NIGERIAN AGRICULTURAL JOURNAL
ISSN: 0300-368X
Volume 49 Number 1, April 2018. Pp.46-56
Available online at: http://www.ajol.info/index.php/naj

THIN-LAYER DRYING KINETICS OF FISH IN A HYBRID SOLAR-CHARCOAL DRYER

[1]*Nwakuba, N.R., [2]Okafor, V.C., [2]Abba, E.C. and [2]Nwandikom, G.I
[1]Agricultural and Bioresources Engineering Department, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria
[2]Agricultural and Bioresources Engineering Department, Federal University of Technology, Owerri, Imo State, Nigeria
*E-mail: nrnwakuba@mouau.edu.ng; nrnwakuba@gmail.com

ABSTRACT
This paper presented an empirical thin-layer model describing the drying kinetics of titus and sardine fish samples using an indirect passive hybrid solar-charcoal smoke dryer. The experiment was designed using a Complete Randomized Design (CRD) with two treatments (Titus and Sardine fish species), three levels of thicknesses (3, 5, and 7mm fish fillets) replicated three times. The effect of fillet thickness on the moisture ratio of the two fish species showed that the smoking process of fish samples took place in the falling rate period. The experimental drying data of the fish fillets at varying thicknesses was fitted into seven different commonly used thin-layer models by curve fitting methods and all were compared according to three statistical parameters: R2, χ2, and RMSE. The Page model was found most suitable for describing the drying process of titus fish sample with R2, χ2, and RMSE values of 0.9985, 0.00121, and 0.012 respectively; whereas the Lewis model best suited the sardine samples with R2, χ2, and RMSE values as 0.9995, 0.00125, and 0.015 respectively. The models were validated using the experimental and predicted values of moisture ratios (MR). The times required to reduce 50% initial moisture content (wet basis) of titus fish species (75.24%wb) were 90,120, and 160 minutes at fillet thicknesses of 3, 5, and 7mm respectively; whilst that of sardine (79.61%wb) was 60, 75, and 110 minutes of fillet thicknesses of 3, 5, and 7mm respectively. The maximum and minimum times required to smoke dry titus and sardine fish samples at varying fillet thicknesses were 4½ to 7 hours and 4 to 6½ hours respectively.

Keywords: Hybrid dryer, fish, mathematical model, charcoal and solar heat

Introduction

Fish is a very important source of animal protein. It is of high nutritive value in the diet of Nigerians (Akande, 1997). It also contains many vitamins and minerals which are also available in meal due to the cheapness of the product, these essential nutrients are available to many people (Babiker *et al.*, 2016). Since fish flesh deteriorates rapidly as soon as it dies (Fellow and Hamptum, 1992), it must be processed as soon as it is harvested. Spoilage is caused by bacterial action and deterioration is quickened by the high temperatures. Preservation is a very essential unit operation for fish farmers and processors due to the easily perishable characters. Drying refers to any process involving removal of water from a material (fish product) mainly by evaporation. Salting, smoking, application of pressure and use of absorbent pads are other methods of dehydration (Eye, 2001). Fish preservation by drying is aimed at extending it's shelve life or safe storage period by reducing microbiological activity (Shitanda and Wanjala, 2006). Preservation by drying is affected by lowering the water pressure of fish sample to a level where microbial activities are reduced considerably. Despite the health and environmental concerns arising from the use of smoke for preservation of fish and other food materials (Guan *et al.*, 2013), the use of smoke (in traditional fish processing) from smoldering hard wood or hardwood charcoal in most developing countries has been found quite effective in preservation of fish products. This is because of its bacteriostatic, bactericidal and antioxidant functions of smoke and the dehydration effect of the process. However, studies have shown that charcoal from hard wood is more preferred by local fish processors not only because it is cleaner, easier, and less smoky than other biomass fuels, but due to the fact that hardwood contains higher hemi-cellulose content which produces lower pH, hence provides hardwood derivative (charcoal) with greater preservative power and a more stable product. This fact brought about the traditional preference for hardwood for smoking which can also be used in smaller quantities with cheap burning devices for domestic and on-farm applications (Akande, 1997; Eye, 2001).

The use of solar energy for drying of fish products is perhaps one of the important applications the sun's energy is put to effective use. Solar drying in the tropics, however, provides higher air temperature, lower relative humidity and enhanced drying rates. Under this condition, lower moisture content could be achieved in the dried fish product compared to direct sun-drying, thereby, resulting in higher quality of fish products and reduced risk of spoilage. In Nigeria, drying of fish using a solar device has not been a widespread technique despite the fact that the country lies within the high sunshine belt of the world receiving between 3.5 – 7kWm^{-2}day^{-1} from coastal latitude to the far north (Okonkwo and Mageswaran, 2001). Coupled with the fact that electricity and other forms of conventional energy are not readily available to the intended users – the rural dwellers. Since smoked fish is economically and nutritionally preferred compared to sun-dried and refrigerated ones, urban dwellers find it somewhat difficult to get fuel wood. This scenario has resulted into acute shortage and supplies occasioned by disruption due to poor road network, inadequate transportation facilities, hoarding of firewood and charcoal by wood processors as well as high product prices during rainy season (in some localities) thereby creating unending hardship for fish farmers. These underscore the need for alternative drying/smoking fuel to supplement if not eliminate the conventional drying fuel system. Such alternative should be cheap, clean, readily available and in abundance supply, and also environmental friendly. This therefore, makes solar energy a very attractive option for domestic drying fuel in Nigeria.

In order to properly analyze the drying behaviour of any product, it is essential to study its drying kinetics in thin layers (Steinfeld and Segal, 1986; Doymaz, 2004; Darvish, 2012; Darvish *et al.*, 2013). Thin layer drying is a common method and widely used for agricultural and food materials to prolong their shelf life (Hossain *et al*., 2009). It refers to a layer of material exposed fully to an air stream during drying. There is a wide range of thin layer drying models which have found good applications because of their ease of use. Thin layer drying equations are often empirical to describe drying phenomena in a unified manner regardless of the control mechanism (Sahari and Driscoll, 2013). Several mathematical models such as the Midilli *et al.* (2002), Page model, Newton model, Fick's-diffusion model, Logarithmic model, Henderson and Pabis model *etc*. have been used to describe the thin layer drying process of agricultural and food materials. These models which describe the characteristics of a particular product being dried are used to estimate the drying time of several products and also to generalize drying curves needed for dryer design and process optimization. The drying characteristics of fresh titus and sardine fillets have not been adequately studied especially in a hybrid solar-charcoal dryer which can satisfy the need of both traditional and large scale fish processors as well as food processing industry. The objective therefore is to investigate the drying kinetics of the fresh titus and sardine fillets in an indirect (passive) hybrid solar-charcoal dryer, develop its thin-layer mathematical model, and determine their moisture diffusivity (D_e) and activation energy (E_a).

Materials and Methods

Figure 1 shows the isometric view of the indirect natural convective hybrid fish smoke kiln used for the experiment. It mainly consists of a rectangular solar collector, A (air heater) and air duct connecting the solar heater and the drying chamber. The solar collector consists of an absorber plate made of mild steel that was painted dull black to absorb maximum incident radiation. It was designed and constructed to generate the necessary enthalpy increase of the warm air that flowed through it to provide adequate drying temperature (Nwakuba, 2011). A plain glass (4mm thick) with the same cross-sectional area with the collector was used to place over it. Plain glass was selected in preference to other glazing materials used in solar dryers due to certain desirable economic and engineering properties of plain glass, and also because the other materials deteriorate on exposure to the sun, rain and hail. The collector has inlet openings, H covered with wire mesh to prevent any foreign material from entering the drying chamber, and outlets circular opening for connection to the drying chamber plenum.

ALPHABET	DESCRIPTION
A	SOLAR COLLECTOR
B	DRYING CHAMBER
C	LOADING/ UNLOADING DOOR
D	BURNER CHAMBER DOOR
E	DRYER HOOD
F	CHIMNEY
G	CHIMNEY ADJUSTER
H	AIR INLET HOLE
I	AIR OUTLET
J	METAL FRAME
K	CHARCOAL DISCHARGE
L	DOOR HINGES
M	THERMOMETER
N	DRYER DOOR STAPLE
O	BURNER DOOR HANDLE

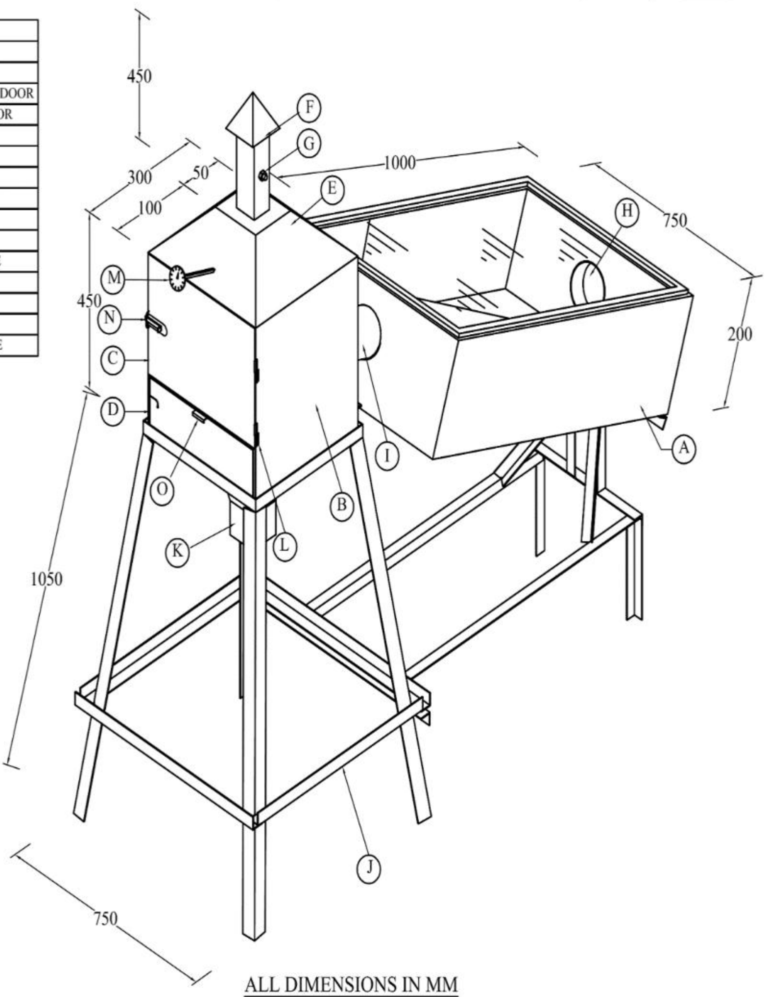

Fig. 1: Isometric view of the hybrid solar-charcoal fish dryer

The collector was oriented to the south and tilted to form an angle of 15.45° with the free edge mounted on a pair of ball bearings, which is the latitude angle of the experimental site. The drying chamber, B consisted of a square box constructed with a mild steel metal sheet painted black and lagged with fibre glass. The inside top of the drying chamber has a hood, E (trapezoidal configuration) to guide the exiting air from the fish samples through the chimney. A thermometer, M was mounted on the hood of the drying chamber to measure the chamber temperature. The drying chamber had a chimney, F painted dull black to create an updraft of air and to enhance drying rate. Directly beneath the drying chamber is the biomass/charcoal burner chamber, K. This unit consisted of a discharge made of wire mesh through which ashes from burnt charcoal crumbs drop out, and also allows air to blow the glowing charcoal through it. This chamber has a separate load/unloading door, D aligned with the top of the burner unit for easy recharging of the burner.

Experimentation

The experiments were conducted between 28th of October and 8th of November at Federal University of Technology, Owerri, Nigeria. Each experiment started at 8:30 and ended at 17:00. Temperature and relative humidities of ambient air, heated air and exhaust air were measured and recorded. Titus and Sardine fish samples of the same size bought from a local market (Ihiagwa market) were used. A representative sample of each specie was selected at random was used to determine the initial moisture content by the oven method at 105°C (AOAC, 2005). Eight fish samples of total weight 5.2kg (4 fishes per specie) were cleaned, eviscerated, washed and filleted longitudinally to expose the backbone in preparation for thin layer drying. Three different thicknesses (3mm, 5mm, and 7mm) were selected. The work was conducted as a factorial experiment in a Complete Randomized Design (CRD) with two treatments (Titus and Sardine fish species), three levels (3, 5, and 7mm), and three replications. Their initial weight was measured and recorded with the use of an electronic weighing balance (± 0.01g accuracy). The dryer was positioned in the North-South direction and the biomass burner loaded with glowing charcoal crumbs a steady-state condition is reached in the drying chamber then the fish samples were introduced. An optimal smoking temperature of 60°C was maintained in the chamber. For each batch of the smoke-dried sample, the weight and moisture content of the samples were measured at every 30 minutes intervals until no change in weight was observed. The experiment lasted between 4 to 6½ hours for a batch of the Sardine specie, and 4½ to 7 hours for the Titus specie per batch at different fillet thicknesses under the same heat condition. A digital weighing balance (Camry Rz281 model, Shanghai balance instrument plant, China) with measurement precision of ±0.01g was used for measuring the fish weight. Temperature inside the drying chamber and solar collector was carried out with an industrial stem thermometer (Ashcroft model TK92317 by Doyle instruments, USA) and pocket thermometer (Checktemp model HI98501 by Hanna instruments, USA). The relative humidity of the drying chamber, solar collector, and ambient was measured with the use of a hygrometer.

Mathematical Modelling of the Drying Curves

The experimental data were fitted into 7 commonly used thin-layer drying models. (Table 2.1). Moisture ratio was simplified to Equation (1) expressed as:

$$MR = {}^{M}\!/_{M_O} \qquad (1)$$

Instead of Equation (2), given by:

$$MR = {}^{M - M_e}\!/_{(M_O - M_e)} \qquad (2)$$

Where: M = Moisture content after a period of time, t (% db.); M_e = equilibrium moisture content (%); M_O = moisture content at the beginning of the drying period, at time zero (% db.).

This is because relative humidity of the drying air fluctuated continuously in the drying chamber (Babiker *et al.*, 2016), and the values of M_e are relatively little when compared to those of M or M_O, the error involved in the simplification is always negligible (Aghbashlo *et al.*, 2009). Non-linear regression analyses were performed using Minitab software (version 17). The model parameters were determined by statistical methods using experimental time variation data of the fish samples moisture removal. Matlab and Minitab (version 17) softwares were used in analyzing the numerical values of the sample drying kinetics.

Table 1: Thin layer drying models for variation of moisture ratio (MR) with time (t)

Model No.	Model name	Model equation	References
1	Lewis	$MR = e^{(-kt)}$	Zarein *et al.*, 2013; Darvishi, 2012
2	Page	$MR = e^{(-kt^n)}$	Zarein *et al.*, 2013; Darvishi, 2012
3	Modified Page	$MR = e^{(-kt)^n}$	Karathanos, 1999; Sahari and Driscoll, 2013
4	Henderson and Pabis	$MR = ae^{(-kt)}$	Zarein *et al.*, 2013, Darvishi, 2012.
5	Simplified Fick's diffusion	$MR = e^{(-kt)} + c$	Taheri-Garavand *et al.*, 2011
6	Logarithmic	$MR = a\exp(-kt) + c$	Zarein *et al.*, 2013
7	Wang and Singh	$MR = 1 + at + bt^2$	Taheri-Garavand *et al.*, 2011; Darvishi, 2012;

The validity or suitability (goodness of fit) of the drying models was tested by comparison with experimental data, while the modeling efficiency (E) was estimated by the following parameters: Root mean Square Error (RMSE), Sum of Square Error (SSE) or reduced Chi-square (χ^2), and coefficient of determination (R^2) (Karathanos, 1999; Taheri-Garavand *et al.*, 2011; Darvishi, 2012; Zarein *et al.*, 2013; Sahari and Driscoll, 2013). The best model describing the drying process (kinetics) of each fish sample specie was chosen based on the higher value of R^2 and lower values of χ^2 and RMSE (Demir *et al.*, 2004; Taheri-Garavand *et al.*, 2011). The expressions for each of these statistical parameters are given by Equations (3) to (5):

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}\left(MR_{pre} - MR_{exp.i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR}_{pre} - MR_{expi}\right)^2}\right] \quad (3)$$

$$\chi^2 = \sum_{i=1}^{n} \frac{\left(MR_{exp.i} - MR_{pre,i}\right)^2}{N-m} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre.} - MR_{exp,i}\right)^2}{N}} \quad (5)$$

Where: $MR_{exp.\ i}$ = the ith experimental moisture ratio; $MR_{pred.i}$ = the ith predicted moisture ratio; N = number of observation; m = number of constants in the drying model; bar-MR_{pre} = mean of predicted moisture ratio.

Results and Discussion

The thermal profile of the hybrid solar-charcoal fish dryer was obtained under no-load condition by measuring the following ambient dry bulb temperature (ADT), ambient relative humidity (ARH), dry bulb temperature (DDT), and dryer relative humidity (DRH) between 8:30 and 17:00. ADT varied between 19.82 to 33.91°C, whereas ARH recorded were in the rage of 51.4 to 92.6%. DDT varied between 64.8 to 66.2°C with DRH between 15.7 to 64.5% as presented in Figure 2. The drying chamber temperature is always higher than that of the ambient as a result of increased thermal gradient between the air from the heat source and the drying chamber (Motevali *et al.*, 2012) and also the ability of the dryer system to convert the incident solar flux and store them as heat through it absorbent material (Komolafe and Osunde, 2005; Okparaku, 2003; Ikrang *et al.*, 2014). The ambient air temperature increases with hourly time from 8:30 until about 1 to 14:30 then decreased towards the evening. Its relative humidity was conspicuously decreasing with hourly time. This is probably as a result of increased air temperature and vapour pressure deficit which causes more moisture to be evaporated. As time progressed, ADT gradually increased due to increased solar flux until around 14:30 and 15:00 when it got to its peak and began to decrease. This rise in air temperature increases the vapour pressure of the air entering the drying system, reducing its relative humidity and thereby increasing its moisture-carrying capacity. DRH showed significant decrease with time as a result of increased kinetic energy of the air moisture which necessitated rapid evaporation, thus decrease in the relative humidity of air in the drying chamber.

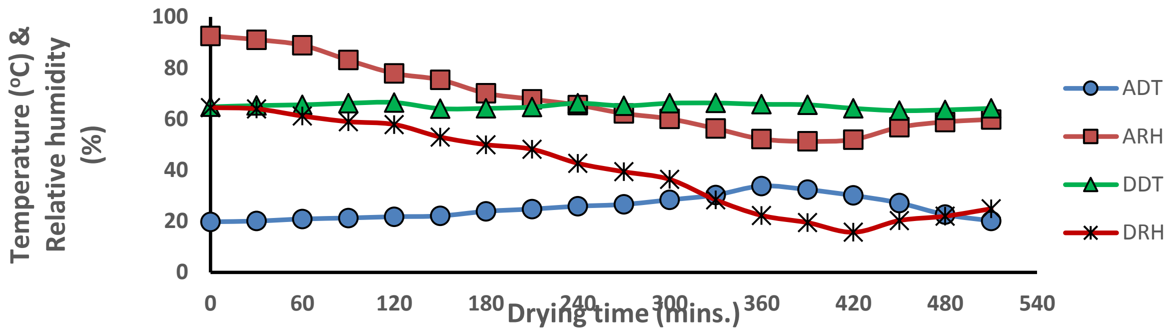

Figure 2: Plots at no load of ambient air and drying chamber conditions against dying time

Drying Kinetics of Fish Samples

The average initial moisture contents of the titus and sardine samples after brining were 75.24% (wb) and 79.61% (wb) respectively. Then, they were smoke-dried to a moisture contents of 13.37% (wb) and 11.24% (wb) respectively using the hybrid solar-charcoal fish dryer. Variation in moisture ratios obtained from moisture content values at 30-minutes time interval at different thickness of fish species' fillets (3, 5, and 7mm) are illustrated in Figures 3 and 4. The times taken to reduce 50% moisture content of titus fish species were 90, 120, and 160 minutes at fillet thicknesses of 3, 5, and 7mm respectively; whilst that of sardine is 60, 75, and 110 minutes at fillet thicknesses of 3, 5, and 7mm respectively. Sardine fish irrespective of its higher initial moisture content (79.61% w.b) had shorter drying time (higher drying rate) at any given fillet thickness than titus species. This could probably be as a result of its biological characteristics such as surface permeability index, intra-cellular structure, and size of capillary pores.

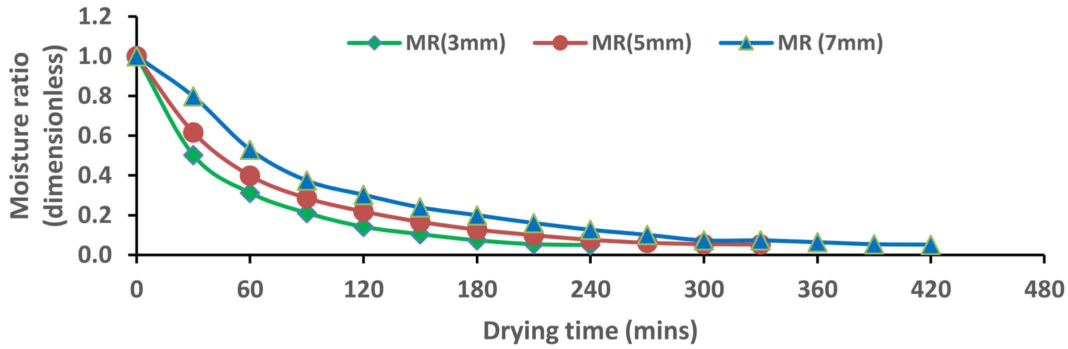

Figure 3: Effect of fillet thickness of Titus specie on moisture ratio

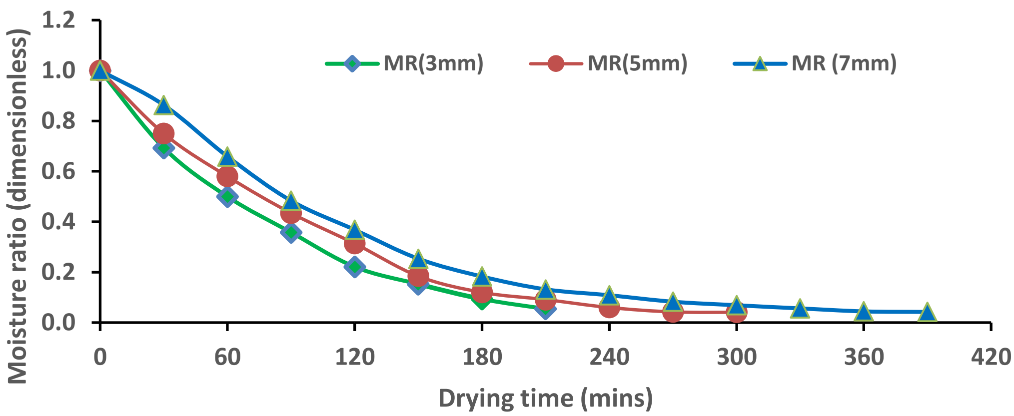

Figure 4: Effect of fillet thickness of Sardine specie on moisture ratio

From visual inspection and results obtained, titus species appear to have an impermeable type of surface tissue which poses great resistance to diffusion of internal water that results in longer drying time. At constant smoking temperature, increase in fillet thickness increases the drying time due to longer capillary distance which the internal moisture of the fish species must travel during mass transfer before surface evaporation, hence increase in the smoking time. This trend was observed in the works of Doymaz, 2004; Abano *et al.*, 2011; Motevali *et al.*, 2012; Guan *et al.*,2013; in the drying of sliced carrot, tomato, okra slices, fish fillets respectively. It is apparent that internal moisture diffusion is a critical control factor in fish smoking, reduction in fillet thickness could shorten the diffusion/capillary distance of internal moisture and thus decrease the resistance to internal mass diffusion. Generally, the drying kinetics illustrate the absence of constant falling rate period. This indicates that diffusion is the most likely physical mechanism governing moisture movement in fish samples. This observation is in agreement with Guan *et al.*, 2013; Ikrang *et al.*, 2014, Babiker *et al.*, 2016; Nwakuba *et al.*, 2016.

Mathematical Modeling

The plots of moisture ratio with drying time at constant temperature and varying fillet thickness was used to represent the experimental drying data of the studied fish species. This is because since the initial value for moisture ratio is unity for each of the experiments (Figures 3 and 4), the moisture ratio curve will explain the drying kinetics better than that of the moisture content curve (Abano *et al.*, 2011a and b; Taheri-Garavand *et al.*, 2011; Afolabi *et al.*, 2014). Tables 1 and 2 present the result of the regression analyses on the experimental data, which show that Page model and Lewis model are the most suitable thin-layer dying models for describing the drying kinetics of titus and sardine species respectively in a hybrid solar-charcoal fish dryer; given their relatively high mean values of correlation coefficient, R^2 = 0.9985, 0.9995; low chi-square, ξ^2 = 0.00121, 0.00125, and RMSE values of 0.012, 0.015 for titus and sardine samples respectively. However, the results of fitting the experimental data into the best suited models using the Minitab (version 17) curve fitting tool yielded the drying constant, k and the product constant, n (Tables 3 and 4) as well as other coefficients of titus and sardine fish species smoke-dried at a constant temperature of 65°C and varying fillet thicknesses. The established drying models (Page and Lewis) were validated by comparing the experimental and predicted values of the moisture ratio data obtained every thirty (30) minutes of each of the drying run which gave a linear relationship with high coefficient of correlation values (R^2) of 0.9984, and 0.9963 as shown in Figures 5 and 6 for titus and sardine species respectively. The closeness of the plotted data to the straight lines and the high values of the correlation coefficient (R^2) indicate that the values of the experimental MR data are closely correlated with the thin-layer model parameters of Page and Lewis, which in turn illustrates the suitability of the models in describing the drying kinetics of the studied fish species.

Equations (6) and (7) describe the mean drying kinetics of the studied titus and sardine fish species using the Page and Lewis models respectively as:

$$MR_{Titus} = e^{-0.55t^{1.07}} \quad (6)$$

$$MR_{Sardine} = e^{-0.074t} \quad (7)$$

The validation of these drying models (Figures 5 and 6) for titus and sardine yielded linear functions given by Equations (8) and (9) as:

Table 3: Summary of statistical results for titus fish samples obtained from different thin-layer drying models

S/N	Model name	Fillet thickness (mm)	Constant						R2	ξ2	RMSE
			k	a	b	c	l	n			
1.	Lewis	3	0.093						0.9963	1.51x10-3	0.021
		5	0.077						0.9978	1.72x10-3	0.032
		7	0.053						0.9954	2.1 x10-3	0.019
2.	Page	3	0.74					0.88	0.9986	1.22x10-3	0.015
		5	0.51					0.79	0.9991	1.1x10-3	0.010
		7	0.40					1.53	0.9978	1.32x10-3	0.012
3.	Modified Page	3				0.52	1.97	0.56	0.9568	2.39x10-3	0.049
		5				0.34	2.06	1.38	0.9533	2.11x10-3	0.043
		7				1.21	2.11	0.42	0.9571	1.99x10-3	0.051
4.	Henderson and Pabis	3	0.64	0.73					0.9769	1.41x10-3	0.038
		5	0.53	0.51					0.9788	1.98x10-3	0.032
		7	0.34	0.44					0.9763	2.53x10-3	0.051
5.	Simplified Fick's diffusion	3		0.96		2.59	1.95		0.9411	2.13x10-3	0.044
		5		0.88		1.94	3.39		0.9482	2.81x10-3	0.039
		7		0.74		2.63	8.02		0.9459	3.1 x10-3	0.047
6.	Logarithmic	3	0.56	0.89		0.056			0.9948	1.27x10-3	0.031
		5	0.41	0.73		0.033			0.9951	1.91x10-3	0.037
		7	0.27	0.56		0.021			0.9939	2.1 x10-3	0.033
7.	Wang and Singh	3		-0.062	0.007				0.9442	2.71x10-3	0.045
		5		-0.047	0.003				0.9438	2.19x10-3	0.039
		7		-0.043	0.001				0.9411	2.61x10-3	0.038

Table 4: Summary of statistical results for sardine fish samples obtained from different thin-layer drying models

S/N	Model name	Fillet thickness (mm)	Constant						R^2	ξ^2	RMSE
			k	a	b	c	l	n			
1.	Lewis	3	0.032						0.9993	$1.13x10^{-3}$	0.014
		5	0.024						0.9995	$1.22x10^{-3}$	0.018
		7	0.016						0.9997	$1.41x10^{-3}$	0.012
2.	Page	3	0.87					0.59	0.9986	$1.72x10^{-3}$	0.022
		5	0.63					0.98	0.9991	$1.95x10^{-3}$	0.026
		7	0.45					1.21	0.9988	$2.01x10^{-3}$	0.019
3.	Modified Page	3				0.22	1.52	0.95	0.9512	$6.22x10^{-3}$	0.081
		5				0.19	1.71	1.02	0.9538	$6.41x10^{-3}$	0.073
		7				1.27	1.09	0.67	0.9619	$5.98x10^{-3}$	0.076
4.	Henderson and Pabis	3	0.32	0.88					0.9737	$5.51x10^{-3}$	0.057
		5	0.21	0.85					0.9741	$5.14x10^{-3}$	0.049
		7	0.14	0.79					0.9774	$4.88x10^{-3}$	0.055
5.	Simplified Fick's diffusion	3		0.74		2.15	1.49		0.9672	$4.97x10^{-3}$	0.071
		5		0.83		1.67	4.31		0.9682	$4.78x10^{-3}$	0.065
		7		0.89		2.13	6.14		0.9649	$4.81x10^{-3}$	0.083
6.	Logarithmic	3	0.79	0.52		0.034			0.9956	$3.24x10^{-3}$	0.059
		5	0.65	0.48		0.029			0.9949	$2.99x10^{-3}$	0.051
		7	0.53	0.29		0.041			0.9961	$2.67x10^{-3}$	0.047
7.	Wang and Singh	3		-0.023	0.007				0.9712	$6.14x10^{-3}$	0.093
		5		-0.017	0.003				0.9732	$6.11x10^{-3}$	0.081
		7		-0.01	0.001				0.9698	$5.72x10^{-3}$	0.086

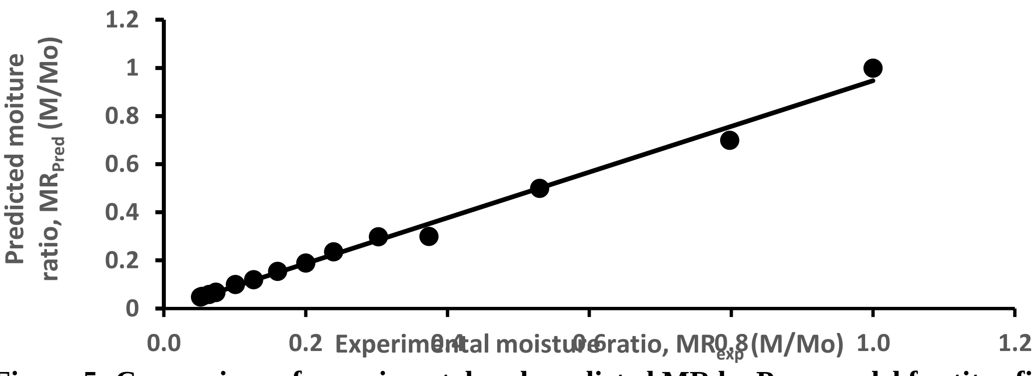

Figure 5: Comparison of experimental and predicted MR by Page model for titus fish species

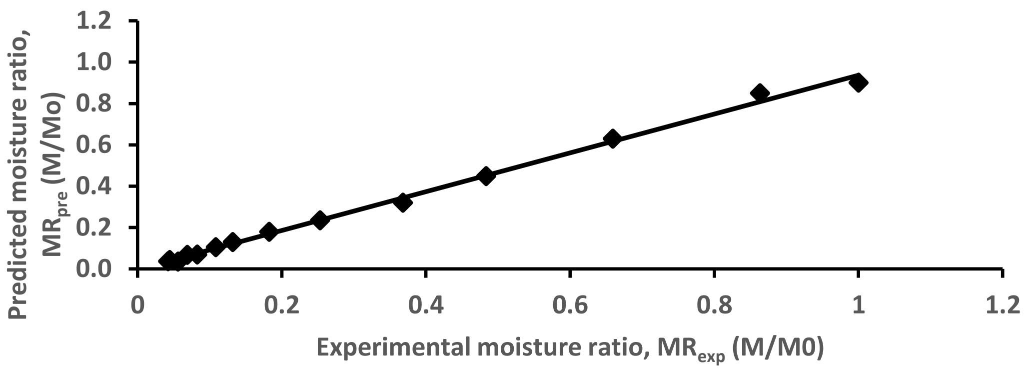

Figure 6: Comparison of experimental and predicted MR by Lewis model for sardine fish species

$MR_{pre} = 0.9496MR_{exp} - 0.0029$ [$R^2 = 0.9984$] (6)

$MR_{pre} = 0.8363MR_{exp} - 0.0042$ [$R^2 = 0.9963$] (7)

The coefficient of determination, R^2 which is close unity indicates close fit of the model to describe the drying kinetics of the titus and sardine species in a solar-assisted biomass convective dryer.

Conclusion

Curve fitting method was used in determining and selecting the most suitable thin-layer drying model that described the smoking process of titus and sardine fish samples in a direct passive hybrid solar-charcoal dryer. Constant drying rate was not observed, drying took place in falling rate period. The times required to reduce 50% initial moisture content of titus fish species (75.24%wb) were 90,120, and 160 minutes at fillet thicknesses of 3, 5, and 7mm respectively; whilst that of sardine (79.61%wb) was 60, 75, and 110 minutes at fillet thicknesses of 3, 5, and 7mm respectively. The maximum and minimum times required to smoke dry titus and sardine fish samples at varying fillet thicknesses were 4½ to 7 hours and 4 to 6½ hours respectively. Sardine sample was observed to have shorter drying time at any given fillet thickness than titus species due its biological characteristics.

References

Abano, E.E., Ma, H. and Qu, W. (2011). Influence of air temperature on the drying kinetics and quality of tomato slices. *Journal of Processing and Technology, 2(*5*), 1 – 9.*

Afolabi, T.J. and Agarry, S.E. (2014). Thin layer drying kinetics and modelling of okra (*Abelmoschus Esculentus L.*) slices under natural and forced convective air drying. *Food Science and Quality Management,* 28:30-44.

Aghbashlo, M., Kianmehr, M.H., Khani, S., Ghasemi, M. (2009). Mathematical modelling of thin-layer drying of carrot, *International Agro physics* 23: 313-317.

Akande, J.O. (1997). Fermented Fish in Africa: A Study in Processing, Marketing and Consumption. FAO Fisheries Technical Paper No. 329, pp.80.

Association of Official Agricultural Chemists, AOAC (2005) International Maryland, USA.

Babiker, A.M., Osman, O.E., Bukhari, M.M., Abdulla, E.A., Ibrahim, J.N. and Aboshora, W. (2016).Mathematical modelling of thin layer solar drying of fish (Bagrusbayad). *International Journal of Multidisciplinary and Current Research,* 4(2016):260-264.

Crapo, C. (2007). Smoking Fish at Home. Seafood Quality specialist, University of Alaska Fairbanks Marine Advisory Program, Pp. 12-18.

Darvish, H. (2012). Energy consumption and mathematical modeling of microwave drying of potato slices. *Agricultural Engineering International, CIGR Journal, 14(1), 94- 102.*

Darvishi, H., Asi, R.A., Asghari, A., Najafi, G., and Gazori, H.A. (2013). Mathematical modeling, moisture diffusion, energy consumption and efficiency of thin-layer drying of potato slices. *Journal of Food Process Technology 4 (*3*), 215 - 229.*

Doymaz, I. (2004). Convective air drying characteristics for thin-layer carrots. *Journal of Food Engineering*, 61(3), 359-364.

Demir, V., Gunhan, T., Yagcioglu, A.K. and Degirmencioglu, A. (2004). Mathematical modelling and determination of some quality parameters of air-dried bay leaves. *Biosystems Engineering*, 88:325-335.

Eye, A.A. (2001). Fish Processing Technology in the Tropics. The University of Ilorin Press, Nigeria. Pp.54 – 60.

Fellows, P. and Hamptum, A. (1992). Small-scale food processing. A guide to appropriate equipment. Pp.23-25.

Guan, Z., Wang, X., Li, M. and Jiang, X. (2013). Mathematical modelling on hot air drying of thin layer fresh tilapia fillets. *Poland Journal of Food Nutrition Science*, 63(1):25-34.

Hossain, M.A, Gottschalk, K. and Amer, B.M. (2009). Mathematically modeling for drying of tomato in hybrid dryer. *Arabian Journal for Science and Engineering*, 12:2-6.

Ikrang, EG., Okoko, J.U., Obot, M.C. and Akubuo, C.O. (2014). Modeling of thin layer drying kinetics of salted fish fillets (*Tilapia ZilliI) in a direct passive solar dryer*. IOSR Journal of Environmental Science, Toxicology and Food Technology, 8(1):16-24.

Karathanos, V.T. (1999) Determination of water content of dried fruits by drying kinetics. *Journal of Food Engineering*, 39: 337–344.

Komolafe, G.O. and Osunde, Z.D. (2001). Design and performance evaluation of small size natural convection solar vegetable dryer. Proceedings of the Nigerian Institution of Agricultural Engineers, 23: 215 – 219.

Midilli, A., Kucuk, H. and Yapar, Z. (2002). A new model for single-layer drying. *Drying Technology, 20: 150-160.*

Motevali, A., Abbaszadeh, A., Minaei, S., khostaghaza, M.H. and Ghobadian, B. (2012). Effective moisture diffusivity, activation energy and energy consumption in thin-layer drying of jujube (*Zizyphus jujube Mill)*. *Journal of Agricultural Science and Technology*, 14:523-532.

Nwakuba, N.R., Asoegwu, S.N. and Nwaigwe, K.N. (2016). Energy requirements for drying of sliced agricultural products: a review. *Agricultural Engineering International: CIGR Journal*, 18(2):144-155.

Shitanda, D. and Wanjala, N.V. (2006). Effect of different drying methods on the quality of jute (*Corchorus olitorius L.*). *Drying Technology,* 24:95-98.

Okonkwo, A.K. and Mageswaran, P.I. (2001). Design and development of a forced convention solar dryer. . *Proceedings of the Nigerian Institution of Agricultural* Engineers*, 23:275 – 280.*

Omojiba, G.O. (2005). Performance Evaluation of a Solar Dryer using Okra and Tomatoes. Unpublished Master Thesis, Department of Agric. Engineering, Federal University of Technology, Minna, Nigeria.

Oparaku, N.F., Unachukwu, G.O. and Okeke, C.E. (2003). Design, construction and performance evaluation of solar cabinet dryer with auxiliary heater. *Nigerian Journal of Solar Energy, 14:41–50.*

Sahari, Y. and Driscoll, R. H. (2013). Thin layer drying of agricultural products: a review. Malaysian Postgraduate Conference, 2013. Pp. 8-21.

Steinfeld, A. and Segal, I. (1986). A simulation model for solar thin layer drying process. *Drying Technology, 4: 535.*

Taheri-Garavand, A., Rafieea, S. and Keyhania, A. (2011). Mathematical modeling of thin layer drying kinetics of tomato influence of air dryer conditions. International Transaction Journal of Engineering, Management and Applied Sciences and Technologies, *2(*2*), 147-160.*

Zarein, M., Banakar, A. and Khafajeh, H. (2013). Mathematical modeling, energy consumption and thin-layer drying kinetics of carrot slices under microwave oven. *International Journal of Agriculture and Crop Sciences*, 13(5):2057-2063.