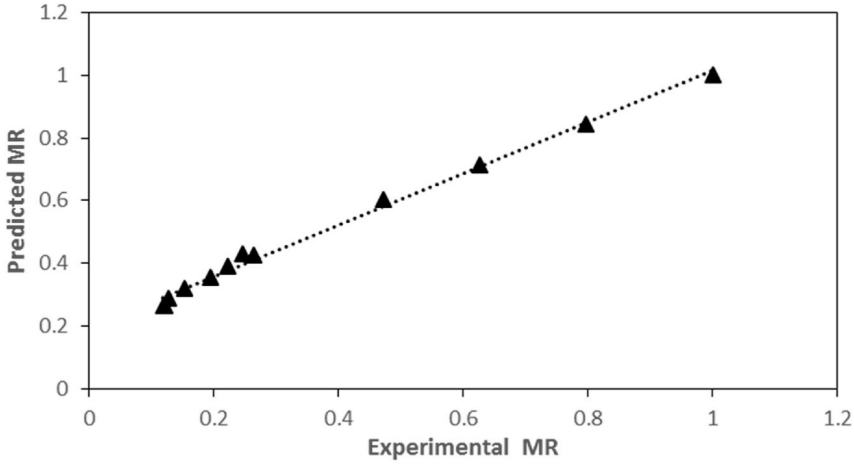

Fig. 6. Comparison of the experimental and predicted moisture ratio of locust beans dried under forced convection mode by Lewis model.

3.3. Mathematical modelling of the drying curves

Tables 3 and 4 provide the outcomes of non-linear regression assessments of selected thin-layer drying models under forced and natural solar convection drying techniques. The eleven selected drying models with their derived constants, coefficients and other statistical parameters (i.e. R^2, χ^2, RMSE, and NRMSE) for the two experimental conditions are shown in Tables 3 and 4 The value of R^2 obtained from all the tested models varied from 0.84212 to 0.97178 for drying process under the forced convective mode, while it varied from 0.97028 to 0.99329 for drying process under natural convection mode. It can be seen that all the tested models gave better fits for solar drying under natural convection than forced convection mode because the values of R^2 exceeded the acceptable 0.90 [53] limit. The nearer the value of R^2 is to 1.0, the better the outcome. This may be connected to the effects of the forced convection drying mode on the product. However, the R^2 values for the Lewis model 0.97178 and 0.99329 for both drying modes were highest. The higher values of R^2 for Lewis, therefore, shows that it represents a better relationship between the moisture ratio and drying time than other tested models. Also, the value of χ^2, RMSE, SSE and NRMSE for the drying process under forced convection mode varied from 5.486×10^{-03} to 1.7831×10^{-02}; 7.09166×10^{-02} to 1.42284×10^{-01}; 6.03499×10^{-02} to 1.42284×10^{-01}; and 1.219213×10^{-01} to 1.88200×10^{-01} respectively; while for the drying process under natural convection mode, the values varied from 2.790×10^{-04} to 1.721×10^{-03}; 1.6138×10^{-02} to 3.5746×10^{-02}; 3.91×10^{-03} to 1.917×10^{-02}; and 3.26245×10^{-02} to 1.4257×10^{-01}. The findings indicate that the Lewis model being the model with the largest value of R^2 and the lowest values of other parameters, gave the best outcomes to describe the drying characteristics of solar and sun drying processed locust beans as compared to other models. This is in agreement with the report of Koua et al. [54] for banana, mango and cassava, and Babike et al. [55] for fish. This model can therefore, be assumed to represent the solar drying behaviour of locust beans within the experimental range of study in a thin layer under forced and natural convection modes.

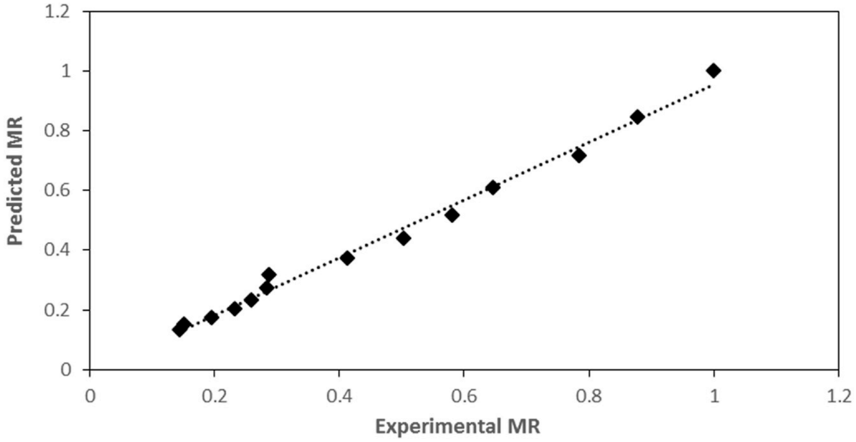

Fig. 7. Comparison of the experimental and predicted moisture ratio of locust beans dried under natural convection mode by the Lewis model.

3.4. Model validation

Figs. 6 and 7 present the comparison between the experimental moisture ratio and the expected moisture ratio in forced and natural convection modes. The figures show that the moisture ratio profiles predicted by the models compared with the experimental data for solar drying under forced convection (Fig. 6) and natural convection (Fig. 7). It can be seen in the figures that the experimental moisture ratio and the Lewis model lie closer to each other, indicating that they are in good agreement. This shows that the Lewis mathematical model could be used within the experimental scope of study to explain the thin layer of solar drying behaviour of locust beans in forced and natural convection mode.

4. Conclusion

Modelling of moisture diffusivity of solar drying of processed locust beans with heat storage material (gravel) under forced and natural convection mode was explored in this research. The drying processes happened during the falling rate period and under the experimental techniques adopted no steady rate period was noted. The experimental information fitness using eleven thin-layer models was accomplished by comparing five statistical instruments: the coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE), the sum of square error (SSE) and the normalised root mean square error (NRMSE). The Lewis model was considered the best to describe the drying characteristics of solar drying of processed locust beans under forced and natural convection mode, with the highest values of R2 and the lowest values of others (χ^2, RMSE, SSE, and NRMSE).

Declaration of competing interest

The authors wish to state the there is no conflict of interest in respect to this submission.

Acknowledgments

The authors sincerely appreciate the contribution of Mr. T. Anisere, O. Togun, M. Daudu, the Management and staff of the Teaching and Research Farm, Landmark University, Omu Aran.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2019.100542.

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