Trop J Nat Prod Res, June 2023; 7(6):3253-3262 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Tropical Journal of Natural Product Research

Available online at https://www.tjnpr.org

Original Research Article

Mathematical Modelling of the Drying Kinetics and Optimization of Process Conditions for *Tilapia zillii* Fillets Dried in a Convection Oven

Olayinka Sanda[1]*, Deborah A. Sanda[3], Elijah A. Taiwo[1], Charity O. Aremu[4], John O. Ojediran[5], Bamidele S. Fakinle[2]

[1]*Department of Chemical Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria*
[2]*Department of Chemical Engineering, Landmark University, Omu-Aran, Nigeria*
[3]*Department of Food Science and Technology, Obafemi Awolowo University, Ile-Ife, Nigeria*
[4]*Department of Crop Science, Landmark University, Omu-Aran, Nigeria*
[5]*Department of Agricultural and Biosystems Engineering, Landmark University, Omu-Aran, Nigeria*

ARTICLE INFO

Article history:
Received 16 March 2023
Revised 26 May 2023
Accepted 30 May 2023
Published online 01 July 2023

Copyright: © 2023 Sanda *et al*. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

ABSTRACT

This study investigated the thin layer drying behaviour of *Tilapia zillii* fillets under various drying conditions in a convection oven. The fish fillet samples were dried in a single layer at 60ºC, 70ºC and 80ºC with the drying air speed varied between 1.5 and 3.5 m/s over a drying period of 10 h. The drying data were then fitted to six thin layer drying models. In addition to the experiments on drying kinetics, a Box-Behnken experimental design with three factors (temperature, fillet thickness and drying time) was used to determine the optimum process conditions that will give a final moisture content of ≤10 wt.%. It was observed that the drying occurred mainly in the falling rate period with the drying rate increasing with increasing temperature and decreasing fillet thickness. The Two-term exponential model gave the best fit to the experimental drying data, with corresponding R^2, RMSE and χ^2 varying from 0.9988 to 0.9995, 0.00115 to 0.0106, and 3.41×10^{-5} to 1.39×10^{-4}, respectively. Although effective moisture diffusivity follows an Arrhenius-type relation, it is a non-linear function of temperature, fillet thickness and air speed, with a drying activation energy of 13.44 kJ/mol for 5mm fillets dried at air speed of 2.5 m/s. From the response surface optimization studies, it is possible to dry the fillets to a moisture content of ≤ 10wt.% at 65ºC and drying time of 6.25 h, provided the thickness of the fillets are within 3.5 mm.

Keywords: Tilapia fillets, Drying Kinetics, Moisture Diffusivity, Optimization

Introduction

Due to its great nutritional value, fish plays a significant role in the human diet. Fish nutritional content varies greatly based on a variety of factors, including species, maturity and health status, type of muscle or body part, processing method, and time spent in storage following harvest.[1,2] Fish proteins play a vital role in many other countries' diets as well as in other densely populated nations where overall protein intake may be inadequate. Overall, fish contributes at least 20% of the average per capita animal protein diet of more than 2.6 billion individuals[3]. In addition to being a very important source of animal protein, fish is also a very good source of polyunsaturated fatty acids (PUFAs) such as omega-3 and omega-6, which have preventive effects on various cardiovascular diseases.[4, 5]
The production of fish from capture fisheries and aquaculture was anticipated to be over 179 million tonnes in 2018, according to FAO statistics on global fish production. A deeper analysis of this number reveals that 7 percent of total fish production came from interior captures, while approximately 47% of it came from marine catches[3].

*Corresponding author. E mail: osanda@oauife.edu.ng
sanchemie02@gmail.com
Tel: +2348027910255

Citation: Sanda O, Sanda DA, Taiwo EA, Aremu CO, Ojediran JO, Fakinle BS. Mathematical Modelling of the Drying Kinetics and Optimization of Process Conditions for *Tilapia zillii* Fillets Dried in a Convection Oven. Trop J Nat Prod Res. 2023; 7(6):3253-3262 http://www.doi.org/10.26538/tjnpr/v7i6.29

Official Journal of Natural Product Research Group, Faculty of Pharmacy, University of Benin, Benin City, Nigeria

About 46% of the entire production is accounted for by aquaculture, with inland aquaculture making up 62% of the total.[3] In Nigeria, Fish are primarily obtained from coastal waterways, lakes, rivers, and lagoons, with the artisanal fishery industry handling the majority of the production and processing. Most of the fish caught by the artisanal fishermen are either smoked or dried, with a small amount being sold fresh. [6]
However, because fish is highly perishable, spoilage processes begin as soon as it is harvested. Fresh fish is susceptible to rapid quality degradation due to a number of factors, such as environmental changes brought on by removal from its natural aquatic environment, high moisture content, microbial activity, and damage to the body from the use of improper harvesting tools and rough handling techniques.[7, 8] In addition to being an aesthetic flaw that lowers the quality of fresh fish, physical damage from harsh handling puts fresh fish at risk for rapid water loss and opportunistic microbial infection during subsequent handling operations. [9 – 11]
With published annual estimates of worldwide fish losses ranging from 3 to 12 million tonnes, levels of fish losses are frequently reported to be 20–40% of the annual production.[12, 13] In underdeveloped nations where fish harvesting and post-harvest handling technology fall short of the requirements for modern integrated long-supply chains and marketing systems, it is anticipated that these numbers will be far higher. Additionally, post-harvest losses are greater in countries where the populace consumes less protein. [14, 15] Fish makes up roughly 40% of the animal protein consumed in Nigeria, so any decrease in fish supply will have an impact on how much animal protein is consumed by the populace. [16]
Although there are several methods of preservation, including salting, [17–18] pickling,[19] marinating,[20] freezing,[21, 22] and drying, [23, 24] drying is the oldest method of fish preservation known to man. [25, 26] Despite being the simplest drying method historically employed for fish preservation, sun-drying is typically characterized by qualitative and quantitative

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

losses due to contamination by insects and microbes. Additionally, problems including insufficient drying, foreign material contamination, ultraviolet radiation-induced coloration, and loss of nutritional and functional elements have a negative impact on the quality of the fish. [27] Weather changes have a significant impact on the quality of dried fish, thereby resulting in fungal and bacterial growth can lead to off flavours, undesirable odours, and unpleasant tastes.

The use of a drying unit such as a hot-air convection oven reduces drying time while removing the possibility of contamination and uneven drying. Depending on the characteristics of the drying air (such as temperature, velocity, and relative humidity), drying fish in a convection oven guarantees that the moisture content is as low as possible. This will extend the shelf life of the processed fish and significantly lower fish spoilage.

Thin-layer drying models for describing the drying phenomenon of agricultural products (fish fillets inclusive) are usually based on liquid diffusion theory and the process can be explained by Fick's second law. [25]

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \nabla^2 M \qquad (1)$$

where M is the local moisture content on a dry basis (d.b.), t is the drying time and D_{eff} is the effective moisture diffusivity. Since the food product to be dried is often assumed to be a one-dimensional solid with a uniform initial moisture content, equation (1) can be written as

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \frac{\partial^2 M}{\partial z^2} \qquad (2)$$

where z is the solid's half – thickness.

Semi-theoretical drying models have been developed based on the simplified general series solution of equation (2) and have been applied to modelling the drying kinetics of various agricultural produce, including fish fillets, because theoretical drying models based on Fick's diffusion law tend to be too complex for practical applications. However, the majority of studies on the drying characteristics of fish fillets usually focus on the correlation between moisture content and drying time, ignoring the effects of other factors such as drying air temperature, velocity, and fillet thickness on the overall drying characteristics of the fish fillet being dried. In order to determine the impact of process variables including temperature, drying time, and fillet thickness on the quality of the final products, this study investigated the drying characteristics of tilapia fish fillets in a convection oven.

Materials and methods

Materials

Fresh tilapia (*Tilapia zillii*) were obtained from artisanal fishermen at Asejire Dam area, Ibadan, Nigeria in May, 2021 and transported to the laboratory in a styofoam ice box under ice cover. The mean length and mass of the fish samples was 23.69 cm and 236.73 g, respectively.

After being received, the fish was immediately washed in distilled water, beheaded, and eviscerated to remove the internal organs. The fish was then cut into fillets with an average length of 10 cm and average thicknesses of 3, 5, and 7 mm. All thicknesses were measured using Vernier callipers. To keep their quality until the time of use, the fillets were frozen stored in a Nexus chest freezer (Model NX - 160H, Deekay Group, Nigeria) after being dipped in a 10 wt. % NaCl solution for 15 min, drained for 2 h under refrigeration at 4°C.

The initial dry basis moisture content of the fresh samples was determined prior to the drying operations. Exactly 5 g fish pieces was cut from four different parts from randomly selected fish samples were weighed using a precision weighing balance (Model MS3002TS, Mettler Toledo, Columbus, USA). The samples were subsequently dried in an oven (MRC DFO – 80, Essex, UK) at 105 °C for 24 h, cooled in a desiccator until a constant weight was attained, and the wet basis moisture content was determined using the formula below: [28]

$$\%\ \text{moisture} = \frac{\text{loss in weight of sample}}{\text{original weight of sample}} \times 100 \qquad (3)$$

Drying kinetics experiment

Drying of the fish fillets was performed in a modified Gallenkamp Hotbox oven (Model OVB – 300, Cambridge, UK) equipped with an 800 W heating element and a digital temperature controller, with the fan replaced with a variable speed centrifugal blower. For each run of experiment, 50 g of fish fillet samples was put into the pre-heated drying chamber, arranged on the middle drying tray in a single layer. Drying experiments were conducted at air temperatures of 60, 70, and 80°C, and air velocities of 1.5, 2.5, and 3.5 m/s. The air velocities and humidity were determined for the drying experiments using a Peakmeter digital anemometer (Model 6252A, Semme, USA), and the average recorded relative humidity was 33±2 %. The sample weight was continuously recorded at 30-min intervals throughout the drying period, with the total run time being 10 h. All the drying test results were recorded in triplicates.

The moisture ratio was calculated from each drying result using the formula:

$$MR = \frac{X - X^*}{X_o - X^*} \qquad (4)$$

Where X is the dry-basis moisture content of the fillets measured during drying, X_o is the initial dry-basis moisture content of the fillets prior to the start of drying, while X^* is the dry-basis moisture content of the fillets in equilibrium with mean dry bulb temperature and relative humidity of the drying air. Since the humidity of the air in the drying chamber is not constant, the moisture ratio expression may be written in a simplified form:

$$MR = \frac{X}{X_o} \qquad (5)$$

Where the equilibrium moisture content is taken to be negligible.

The drying curves were compared to the thin-layer drying models in Table 1 to determine which mathematical model best represented the changes in moisture ratio over time. Several studies have reported using these thin layer drying models, some of which are shown in Table 1. [29–38] To fit the test data to the empirical models, nonlinear regression analysis was carried out using Curve Expert software (Version 2.7.3).

To validate the quality of fit of the selected models, statistical parameters such as correlation coefficient (R^2), chi-square (χ^2) and the root mean square error (RMSE) were used. The correlation coefficient was obtained from the curve fit done using the graphing software, while the chi-square and the root mean square error were computed using the formulae below:

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pred,i}\right)^2}{N - z} \qquad (6)$$

$$RMSE = \left[\frac{\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pred,i}\right)^2}{N}\right]^{0.5} \qquad (7)$$

Where $MR_{exp,i}$ is the moisture ratio obtained from experiment i, $MR_{pred,i}$ is the model predicted moisture ratio for experiment i, N is the number of observations and z is the number of constants in the model being considered. The best model for the fit is the one with the highest R^2, the lowest χ^2 and the lowest RMSE.[39, 40]

Determination of effective diffusivity

The effective moisture diffusivity (D_{eff}) is commonly used to describe the movement of moisture from materials being dried during the falling rate period. The effective moisture diffusivity can be determined from Fick's diffusion equation and has been adapted for many commonly shaped bodies. For rectangular shaped materials, Fick's diffusion equation can be shortened to:

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

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

Where D_e is the effective diffusivity (m^2/s), L is the half-thickness of slab (m) and t is the drying time (s). This equation can be written in a linearized form as:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left[\frac{\pi^2 D_e}{4L^2}\right] t \quad (9)$$

The effective diffusivities were then determined from the drying data obtained by plotting ln (MR) against drying time.

Response surface experimental design for the drying process

To study the effect of the various process parameters (temperature, time and fillet thickness) on the final moisture ratio of the fish fillets, a 3-level, 3-factor Box Behnken Design (BBD) was used with a total of 15 experimental runs generated. The process variables and their coded and uncoded levels are shown in Table 2. The responses were evaluated using Minitab statistical software (version 17) and fitted to the quadratic model below:

$$Y = a_o + a_{ii}\sum_{i=1}^{n} X_i + a_{ii}\sum_{i=1}^{n} X_i^2 + a_{ij}\sum_{i=1}^{n-1}\sum_{j=2}^{n} X_i X_j + \varepsilon \quad (10)$$

where Y is the predicted moisture ratio, a_o is the intercept term, a_i (i = 1,2,3) represents the linear coefficients, a_{ij} represents the coefficients of the interaction terms, a_{ii} represent the quadratic coefficients and ε is the random error. The terms X_i represent the coded factors, which are related to the actual factors x_i in Table 2 by the equation shown below:

$$\boldsymbol{X_i} = \frac{x_i - x_o}{\Delta x} \quad (11)$$

where X_i is the coded value for the *i*th input (that is, x_i), x_o is the mid value for the experimental design, and Δx is the difference between adjacent values. For all experiments, the total mass of the fillets being dried was kept constant at 50 g, while the blower speed was set such that the air velocity is 2.5 m/s.

Table 1: Some semi-theoretical models used in thin layer drying of food products

Model	Mathematical Representation
Newton	$MR = exp[-kt]$
Page	$MR = exp[-kt^n]$
Modified Page	$MR = exp[-(kt)^n]$
Pabis and Henderson	$MR = a\ exp[-kt]$
Two Term exponential	$MR = a\ exp[-k_0 t] + b\ exp[-k_1 t]$
Wang and Singh	$MR = 1 + at + bt^2$

Table 2: Independent Variables and their Levels for the Central Composite Design

Parameter	Variables		
	Low (-1)	Mid (0)	High (+1)
Drying temperature (x_1), °C	60	70	80
Drying time (x_2), h	3	5	7
Fillet thickness (x_3), mm	3	5	7

Results and Discussion

The fillets were dried from an initial dry basis moisture content of 270 wt.% (dry basis), or 73 wt.% (wet basis) for 10 h and the moisture data obtained were converted to moisture ratios. The variations of the moisture ratios with time are presented in Figures 1 – 3, with temperature, fillet thickness and drying air velocity being the considered parameters.

It was observed from Figure 1 that as the initial gradient of the drying curve increases as the drying temperature increases, with other parameters such as fillet thickness and air velocity kept at their mid values of 5 mm and 2.5 m/s, respectively. This observed trend is common to thermally activated processes. [41] The mean value of time required to reduce the moisture of the fillets from the initial wet basis moisture content of 73 wt. % to the final desired moisture content of 10 % (wet basis) was about 580, 475, and 350 mins at air temperatures of 60°C, 70°C, and 80°C, respectively. As drying temperature increases, the diffusion rate increases according to an Arrhenius type equation which shows the effective diffusivity (D_e) to be a strong function of temperature:

$$D_e = D_o \exp\left[-\frac{E_a}{RT}\right] \quad (12)$$

where D_e is the effective diffusivity (in m^2/s), T is the drying temperature in Kelvin, R is the universal gas constant (8.314 J/K. mol) and E_a is the activation energy for the drying process (in in J/mol). The effective diffusivities can be obtained from the slope of the plot of $\ln(MR)$ against drying time (in seconds), while the required activation energies were obtained from the slope of the plot of $\ln D_e$ against $\frac{1}{T}$. It was observed that although the plot of moisture ratio against time showed no indication of a constant drying rate period followed by a falling rate drying period (usually encountered with wet, granular materials), the plot of ln (MR) against time however indicated the existence of an average critical moisture content (of about 15% dry basis) where the moisture diffusivity decreases as shown in Figure 4. This trend will be evident for the data represented by Figures 2 and 3 if they were to be plots of ln (MR) against time. The position of the observed critical moisture level has been marked on Figure 4 using a dashed line.

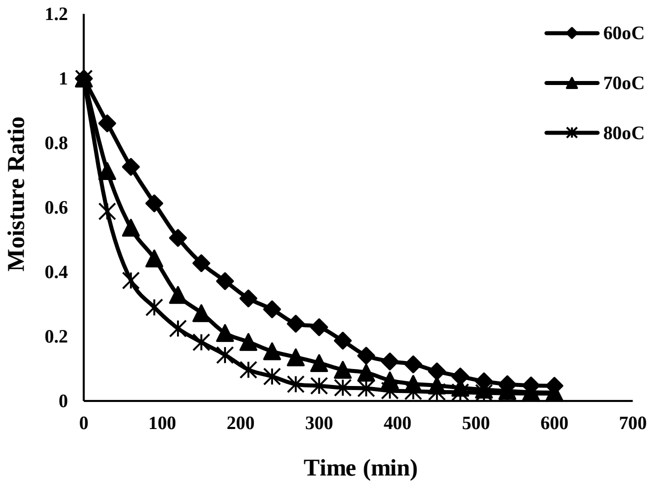

Figure 1: Effect of drying temperature on the variation of moisture ratios with time [air velocity: 2.5 m/s, fillet thickness: 5 mm]

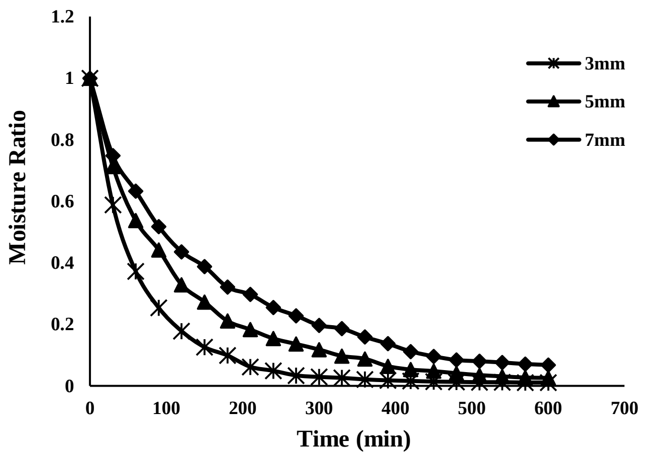

Figure 2: Effect of fillet thickness on the variation of moisture ratios with time [air velocity: 2.5 m/s, drying temperature: 70°C]

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

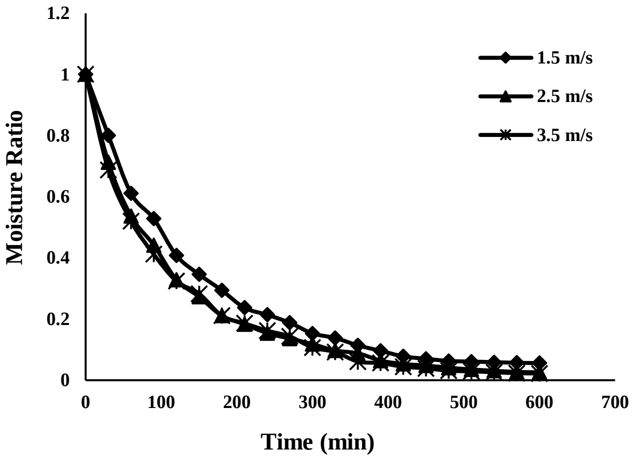

Figure 3: Effect of air velocity on the variation of moisture ratios with time [fillet thickness, 5 mm, drying temperature: 70°C]

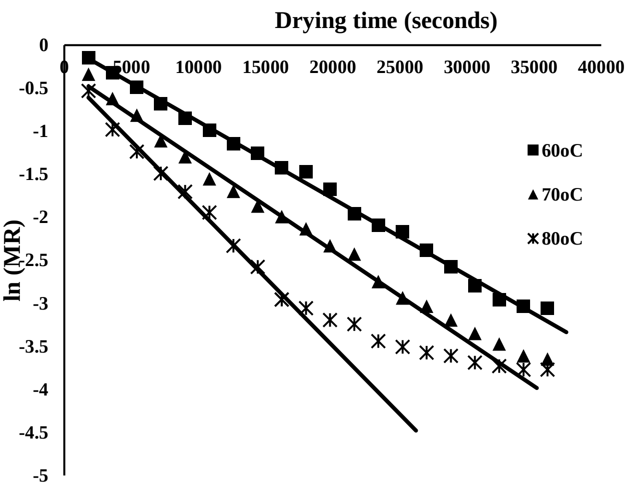

Figure 4: Plot of ln (MR) against drying time (in seconds) at different drying temperatures

From Figure 2, it can be seen that as the drying rate increases with decreasing fillet thickness, where other parameters such as drying temperature and air velocity kept at their mid values of 70°C and 2.5 m/s, respectively. There is a decrease in the mean value of time required to reduce the moisture of the fillets from its initial wet basis moisture to the final desired moisture content of 10% (wet basis) was found to be about 260 and 475 mins for the 3mm and 5mm fillets, respectively. However, the 7mm fillets would require more than 10 h to attain the target moisture content under this drying condition. Since there have been documented evidence of losses in nutritional value of dried fish when dried at high temperatures or for extended drying periods,[42 – 45] the aim is to minimize both drying temperature and time, while keeping the final moisture content at 10% (wet basis) or lower.

The drying pattern shown in Figure 3 for varying air velocities showed that the moisture diffusion rate increases with air velocity, where other parameters such as drying temperature and fillet thickness were kept at their mid values of 70°C and 5 mm, respectively. The mean value of time required to reduce the moisture of the fillets from its initial wet basis moisture to the final desired moisture content of 10 % (wet basis) was found to be 475 min for 2.5 m/s air velocity and 450 min for air velocity of 3.5 m/s. However, it would take more than 10 h to attain this target moisture content using a drying air velocity under this drying condition.

The moisture diffusivities for the various drying conditions are presented in Table 3. These results confirm that in addition to following the Arrhenius-type relation in Equation (12), the diffusion rate varies inversely as the thickness of the material being dried in line with the assumption from Fick's diffusion equation. Although increasing the air velocity from 1.5 m/s to 2.5 m/s increased the moisture diffusivity at 70 °C from 3.14×10^{-11} m²/s to 2.28×10^{-10} m²/s, an increase of the air velocity to 3.5 m/s had little effect on the drying rate. Increasing the speed of the blower any further will only result in energy wastage. The activation energy for the drying operation based on the moisture diffusivities obtained for the 5mm fillets dried using air speed of 2.5 m/s is 13.44 kJ/mol.

Since the moisture diffusivity depends on the three chosen parameters (that is, temperature, fillet thickness and drying air speed), a general correlation can be obtained showing the required relationship. Multivariable regression analysis was done on the information in Table 3 using the data analysis tool in Microsoft Excel 2013 and this gave the relation below:

$$\ln D_{eff} = -23.4366 - 1634.35\left(\frac{1}{T}\right) + 0.1606\delta + 2.1429v, \quad R^2 = 0.9936 \qquad (13)$$

where D_{eff} is the effective moisture diffusivity in m²/s, T is the drying temperature in Kelvin, δ is the fillet thickness in millimetres and v is the air speed in m/s.

Evaluation of the thin layer drying models

The experimental moisture ratios were fitted to the six thin-layer drying models is shown in Table 1. The results of the statistical evaluation of the models is shown in Tables 4 – 6 for varying temperature, fillet thickness and drying air speed, respectively. The model with the best fit is one with the highest correlation coefficient and the lowest root mean square error (RMSE) and Chi – square (χ^2) values. From the models tested, the two-term exponential model was found to give the best fit for the three conditions tested with R^2 varying between 0.9988 and 0.9995, followed by the Page model. The model parameters varies with drying conditions, indicating that there is possibility of presenting these model parameters as functions of temperature, fillet thickness and air speed.

Table 3: Effective moisture diffusivities for the drying fillets for the various drying conditions

Fillet thickness (mm)	Drying temperature (°C)	Air speed (m/s)	Moisture diffusivity (m²/s)*	R^2
3	70	2.5	2.12×10^{-10}	0.9914
5	60	2.5	2.21×10^{-10}	0.9962
5	70	2.5	2.48×10^{-10}	0.9907
5	80	2.5	2.91×10^{-10}	0.9931
5	70	1.5	3.14×10^{-11}	0.9938
5	70	3.5	2.71×10^{-10}	0.9942
7	70	2.5	4.03×10^{-10}	0.9923

* The diffusivities are based on the moisture contents recorded up to the critical moisture level of 15% (dry basis)

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Table 4: Modelling of drying kinetics as a function of temperature (thickness = 5mm, v = 2.5 m/s)

Model	Model parameters	Drying Temperature		
		60ºC	70ºC	80ºC
Newton	k	0.3216	0.5120	0.8195
	R^2	0.9992	0.9882	0.9877
	χ^2	0.00012	0.00108	0.001441
	RMSE	0.0107	0.0312	0.0371
Page	k	0.3313	0.6153	0.9220
	n	0.9970	0.7974	0.7118
	R^2	0.9993	0.9991	0.9990
	χ^2	0.00017	6.56×10^{-5}	0.00012
	RMSE	0.0125	0.00770	0.01073
Modified Page	k	0.3224	0.5438	0.8921
	n	0.9774	0.7974	0.7118
	R^2	0.9935	0.9991	0.9990
	χ^2	0.000123	6.56×10^{-5}	0.00012
	RMSE	0.01056	0.00770	0.01074
Pabis and Henderson	a	0.9966	0.9406	0.9401
	k	0.3205	0.4788	0.7477
	R^2	0.9992	0.9943	0.9894
	χ^2	0.00012	0.00076	0.00122
	RMSE	0.0106	0.0269	0.0341
Two Term exponential	a	0.0985	0.5453	0.5062
	b	0.9091	0.4517	0.4943
	k_0	0.746	0.3201	2.018
	k_1	0.3024	1.1327	0.4320
	R^2	0.9994	0.9993	0.9989
	χ^2	0.000114	5.78×10^{-5}	0.000139
	RMSE	0.00960	0.00149	0.0106
Wang and Singh	a	-0.2370	-0.2944	-0.3327
	b	0.0148	0.0211	0.0253
	R^2	0.9878	0.9237	0.7914
	χ^2	0.00204	0.00099	0.0229
	RMSE	0.04294	0.00619	0.1439

Table 5: Modelling of drying kinetics as a function of fillet thickness (Temperature = 70ºC, v = 2.5 m/s)

Model	Model parameters	Fillet thickness		
		3 mm	5 mm	7 mm
Newton	k	0.910501	0.5120	0.3553
	R^2	0.9938	0.9882	0.9817
	χ^2	0.020148	0.00108	0.0187
	RMSE	0.000449	0.0312	0.04111
Page	k	0.9698	0.6153	0.4759
	n	0.8159	0.7974	0.7663
	R^2	0.9994	0.9991	0.9991
	χ^2	4.70×10^{-5}	6.56×10^{-5}	6.41×10^{-5}
	RMSE	0.00655	0.00770	0.00761

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

Modified Page	k	0.9632	0.5438	0.3794
	n	0.8159	0.7974	0.7663
	R^2	0.9994	0.9991	0.9991
	χ^2	4.70×10^{-5}	6.56×10^{-5}	6.41×10^{-5}
	RMSE	0.00655	0.00770	0.00761
Pabis and Henderson	a	0.9717	0.9406	0.7998
	k	0.8838	0.4788	0.4131
	R^2	0.9940	0.9943	0.9647
	χ^2	0.0004	0.00076	0.01288
	RMSE	0.01903	0.0269	0.10796
Two Term exponential	a	0.3801	0.5453	0.707261
	b	0.6186	0.4517	0.289465
	k_0	0.4924	0.3201	0.253503
	k_1	1.4817	1.1327	1.458288
	R^2	0.9995	0.9993	0.9989
	χ^2	3.41×10^{-5}	5.78×10^{-5}	8.02×10^{-5}
	RMSE	0.001152	0.00149	0.001761
Wang and Singh	a	-0.3447	-0.2944	-0.2540
	b	0.0265	0.0211	0.0172
	R^2	0.8226	0.9237	0.9533
	χ^2	0.00217	0.00099	0.00050
	RMSE	0.00914	0.00619	0.00438

Table 6: Modelling of drying kinetics as a function of drying air speed (*thickness = 5mm, Temperature = 70°C*)

Model	Model parameters	Air speed		
		1.5 m/s	**2.5 m/s**	**3.5 m/s**
Newton	k	0.40083	0.5120	0.5276
	R^2	0.9915	0.9882	0.9860
	χ^2	0.000780	0.00108	0.00129
	RMSE	0.0266	0.0312	0.0342
Page	k	0.4734	0.6153	0.4759
	n	0.8516	0.7974	0.7663
	R^2	0.9978	0.9991	0.9229
	χ^2	0.00017	6.56×10^{-5}	0.00761
	RMSE	0.0123	0.00770	0.0830
Modified Page	k	0.4156	0.5438	0.5677
	n	0.8516	0.7974	0.7663
	R^2	0.9978	0.9991	0.9229
	χ^2	0.00017	6.56×10^{-5}	0.00761
	RMSE	0.0123	0.00770	0.0830
Pabis and Henderson	a	0.9580	0.9406	0.9294
	k	0.3828	0.4788	0.4868
	R^2	0.9921	0.9943	0.9875
	χ^2	0.00062	0.00076	0.00091

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

	RMSE	0.0237	0.0269	0.0286
Two Term exponential	a	0.4057	0.5453	0.6887
	b	0.5954	0.4517	0.3112
	k_0	0.2254	0.3201	0.3739
	k_1	0.6591	1.1327	1.9457
	R^2	0.9988	0.9993	0.9993
	χ^2	0.00010	5.78×10^{-5}	5.61×10^{-5}
	RMSE	0.00198	0.00149	0.00147
Wang and Singh	a	-0.2703	-0.2944	-0.2944
	b	0.0186	0.0211	0.0210
	R^2	0.9600	0.9237	0.9514
	χ^2	0.0006	0.00099	0.00099
	RMSE	0.00481	0.00619	0.00619

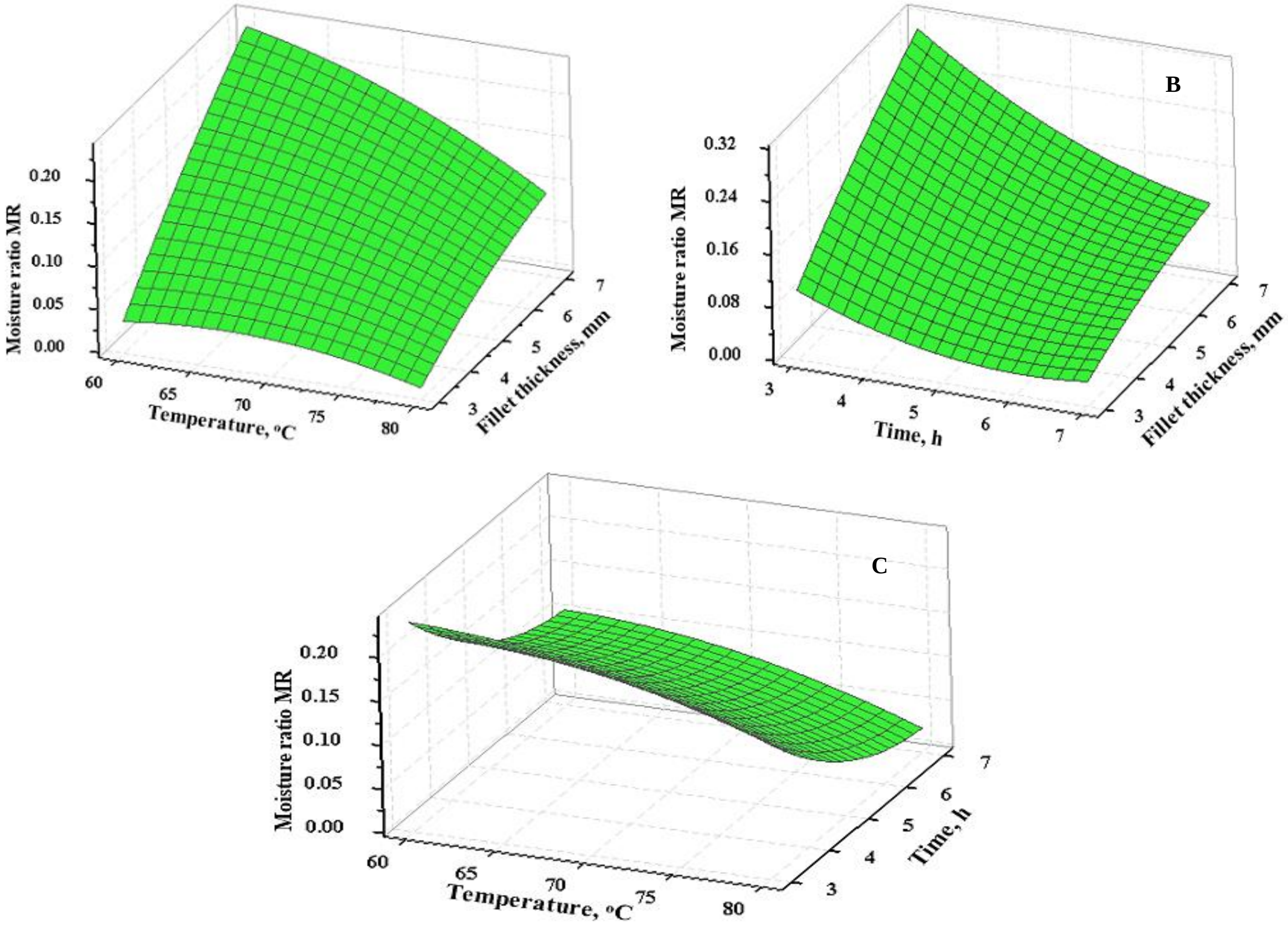

Figure 5: 3-D plots showing the relationship between the process variables and the final moisture ratio

Statistical analysis and optimization of the drying process

The effect of combination of factors such as temperature, drying time and drying temperature on the final moisture content of the fish fillets was studied via response surface methodology with a view to determine the optimal combination of factors that will give fillets of the desired degree of dehydration without compromising nutritional quality. For these experiments, the blower speed was adjusted to keep the drying air speed at around 2.5 m/s. The final moisture contents obtained at the end of each experiment were used in computing the moisture ratios presented in Table 7.

The results of the analyses of variance (ANOVA), and the final regression analysis for the quadratic model are as shown in Tables 8 and 9, respectively. The model's F-value of 49.43 and p-value of less than 0.001 imply that it adequately explains the effect of variations in the process parameters. In addition, a regression coefficient (R^2) of 0.9889 and an adjusted R^2 value of 0.9688 further confirms the adequacy of the model fit. From the regression analysis and ANOVA tables, most of the

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

model terms are significant, except the square term for the thickness component (X_3^2) and the temperature – time interaction term (X_1X_2). These insiginificant model terms are shown in bold letters in Tables 8 and 9.

The relationship between the final moisture ratio and the process conditions (time, temperature and fillet thickness) is illustrated by the surface plots in Figure 5. From Figure 5a where the drying time is kept at 5 h, the moisture ratio decreases with increase in temperature but the final moisture level depends on the fillet thickness. Thus, drying the fish under this condition to the target moisture content of 10 wt. % without increasing the temperature beyond 80 ºC would require having to prepare fillets of impractically low thickness. This dilemma of having to prepare impracticably thin fillets could also be observed in the surface plot in Figure 5b where the drying temperature was fixed at 70 ºC. However, maintaining the fillet thickness at 5 mm would require over 6h of drying time if the temperature is not to exceed 80 ºC (as illustrated in Figure 5c).

From the response surface design results, the target moisture content of 10 wt.% (or a moisture ratio of 0.05) can be achieved at a relatively low temperature of about 65 ºC and drying time of 6.25 h with a composite desirability level of 0.9988, provided the fillets can be prepared such that each slice is about 3.5 mm thick (as shown by the optimization diagram in Figure 6).

Conclusion

It can be concluded from the study that the thin layer drying kinetics of *Tilapia zillii* fillets closely matched the 2-term exponential model, which had the lowest RMSE and χ^2 values, and R^2 values above 0.99. The effective moisture diffusivity under the different drying scenarios though followed an Arrhenius-type relationship, is a nonlinear function of temperature, fillet thickness, and drying air speed. From the response surface optimization studies, an optimal moisture content of 10 weight percent (wet basis) can be achieved for the fillets at a relatively low temperature of about 65 ºC and drying time of 6.25 h under similar process conditions while maintaining the nutritional qualities, provided the thickness of the fillets is within 3.5 mm.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Declaration

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

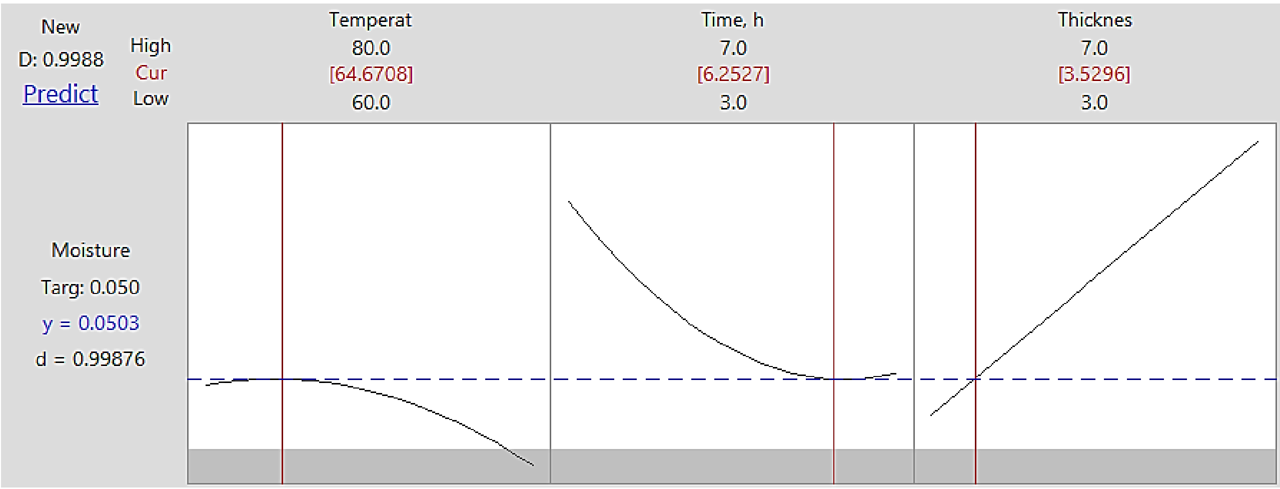

Figure 6: Response optimization plot for a target moisture ratio of 0.05

Table 7: Moisture ratio values from the Response Surface Methodology (RSM) Experiments

Std Order	Run Order	Temperature (ºC)	Drying time (h)	Fillet thickness (mm)	Moisture Ratio	
					Actual	Predicted
8	1	80	5	7	0.083	0.090
1	2	60	3	5	0.229	0.236
7	3	60	5	7	0.221	0.231
5	4	60	5	3	0.038	0.031
4	5	80	7	5	0.03	0.023
13	6	70	5	5	0.118	0.117
3	7	60	7	5	0.114	0.105
10	8	70	7	3	0.016	0.033
12	9	70	7	7	0.112	0.111
14	10	70	5	5	0.116	0.117
15	11	70	5	5	0.117	0.117
9	12	70	3	3	0.099	0.100
11	13	70	3	7	0.321	0.304
6	14	80	5	3	0.017	0.007
2	15	80	3	5	0.143	0.152
8	1	80	5	7	0.083	0.090

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Table 8: Analysis of variance (ANOVA) table for Response Surface Quadratic Model

Source	DF	Sum of Squares	Mean Squares	F-Value	P-Value
Model	9	0.100031	0.011115	49.43	<0.0001
Temperature, ºC (X_1)	1	0.013530	0.013530	60.17	0.001
Time, h (X_2)	1	0.033800	0.033800	150.32	<0.0001
Thickness, mm (X_3)	1	0.040186	0.040186	178.72	<0.0001
X_1^2	1	0.001147	0.001147	5.10	0.073
X_2^2	1	0.003241	0.003241	14.41	0.013
$\mathbf{X_3^2}$	1	0.000342	0.000342	1.52	0.272
$\boldsymbol{X_1X_2}$	1	0.000001	0.000001	0.00	0.949
X_1X_3	1	0.003422	0.003422	15.22	0.011
X_2X_3	1	0.003969	0.003969	17.65	0.008
Lack-of-Fit	3	0.001122	0.000374	374.08	0.003
Pure Error	2	0.000002	0.000001		
Total	14	0.101155			

DF: Degree of freedom

Table 9: Regression Analysis of the Response Surface Model

Term	Coefficient	SE Coef	T-Value	P-Value	VIF
Constant	0.11700	0.00866	13.51	<0.0001	
Temperature, ºC (X_1)	-0.04113	0.00530	-7.76	0.001	1.00
Time, h (X_2)	-0.06500	0.00530	-12.26	<0.0001	1.00
Thickness, mm (X_3)	0.07088	0.00530	13.37	<0.0001	1.00
X_1^2	-0.01763	0.00780	-2.26	0.073	1.01
X_2^2	0.02962	0.00780	3.80	0.013	1.01
$\mathbf{X_3^2}$	-0.00963	0.00780	-1.23	0.272	1.01
$\boldsymbol{X_1X_2}$	0.00050	0.00750	0.07	0.949	1.00
X_1X_3	-0.02925	0.00750	-3.90	0.011	1.00
X_2X_3	-0.03150	0.00750	-4.20	0.008	1.00

SE Coef: Standard error of the regression coefficient terms

References

1. Sogbesan OA, Ibrahim P. Assessment of smoked fish quality using two smoking Kilns and hybrid solar dryer on some commercial fish species in Yola, Nigeria. J. Anim Res Nutr. 2017; 2:6.
2. Zin FFM, Basri NA, Al-Azad SUJJAT, Mustafa S, Shapawi R. Growth performance and post-harvest quality of gift tilapia reared in two different culture systems. Malays. Appl. Biol. 2020; 49(1): 183-192.
3. FAO. The state of world fisheries and aquaculture 2020. Sustainability in action. Rome; 2020
4. Simopoulos AP. The importance of the omega-6/omega-3 fatty acid ratio in cardiovascular disease and other chronic diseases. Exp Biol Med. 2009; 233(6): 674-688.
5. Saini RK, Keum YS. Omega-3 and omega-6 polyunsaturated fatty acids: Dietary sources, metabolism, and significance—A review. Life sci. 2018; 203: 255-267.
6. Kaleem O, Sabi AFBS. Overview of aquaculture systems in Egypt and Nigeria, prospects, potentials, and constraints. Aquac Fish. 2021; 6(6): 535-547.
7. Daramola JA, Alao FO, Adeniyi AE. Estimation of bacteria and fungi in smoked catfish (*Clarias gariepinus*) available in OTA markets. j. res. for. wildl. environ. 2020; 12(2).
8. Aarabi S, Fahime EE, Ninich O, Chauiyakh O, Kettani K, Et-tahir A. Eco-toxicological Health Status of Fish, Quality of the Estuary and their Impacts on Human Health: A Case Study of Consumers in Rabat, Morocco. TJNPR. 7(1):2128-2139
9. Diei-Ouadi Y, Mgawe YI. Post-harvest fish loss assessment in small-scale fisheries: A guide for the extension officer. FAO Fisheries and Aquaculture Technical Paper 559. 2011
10. McCluney JK, Anderson CM, Anderson JL. The fishery performance indicators for global tuna fisheries. Nat. Commun. 2019; 10(1):1641.
11. Opara LU, Al-Jufaili SM, Rahman MS. Postharvest handling and preservation of fresh fish and seafood. In Handbook of Food preservation. CRC Press. 2007; 169 – 190 p
12. Ababouch L. Fish utilization and trade. In Second International Congress on Seafood Technology on Sustainable, Innovative and Healthy Seafood. 2009. 9p.
13. Mavuru A, Mhlanga L, Nhiwatiwa T. An assessment of post-harvest fish losses (PHFLs) in the artisanal fishery of lake kariba, Zimbabwe. Sci. Afr. 2022; 16, e01124.
14. Adeyeye SAO, Oyewole OB. An overview of traditional fish smoking in Africa. J. Culin. Sci. 2016; 14(3):198–215.

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License

15. Tesfay S, Teferi M. Assessment of fish post-harvest losses in Tekeze dam and Lake Hashenge fishery associations: northern Ethiopia. Agric. Food Secur. 2017; 6(1): 1-12.
16. Ibok OW, Ele IE, Antia-Obong EA, Okon IE, Udoh ES. Economic Analysis of Fish Farming in Calabar, Cross River State, Nigeria. Greener J Agric Sci. 2017; 3(7): 542-549
17. Shenderyuk VI, Bykowski PJ. Salting and marinating of fish. In Seafood: resources, nutritional composition, and preservation 2020, (pp. 147-162). CRC Press.
18. Jeyasanta IK, Prakash S, Patterson J. Wet and dry salting processing of double spotted queen fish *Scomberoides lysan* (Forsskål, 1775). Int. j. fish. aquat. sci. 2016; 4(3): 330-338.
19. Babikova J, Hoeche U, Boyd J, Noci F. Nutritional, physical, microbiological, and sensory properties of marinated Irish sprat. Int J Gastron Food Sci. 2020;22, 100277.
20. Shenderyuk VI, Bykowski PJ. Salting and marinating of fish. In Seafood: resources, nutritional composition, and preservation. CRC Press. 2020. 147 – 162p
21. Bilbao-Sainz C, Sinrod AJ., Williams T, Wood D, Chiou BS, Bridges DF, McHugh T. Preservation of tilapia (*Oreochromis aureus*) fillet by isochoric (constant volume) freezing. J. Aquat. Food Prod. Technol. 2020; 29(7):629-640.
22. Gandotra R, Koul M, Gupta S, Sharma S. Change in proximate composition and microbial count by low temperature preservation in fish muscle of Labeo Rohita (Ham-Buch). IOSR J. pharm. biol. sci. 2012; 2(1): 13-17.
23. Gore SB, Relekar SS, Kulkarni AK, Joshi SA, Pathan JG, Telvekar PA, Bankar SS. Quality of traditionally salted and dried fishes of Ratnagiri fish market, Maharashtra. Int. J. Sci. Environ. Technol. 2019; 8:663-673.
24. Kumar GP, Xavier KM, Nayak BB, Kumar HS, Venkateshwarlu G, Balange AK. Effect of different drying methods on the quality characteristics of Pangasius hypophthalmus. Int. J. Curr. Microbiol. Appl. Sci. 2017; 6:184-195.
25. Rasul MG, Yuan C, Yu K, Takaki K, Shah AK. Factors influencing the nutritional composition, quality and safety of dried fishery products. Food Res. 2022; 6(5):444-66.
26. Svanberg I. Ræstur fiskur: air-dried fermented fish the Faroese way. J. Ethnobiol. 2015; 11(1): 1-11.
27. Zebedayo B, Anders D, Lughano JM, Robinson HM. Microbial quality of Nile perch (*Lates niloticus*) and physico-chemical properties of salted sun-dried products sold at regional markets, Tanzania. Afr. J. Microbiol. Res. 2019;13(7):128-133.
28. Kamal MM, Ali MR, Shishir MRI, Mondal SC. Thin-layer drying kinetics of yam slices, physicochemical, and functional attributes of yam flour. J. Food Process Eng. 2020; e13448. https://doi.org/10.1111/jfpe.13448.
29. Agustini TW, Fahmi AS, Riyadi PH. Dried salted anchovy different processing methods: drying kinetics and modelling. Food Res. 2021; 5(3):70-75.
30. Al-Mahasneh MA, Rababah TM, Al-Shbool MA, Yang W. Thin-layer drying kinetics of sesame hulls under forced convection and open sun drying. J. Food Process Eng. 2007; 30(3): 324-337.
31. Aykın-Dinçer E, Erbaş M. Drying kinetics, adsorption isotherms and quality characteristics of vacuum-dried beef slices with different salt contents. Meat Sci. 2018; 145: 114-120.
32. Bualuang O, Tirawanichakul S, Tirawanichakul Y. Thermo-physical properties and mathematical modeling of thin-layer drying kinetics of medium and long grain parboiled rice. ASEAN J. Chem. Eng. 2011; 11(2): 22-36.
33. Yu D, Feng T, Jiang Q, Yang F, Gao P, Xu Y, Xia W. The change characteristics in moisture distribution, physical properties and protein denaturation of slightly salted silver carp (*Hypophthalmichthys molitrix*) fillets during cold/hot air drying processing. LWT. 2021; 137:110466.
34. Tzempelikos DA, Vouros AP, Bardakas AV, Filios AE, Margaris DP. Case studies on the effect of the air drying conditions on the convective drying of quinces. Case Stud. Therm. Eng. 2014; 3:79-85.
35. Inyang UE, Oboh IO, Etuk BR. Kinetic models for drying techniques—food materials. Adv. Chem Eng. Sci. 2018; 8(02):27.
36. Kucuk H, Midilli A, Kilic A, Dincer I. A review on thin-layer drying-curve equations. Dry. Technol. 2014; 32(7): 757-773.
37. Murali S, Delfiya DA, Kumar KS, Kumar LR, Nilavan SE, Amulya PR, Samuel MP. Mathematical modeling of drying kinetics and quality characteristics of shrimps dried under a solar–LPG hybrid dryer. Aquat. Food Prod. Technol. 2021; 30(5): 561-578.
38. Rodríguez-Ramos F, Leiva-Portilla D, Rodríguez-Núñez K, Pacheco P, Briones-Labarca V. Mathematical modeling and quality parameters of Salicornia fruticosa dried by convective drying. J. Food Sci. Technol. 2020; 58(2):474-483.
39. Doymaz I. Sun drying of figs: an experimental study. J. Food Eng. 2005; 71(4): 403-407.
40. Forouzanfar A, Hojjati M, Noshad M, Szumny AJ. Influence of UV-B pretreatments on kinetics of convective hot air drying and physical parameters of mushrooms (Agaricus bisporus). Agriculture. 2020; 10(9): 371.
41. Khazaei J, Chegini GR, Bakhshiani M. A novel alternative method for modeling the effects of air temperature and slice thickness on quality and drying kinetics of tomato slices: superposition technique. Dry. Technol. 2008; 26(6): 759-775.
42. Idah PA, Nwankwo I. Effects of Smoke-Drying Temperatures and Time on Physical and Nutritional Quality Parameters of Tilapia (*Oreochromis niloticus*). Int. J. Fish. Aquac. 2013; 5: 29-34.
43. Duan ZH, Jiang LN, Wang JL, Yu XY, Wang T. Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. Food Bioprod. Process. 2011; 89(4):472-476.
44. Murali S, Sathish Kumar K, Alfiya PV, Delfiya DA, Samuel MP. Drying kinetics and quality characteristics of Indian mackerel (*Rastrelliger kanagurta*) in solar–electrical hybrid dryer. J. Aquat. Food Prod. Technol. 2019; 28(5):541-54.
45. Abraha B, Admassu H, Mahmud A, Tsighe N, Shui XW, Fang Y. Effect of processing methods on nutritional and physico-chemical composition of fish: a review. MOJ Food Process Technol. 2018; 6(4):376-82.

.

© 2023 the authors. This work is licensed under the Creative Commons Attribution 4.0 International License