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Original Article

Functional Capability of Nigerian Stored Products Research Institute Smoking Kiln in Drying Herring Fish

Adedolapo Shotonwa [1] , Popoola ST [2] , Taiwo Oluwatoyin AJAO [3, ✉] , JO Famakinwa [3] , Oluwatosin A OJO [4] , Olayiwola A [1] , Jimoh AA [1] , Akeju BM [5] , Solomon I [2] , Dauda A. Dikko [6]

1. *Research Outreach Department, Nigerian Stored Products Research Institute, Ibadan, NGA*
2. *Perishable Crops Research Department, Nigerian Stored Products Research Institute, Ibadan, NGA*
3. *Postharvest Engineering Research Department (PHERD), Nigerian Stored Products Research Institute, Ibadan, NGA*
4. *Research Outreach/Agricultural Economist Department, Nigerian Stored Products Research Institute, Ibadan, NGA*
5. *Durable Crops Research Department, Nigerian Stored Products Research Institute, Ibadan, NGA*
6. *Department of Mathematics, University of Ibadan, Ibadan, NGA*

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Abstract

This study evaluated the functional capability of the Nigerian Stored Products Research Institute Smoking Kiln (NSPRI SK) in drying herring fish (*Clupeidae*), which are widely consumed in southwestern Nigeria. Due to the highly perishable nature of herring fish and its rich nutritional profile, high in omega-3 fatty acids, proteins, and essential vitamins, efficient preservation techniques are essential. Traditional drying methods often result in quality deterioration and prolonged drying times; therefore, there is a need to optimize modern drying technologies.

A total of 24.3 kg of herring fish was sectioned into head, middle, tail, and whole parts and subjected to drying using the NSPRI SK. The study employed mathematical modeling (Page, Logarithmic, Two-Term Exponential, and Approximation of Diffusion models) and machine learning techniques to analyze drying kinetics, with time and temperature as predictors. Moisture ratios were determined, and multiple linear regression analysis was used to assess the significance of variables on the drying rate. Data analysis was performed using Microsoft Power BI and R version 4.2.2.

The results revealed that time had a significantly greater influence rate than temperature across all fish parts ($p < 0.05$). Among the models tested, the logarithmic model best described the drying behavior of the head and whole fish sections, while the approximation of diffusion model provided the best fit for the middle and tail sections, each exhibiting the lowest RMSE values. Machine learning models explained up to 97% of drying rate variations, indicating high predictive accuracy. Proximate analysis showed that smoke drying with the NSPRI SK significantly reduced moisture content from 77.35% in fresh fish to 13.87%, crude fat was reduced from 7.00 to 2.30%, while crude protein increased from 9.00 to 15.00%, thus enhancing protein content. Microbial analysis also confirmed a reduced bacterial and mold load in NSPRI SK-treated samples compared to conventional methods.

Overall, the NSPRI SK demonstrated strong efficacy in drying herring fish while retaining nutritional quality and minimizing microbial growth. This highlights its potential, thereby positioning it as a suitable and sustainable technology for fish preservation in Nigeria. The study recommends the logarithmic and approximation of diffusion models for accurate prediction of drying kinetics in similar contexts.

Categories: Food and Pharmaceutical Engineering, Agricultural Machinery and Automation, Bioprocess Engineering

Keywords: machine learning, mathematical modeling, performance evaluation, drying kinetics, drying rate, fish

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Introduction

Drying of food is a method of food preparation and preservation which has been one of the earliest and currently accepted methods of food processing. This method is more affordable and widely used in Nigeria [1]. In detail, drying is the process of removing water or a process whereby moisture is vaporized from a material and swept away from the surface, normally by means of a carrier gas which passes through the material [2]. Drying is the most adopted unit operation for enhancing the shelf life of some perishable agro produces; however, drying is accompanied by loss of bioactive, color, texture, and sensory characteristics [3]. Moreover, this method has undergo a series of advancements over the years in drying food.

Fish is an essential source of nutrients and is a key component of the human diet; it is widely available in the market and globally consumed in many parts of the world. However, due to its high moisture content and enzymatic activity, fresh fish deteriorates rapidly after harvest. Postharvest losses in the fisheries sector in Nigeria have been estimated to range from 20% to 30%, largely due to inadequate preservation and storage technologies. Thus, these features contribute to the importance of preservation of the fish shelf life, such that it will be readily available for consumption [4].

Specifically, herring fish, which is popularly known in southwestern Nigeria as "eja shawa" is a family of Clupeidae (order Clupeiformes) of oceanic fish. A study [4] indicates that herring fish is rich in omega-3 fatty acids. Herring fish is also rich in protein, vitamin A, vitamin D and vitamin B12, thus making it a vital part of the human diet. It also contains some amount of minerals such as magnesium, potassium, phosphorous, sodium, selenium, and calcium as major composition. The essential nutritional values of herring fish are beneficial to heart health, easing arthritis, improving eye and skin appearance, and other health-related functions of the human body.

Herring fish is well known in Nigeria and mostly consumed by the populace, perhaps due to its availability and affordability in comparison to other types of fishes. As a raw fish, it is highly perishable and prone to oxidation and deterioration [4,5]. Herring fish is also high in protein, this implies that, it is ideal for microbial growth when heat and humidity cannot be controlled [6]. As a perishable product, herring fish is liable to rapid deterioration, thus processing and preservation of herring fish play a vital role in sustaining its availability and affordability in our society. Traditional fish smoking methods commonly used by local processors are often inefficient, characterized by uneven heat distribution, prolonged drying time, contamination, and inconsistent product quality. These limitations can result in reduced nutritional quality and shorter shelf life of smoked fish products. To address these challenges, the Nigerian Stored Products Research Institute (NSPRI) developed an improved smoking kiln designed to enhance drying efficiency, improve product quality, and reduce postharvest losses.

The functionality of drying minimizes the moisture content of the fish; therefore, it definitely improves the shelf-life of the fish due to the elimination of a substantial part of the initial water present, which is extensively applied in the food industry [7,8]. There are different methods of preserving fishes: freezing, addition of preservatives, frying, drying, and smoking. Drying of fishes is more affordable compared to some other methods of food preservation that require electricity for operations.

Machine learning is a subdomain of artificial intelligence that gives systems the capability to learn and improve performance without being explicitly programed. It functions by detecting various patterns from data and improving automatically. As this study aimed to explore relationships, it uses a supervised learning technique such that the algorithm is trained with both input and output features.

The ever-emerging rapid changes in global technology have become a threat to existing technologies. Therefore, existing technologies that cease to be flexible to advancement may likely become obsolete. For regular improvement in technology, it is necessary to have a consistent efficacy of the capability of NSPRI SK to understand the variation in quality of the smoked herring fish, time constraints, and other factors of drying rate.

Although the NSPRI smoking kiln has been introduced as an improved technology for fish processing, limited studies have evaluated its drying performance and functional capability for specific fish species such as herring fish (*Clupeidae*). In addition, data on the drying kinetics, modeling performance, and product quality characteristics of herring fish processed using the NSPRI smoking kiln remain scarce. Therefore, this study evaluates the functional capability of the NSPRI smoking kiln in drying herring fish by analyzing its drying kinetics, modelling the drying behavior using mathematical and machine learning approaches, and assessing the proximate and microbial quality of the dried product.

Materials And Methods

Methodology

Description of the Smoking Kiln

The smoking kiln developed by the NSPRI used in this study has a drying capacity of approximately 25 kg per batch, and it was used to dry degutted whole herring fish and some other cuts under drying conditions for the evaluation of drying kinetics.

The NSPRI smoking kiln comprises of several key components such as; drying racks and trays, a smoking chamber, a combustion chamber, and an oil collection system. The smoking chamber has a cuboid-shaped cabinet fabricated with double walls of galvanized mild steel effectively insulated with 25 mm-thick polyurethane to minimize heat loss. The cabinet has internal dimensions of approximately 550 mm × 550 × 1150 mm (length × width × height). Drying trays are rectangular, constructed from square pipes combined with expanded wire mesh, and each tray measures approximately 535 mm × 535 × 100 mm to fit comfortably within the cabinet. This design ensures uniform airflow and heat distribution across all trays during the drying process, while the durable galvanized mild steel construction provides structural stability and resistance to corrosion. It features top vents, a front-facing access door, and is mounted on metal wheels for mobility. Inside the chamber, the drying racks are affixed to the inner walls.

The trays used for drying are rectangular and made from square pipes combined with expanded wire mesh. These trays rest on the racks, allowing for easy loading and unloading of products. At the back of the smoking chamber lies the combustion chamber, also built with double metal walls and insulated with polyurethane. It includes a detachable compartment that houses both the charcoal box and ash tray.

Additionally, the design includes an oil collection unit, made from stainless steel plates and pipes. This component is positioned directly below the drying trays to collect oil released from the fish during the smoke-drying process, directing it sideways for easy collection as shown in Figure *1*.

FIGURE 1: NSPRI Smoking Kiln

NSPRI, Nigerian Stored Products Research Institute

Materials and Sample Preparation

A pack of frozen herring fish, with a total of 24.3 kg was procured for this study. The fish was degutted, cut into four sectional parts: head, middle, and tail and some left as whole fish according to [9,10]. To ensure unbiasedness, the sectional parts and whole were evenly loaded within the compartment of the NSPRI SK. Each cut had an individual initial weight, which was recorded prior to drying; these values are detailed in the Results and Discussion section due to their relevance to the drying kinetics analysis.

The sample weight was measured periodically within an hour, and changes in weight were recorded according to [10]. Temperature readings were taken using a mercury-in-glass thermometer. Since the NSPRI Smoking Kiln is charcoal-powered and does not have a thermostat, the temperature was manually adjusted as needed to maintain appropriate drying conditions. The temperature inside the kiln could be manually increased or reduced by adjusting the charcoal fire, and readings were recorded throughout the drying period to monitor temperature fluctuations.

Data Description and Transformation

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The variables under study consist of two predictors (temperature and time) and a response (rate of drying). The moisture ratio was computed for the four samples and visualized by a line graph to understand the pattern of the data. Four mathematical models that have been used by researchers in the literature [10] were used for the evaluation of the drying kinetics of the fish samples, and are listed in Table *1*. Comprehensively, the data were transformed by taking the natural logarithm of the response variable and subsequently a supervised learning technique was used to explore the effect of time and temperature on uncertainty in drying degutted herring fish. Where a and b are coefficients, n is the specific exponent of the drying equation, k is the specific coefficient of each drying equation, while t is the drying time.

Models	Equation	References
Page Model	MR = exp(kt^{n})	[11]
Logarithmic Model	MR = aexp^{-kt} + C	[12]
Two-term Exponential	MR = aexp -k_0t + bexp(-k_1t)	[13]
Approximation of Diffusion	MR = aexp -kt + (1-a)exp(-kt)	[14]

TABLE 1: Table of Models

Where MR is Moisture Ratio, t is drying time, and a, k, c, n are drying constants.

Mathematical Modeling

Mathematical model is an equation that expresses the essential features of a physical system or process in mathematical terms [15].

$$MoistureRatio, MR = \frac{M_t - M_e}{M_o - M_e}(1)$$

Mt, is the moisture content at time t, Me is the equilibrium moisture content, and Mo is the initial moisture content (kg water/kg, dry matter).

Specifically, four mathematical models were used to examine the drying kinetics of the degutted herring fish.

Mathematical Model Prediction Criterion

The Root Mean Square Error (RMSE) is a statistical metric used to determine the average distance between the model's predicted values from the actual values in the dataset (equation 2) [16,17]. Whereby, the lower value of the RMSE indicates a better model [18,19]. Therefore, the optimum model will be determined with the consideration of model with the minimum value.

$$RMSE = \sqrt{MSE} = sqrt\frac{1}{n}\sum(y - \dot{y})^2(2)$$

$\dot{y}$: Observed moisture ratio, n: sample size, $\hat{\dot{y}}$: Predicted moisture ratio, MSE: Mean Square Error

Mathematical Theory of Multiple Linear Regression Model

A regression model is a mathematical tool used to represent the relationship between two or more variables [20]. In this research, the focus is on modeling how the drying rate is influenced by two key drying parameters: time and temperature, as expressed in Equation 3:

$$y' = \alpha + \beta_{time} + \varepsilon_i \, (3)$$

The least squares method is used in finding the estimated drying coefficients $\alpha,_{\beta_{Time}}, and\beta_{Temp}$ so as to minimize the sum of squares $\sum \left(y - \hat{y}\right)^2$.

Where $\hat{y}$ is the estimated value of drying rate, which is the value of the intercept, ε_i error term is error term, $\beta_{Time} and \beta_{Temp}$ represent the estimated values of the drying coefficients. A residual error, also referred to as term error is the difference between the experimental moisture ratio and the predicted moisture ratio as shown in Equation 4.

$$\varepsilon = y_i - \hat{y}_i \, (4)$$

Goodness of Fit of the Model

The goodness of fit of a model is usually made up of equations which supplies data on variability level in a regression model and thus produce a basis for tests of significance. Generally, to show that the total variation of the response variable Y can be decomposed into two parts is simple, this includes: the residual variation of Y ; error sum of squares (SSE) and the explained variation of Y; regression sum of squares (SSR) and total sum of squares (SST) as shown in Equation 5-7. The overall regression is not significant such that the variables cannot explain the response variable in a satisfactory way, which is an hypothesis [20].

The significance of this equations is to quantify the presence of variability in the regression model and to help act as a foundation for performing significance tests. Furthermore, the sum of variation in the response variable Y can be categorized into two components which include: the residual variation ((Error sum of squares (SSE)), and the explained variation, known as the regression sum of squares (SSR) and the total sum of squares (SST), as shown in Equations 5 to 7.

Furthermore, the associated hypothesis test evaluates if the regression model is statistically significant, specifically, whether the explanatory variables meaningfully account for the variability in the response variable according to [20].

$$SST = S_{yy} = \sum_{i=1}^{n} y - ny^2 \, (5)$$

$$SSR = \beta_{Time} S_{xy} + \beta_{Temp} S_{zy} \, (6)$$

$$SSE = SST - SSR \, (7)$$

Finally, F-statistic: it is the statistic computed by dividing MSR by MSE (Equation 8)

$$F = \frac{MSR}{MSE} (8)$$

Each sum of squares can be divided by an appropriate constant (degrees of freedom) to derive the mean sum of squares.

Adjusted R-Square

Including too many variables in a regression model can sometimes produce misleading outcomes and hinder the accurate estimation of the slopes for key predictors. To address this issue and discourage the inclusion of unnecessary variables, the adjusted R^2 statistic is employed, as suggested by [21]. This measure accounts for the number of explanatory variables in the model and is calculated using Equation (9).

Sometimes, introducing extra variables can lead to spurious results and can interfere with the proper estimation of slopes for the important variables. Therefore, in order to penalize an excess of variables, adjusted R^2 was considered according to [21], which is computed as presented in Equation (9):

$$r^2 = \frac{\frac{SSR}{T}}{\frac{SST}{n-1}} (9)$$

Correlation Test

Correlation coefficient is a magnitude, which shows degree of linear association between two variables. It is denoted and defined [22] as presented in Equations 10-13.

$$r_{xy} = \frac{n\sum XY - \sum X \sum Y}{\sqrt{\left[n\sum Y^2 - \left[\left(\sum Y\right)^2\right] - n\sum X^2 - \left(\sum X\right)^2\right]}} (10)$$

$$r_{zy} = \frac{n\sum ZY - \sum Z \sum Y}{\sqrt{\left[n\sum Y^2 - \left[\left(\sum Y\right)^2\right] - n\sum Z^2 - \left(\sum Z\right)^2\right]}} (11)$$

$$r_{xz} = \frac{n\sum XZ - \sum X \sum Z}{\sqrt{\left[n\sum Y^2 - \left[\left(\sum Z\right)^2\right] - n\sum X^2 - \left(\sum X\right)^2\right]}} (12)$$

$$R^{y,xz} = \sqrt{\frac{r^2xy + r^2zy - 2r_{xy}r_{zy}r_{xz}}{1 - r^2xz}} (13)$$

Where $R^{y,xz}$ denotes the multiple correlation coefficient. Also, $r_{xy}, r_{zy}, and r_{xz}$ are the correlation coefficients between random variable x and y, x and z, x and z, respectively. Adjusted R-Squared and RMSE are the two metrics used to evaluate the performance of this predictive model.

Data Analysis Execution

For ease of computation, Microsoft Excel 2013 was used during data preparation. Thus, Microsoft Power BI Desktop was used to obtain the drying curves, while R 4.2.2 software was used for the execution of the machine learning and mathematical modeling.

In addition, a regression-based machine learning approach was employed to model and predict the relationship between drying parameters (time and temperature) and the drying rate of degutted whole herring fish. The model was trained using the experimental dataset, and its performance was evaluated using statistical indicators such as the residual standard error (RSE), coefficient of determination (R^2), adjusted R^2, correlation coefficient (r), and F-statistic to assess the predictive accuracy and reliability of the model.

Proximate Analysis

Determination of ash content: Ash content was determined following the procedure outlined by [23] as shown in Equation 14. A specific weight of finely ground sample was placed into a clean, dry crucible with a lid that had been previously weighed (W_1). The lid was removed, and the sample was initially heated over a gentle flame to char the organic material.

Subsequently, the crucible was transferred to a muffle furnace and incinerated at 600 °C for six hours, until complete ashing occurred. After ashing, the crucible was moved directly into a desiccator to cool, and then weighed promptly (W_2).

$$\text{Ash}(\%) = \frac{W_2 - W_1}{\text{Weight of Sample}} \times 100 \, (14)$$

Determination of crude fat: The determination of crude fat content was carried out using the Soxhlet extraction technique as outlined in [23] as shown in Equation 15. A measured quantity of the sample was placed in a pre-weighed filter paper, folded carefully, and then inserted into a pre-weighed thimble (W_1). The thimble containing the sample (W_2) was positioned within the Soxhlet extractor, and the fat extraction was performed under reflux using n-hexane, which has a boiling range of 40 °C to 60 °C, over a period of 6 hours.

After the extraction process, the thimble was dried in an oven at 100 °C for approximately 30 minutes to remove any remaining solvent. It was then allowed to cool in a desiccator before being reweighed (W_3). The crude fat content extracted from the sample was then calculated using the weight differences.

$$Fat\,(w/w) = \frac{(Lossinweightofsample\,(W_2 - W_3))}{(Originalweightofsample\,(W_2 - W_1))}(15)$$

Crude protein determination: Crude protein content was analyzed using the micro-Kjeldahl method, following the procedure outlined in [23] using Equation 16. Approximately 2 grams of the sample were weighed and transferred into a Kjeldahl flask with a long neck. A catalyst tablet was added, along with 25 cm^3 of concentrated sulfuric acid (H_2SO_4). The mixture was gently swirled, then secured in an inclined position and heated electrically within a fume hood until a clear solution was obtained.

After digestion, the solution was allowed to cool and then transferred into a 100 cm^3 volumetric flask, which was subsequently filled to the mark with distilled water. From this diluted digest, 10 mL was introduced into the distillation apparatus through a funnel. At the receiving end, 5 cm^3 of boric acid was pipetted into a 100 cm^3 conical flask, ensuring the delivery tube was fully immersed in the acid solution.

To initiate the release of ammonia under alkaline conditions, 40% sodium hydroxide (NaOH) was added to the digest. Prior to this, two drops of methyl orange were added to indicate the pH change. Once the mixture turned alkaline, the color shifted from red to yellow, confirming excess NaOH. Steam was then introduced via a steam chest to facilitate distillation.

The ammonia released during the process was captured in the boric acid solution, and about 50 cm^3 of the resulting solution was collected. Finally, this solution was titrated with 0.1 M hydrochloric acid (HCl) until a permanent color change signaled the endpoint.

$$\%N = \frac{(\text{Molarity of HCl} \times \text{Sample titre} - \text{Blank titre})}{\text{Weight of sample used} \times 100} \times 0.014 \times DF(16)$$

% N will be converted to the percentage crude protein by multiplying by 6.25.

Where DF is dilution factor, % N is percentage nitrogen, 6.25 is the nitrogen: protein conversion factor.

Crude fiber: The addition of two hundred (200 mL) of freshly prepared 1.25 % (1 M) H_2SO_4 to a known weight of the residue obtained from the extraction of fat was carried out; afterwards, this was brought to a quick boil. Thereafter, boiling continued for 30 minutes. The mixture was then filtered, and washing of the residue was performed until it became free from acid. The residue was quantitatively transferred into a digestion flask. The addition of 1.25 % (0.1 M) NaOH was carried out and the solution was brought to boiling as soon as possible. Boiling continued for 30 minutes. The mixture was filtered, and the residue was washed to be free of alkali. Washing of the residue was done with methylated spirit three times by the application of petroleum ether in small quantities. Proper draining was ensured, and the residue was then transferred into a silica dish (previously ignited at 600 °C and cooled). Constant weight of the dish and its contents was achieved by drying at 105 °C. The organic matter of the residue was burnt by igniting for 30 minutes in a muffle furnace at 600 °C. The residue was then cooled and weighed. The difference in weight of the sample before and after ignition was reported, according to [23].

Treatment was carried out with 200 mL of freshly prepared 1.25 % (1 M) sulfuric acid (H_2SO_4) on a known amount of residue remaining after the fat extraction, and thus brought to a rapid boil. This boiling process was carried out for 30 minutes. Afterwards, the mixture was filtered, and thorough washing of the residue was done until all traces of acid had been removed.

The residue was then quantitatively transferred into a digestion flask, where 1.25 % (0.1 M) sodium hydroxide (NaOH) was added, and the solution quickly heated to boiling. Thereafter, boiling continued for another 30 minutes prior to filtering and washing of the residue to ensure it was free from alkali.

Subsequently, methylated spirit was used to rinse the residue three times with small amounts of petroleum ether to ensure thorough cleaning. After allowing it to drain properly, the residue was then transferred into a silica dish, which had been previously ignited at 600 °C and cooled.

The silica dish and its contents were dried at 105 °C until a constant weight was achieved. In order to remove the organic matter, the residue was incinerated in a muffle furnace at 600 °C for 30 minutes. After cooling, the residue was weighed to determine the difference in weight before and after ignition, and results were recorded accordingly as described by [23].

Estimation of carbohydrate: The carbohydrate content of the Herring fish was determined by method of difference. $\mathbf{\%CHO = 100 - (moisture + ash + fat + protein + crude\ fibre)\ (17)}$

Total viable count: In order to determine the total viable/heterotrophic count, a six-fold (10^{-1} to 10^{-6}) serial dilution was then set up. One gram of sample of Herring fish was moved into a sterile test tube that contained 9 ml of distilled water. Thereafter, it was serially diluted until it reached the dilution factor 10^{-6}. One milliliter of the diluent from dilution factor 10^{-3} and 10^{-6} was afterwards inoculated into a plate of nutrient agar 29 g) that had been prepared by pour plate method and incubated at 37 °C for about 48 hours. Then, pure cultures of the isolate were obtained by sub-culturing on the surface of the freshly prepared nutrient agar plates. Afterwards, counting of the colonies was carried out by the use of colony counter, and the isolates were gram-stained for identification of each bacteria and fungi species according to [24].

Results

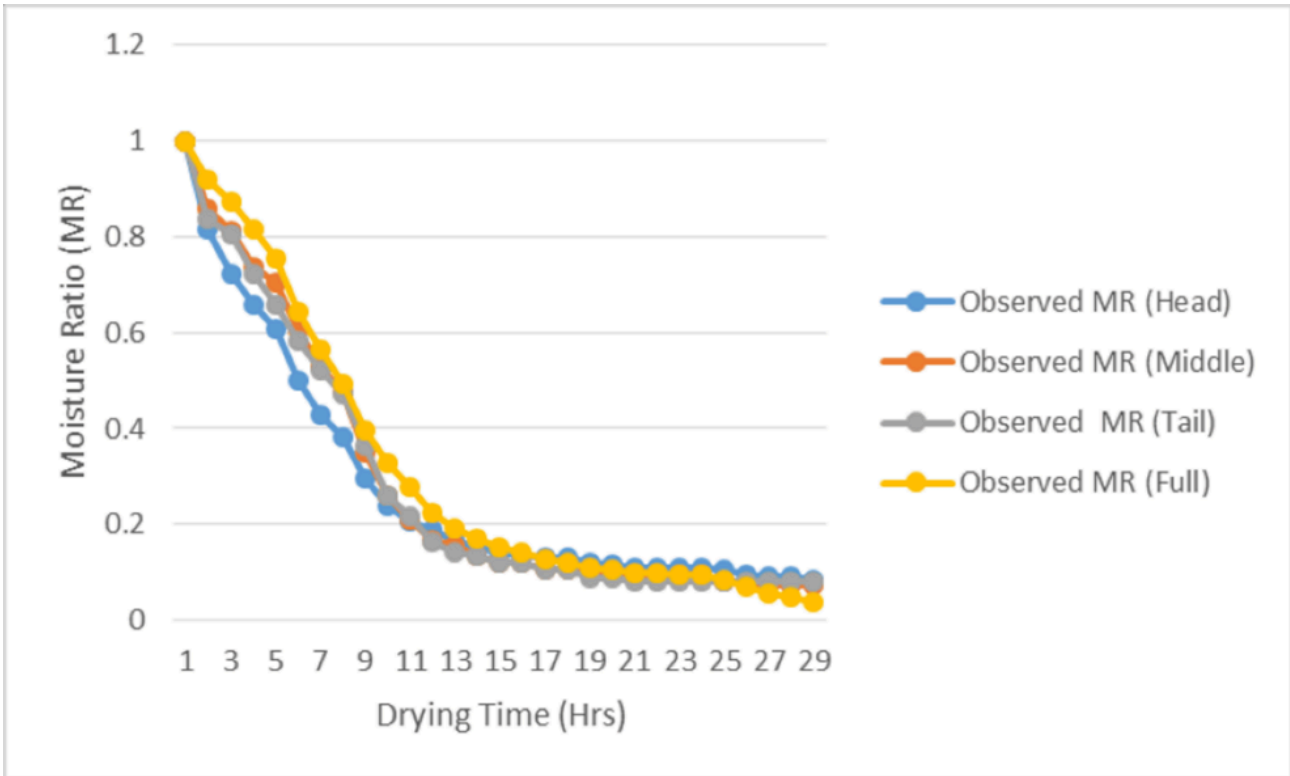

FIGURE 2: Drying Curves of the Observed Moisture Ratio for Degutted Herring Fish

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.64823	0.03862	-42.674	< 2e-16 ***
Time	-0.92220	0.05575	-16.542	9.73e-13 ***
Temp	0.06059	0.05575	1.087	0.291

TABLE 2: Regression Analysis in Machine Learning Showing the Effect of Time and Temperature on Drying Rate of Degutted Herring Fish (Whole)

Model (Control)	Parameters	t-values	P-values	RMSE
Page	K = 0.15973 n = 0.9614	15.79 33.41	3.68e-15 *** < 2e-16 ***	0.02606
Logarithmic	k = 0.171428 a = 0.977090 b = 0.044931	31.732 87.449 6.062	< 2e-16 < 2e-16 2.1e-06	0.01826
Two-Term Exponential	k = 0.1523696 a = 0.9990061	60.97 5048.77	<2e-16 <2e-16	0.01994
Approximation of Diffusion	k =.158192 a = 0.989167 b = -0.353523	23.882 59.997 -0.859	<2e-16 <2e-16 0.398	0.01899

TABLE 3: Modeling of the Drying Processing Herring Fish (Degutted Whole) Using NSPRI Smoking Kiln

NSPRI, Nigerian Stored Products Research Institute; RMSE, Root Mean Square Error

Coefficient	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.62711	0.05274	-30.853	< 2e-16 ***
Time	-0.61612	0.07612	-8.094	1.41e-07 ***
Temp	0.16814	0.07612	2.209	0.0397 *

TABLE 4: Regression Analysis in Machine Learning Showing the Effect of Time and Temperature on Drying Rate of Degutted Herring Fish (Head)

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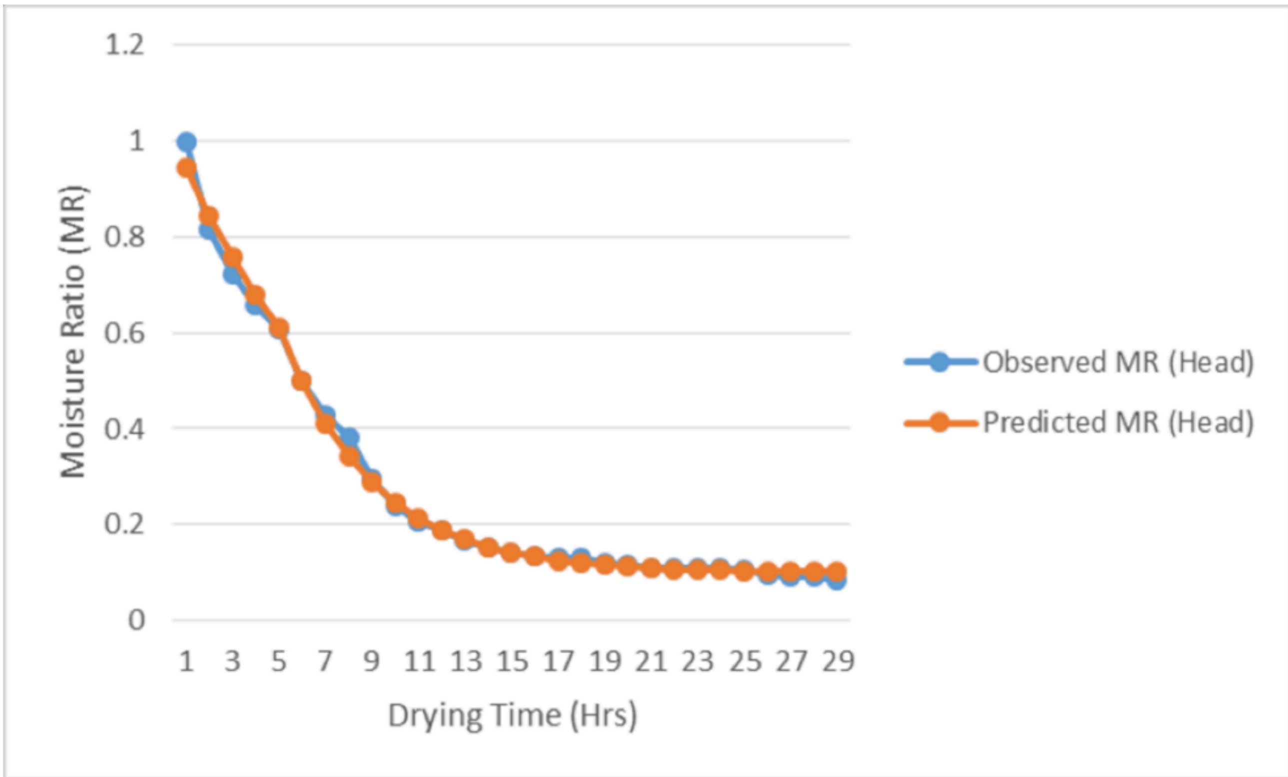

FIGURE 3: Comparison of Experimental Values and Logarithmic Model Predicted Values for the Head Part

Model (Control)	Parameters	t-values	P-values	RMSE
Page	K = 0.34671 n = 0.66212	20.89 29.93	<2e-16 < 2e-16	0.0279
Logarithmic	k = 0.249019 a = 0.844254 c = 0.099552	29.11 69.80 18.43	< 2e-16 < 2e-16 <2e-16	0.01811
Two-Term Exponential	k = 0.1965792 a = 0.9991317	23.67 4477.10	<2e-16 <2e-16	0.05038
Approximation of Diffusion	k = 0.32994 a = 0.78441 b = 0.11094	13.501 18.487 4.212	2.95e-13 <2e-16 0.000268	0.02116

TABLE 5: Modeling the Drying Process of Herring Fish Using NSPRI Smoking Kiln (Degutted Head)

NSPRI, Nigerian Stored Products Research Institute; RMSE, Root Mean Square Error

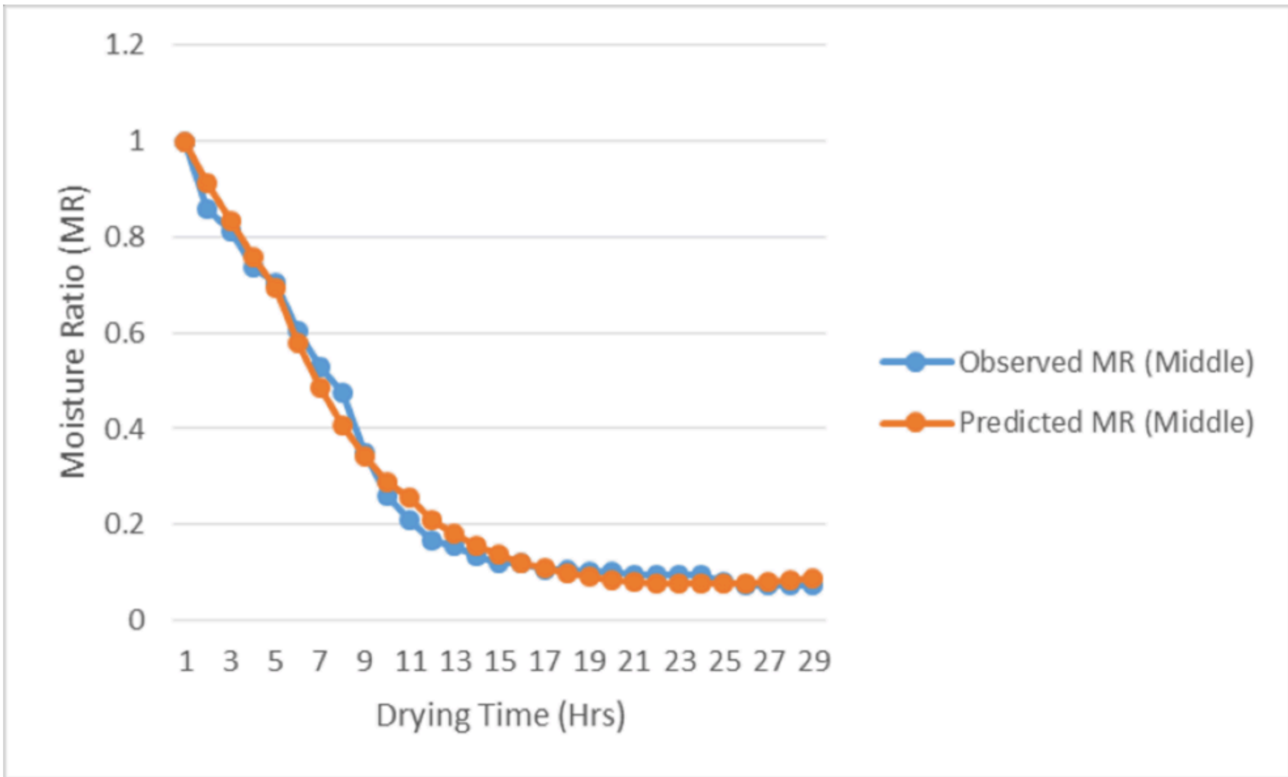

FIGURE 4: Comparison of Experimental Values and Approximation of Diffusion Model Predicted Values of Degutted Herring Fish (Middle Part)

Coefficient	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	-1.63719	0.05976	-27.396	< 2e-16 ***
Time	-0.63054	0.08531	-7.391	5.32e-07 ***
Temp	0.14648	0.08531	1.717	0.102

TABLE 6: Regression Analysis in Machine Learning Showing the Effect of Time and Temperature on Drying Rate of Degutted Middle Part of Herring Fish

Model (Control)	Parameters	t-values	P-values	RMSE
Page	K = 0.21619 n = 0.86856	12.23 22.63	1.61e-12 < 2e-16	0.03798
Logarithmic	k = 0.199891 a = 0.931199 c = 0.060706	20.473 53.002 6.196	<2e-16 < 2e-16 1.49e-06	0.02793
Two-Term Exponential	k = 0.1756184 a = 0.9990016	41.91 5761.77	<2e-16 <2e-16	0.02893
Approximation of Diffusion	k = 0.187532 a = 0.984557 b = -0.334250	20.202 60.642 -1.312	<2e-16 <2e-16 0.201	0.02654

TABLE 7: Modeling of the Drying Rate of Herring Fish Using NSPRI Smoking Kiln (Degutted Middle Part)

NSPRI, Nigerian Stored Products Research Institute; RMSE, Root Mean Square Error

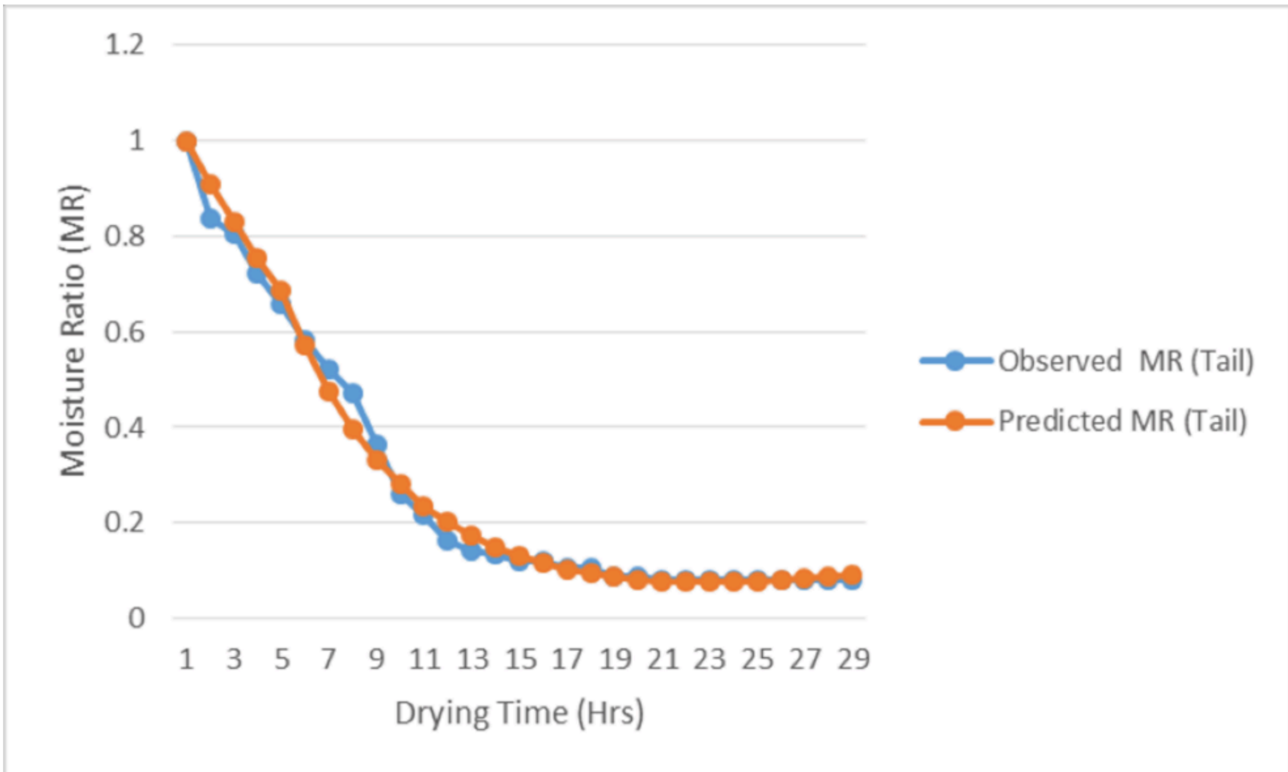

FIGURE 5: Comparison of Experimental Values and Predicted Values Otained from Approximation of Diffusion Model (Tail Part)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.73121	0.06177	-28.027	2.66e-16 ***
Time	-0.68494	0.08606	-7.959	2.64e-07 ***
Temp	0.25576	0.08606	2.972	0.00817 **

TABLE 8: Regression Analysis in Machine Learning Showing the Effect of Time and Temperature on Drying Rate of Degutted Tail Part of Herring Fish

Model (Control)	Parameter	t-values	P-values	RMSE
Page	K = 0.23464 n = 0.83791	12.97 23.08	4.11e-13 < 2e-16	0.03715
Logarithmic	k = 0.200752 a = 0.914735 c = 0.059830	19.680 50.865 5.994	<2e-16 < 2e-16 2.5e-06	0.02856
Two-Term Exponential	k = 0.1802200 a = 0.9990507	40.52 6085.61	<2e-16 <2e-16	0.0298
Approximation of Diffusion	k = 0.191483 a = 0.986946 b = -0.373625	20.676 70.930 -1.469	<2e-16 <2e-16 0.154	0.028

TABLE 9: Modeling of the Drying Process of Herring Fish using NSPRI Smoking Kiln (Degutted Tail-Part)

NSPRI, Nigerian Stored Products Research Institute; RMSE, Root Mean Square Error

	Moisture	Ash	Crude Fat	Crude Protein %	Crude Fiber	Carbohydrate
Fresh Fish	77.35 ± 0.50^{d}	$1.90 \pm 0.16^{a,b}$	7.00 ± 0.29^{b}	9.00 ± 0.58^{a}	0.09 ± 0.01^{a}	4.65 ± 0.91^{a}
Half-Smoked Fish	21.80 ± 0.76^{b}	2.77 ± 0.43^{b}	37.30 ± 1.35^{c}	14.37 ± 0.32^{b}	0.99 ± 0.01^{c}	22.78 ± 1.54^{b}
Smoked Fish	13.87 ± 3.26^{a}	2.53 ± 0.43^{b}	2.30 ± 0.12^{a}	15.00 ± 1.00^{b}	0.50 ± 0.12^{b}	65.83 ± 4.33^{c}
Conventional Smoked Fish	34.83 ± 1.99^{c}	1.40 ± 0.17^{a}	40.40 ± 0.23^{d}	7.00 ± 1.16^{a}	0.99 ± 0.01^{c}	15.17 ± 0.72^{b}

TABLE 10: Result of Proximate Analysis of Herring Fish

	After 24 Hours		After 48 Hours	
	10^{-3} (cfu/ml)	10^{-6} (cfu/ml)	10^{-3} (cfu/ml)	10^{-6} (cfu/ml)
Fresh Fish	2.0×10^{-3}	-	5.0×10^{-4}	-
Half-Smoked Fish	-	-	1.0×10^{-3}	-
Smoked Fish	$1.0 \times 10^{-}$	-	1.0×10^{-3}	-
Conventional Half-Smoked Fish	TNTC	TNTC	TNTC	TNTC

TABLE 11: Result of Bacterial Count

TNTC, Too Numerous To Count

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	After 24 Hours		After 48 Hours		After 72 Hours	
	10^{-3} (cfu/ml)	10^{-6} (cfu/ml)	10^{-3} (cfu/ml)	10^{-6} (cfu/ml)	10^{-3} (cfu/ml)	10^{-6} (cfu/ml)
Fresh Fish	-	-	-	-	TNTC	-
Half-Smoked Fish	-	-	-	-	5.0×10^{-4}	5.0×10^{-4}
Smoked Fish	-	-	1.0×10^{-3}	-	-	-
Conventional Half-Smoked Fish	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC

TABLE 12: Result of Mould Load

TNTC, Too Numerous To Count

Discussion

Functional capability of NSPRI smoking kiln and drying kinetics of herring fish

Basically, four models (Page, Logarithmic, Two-Term Exponential, and Approximation of Diffusion Models) were considered for the analysis while the optimum model was used for prediction of drying rate of the herring fish. The study considered degutted drying parts as head, middle, and tail with an average initial weight of 87.00, 99.00, and 93.00 g, respectively. While the fourth sample consisted of full whole degutted fish of an average weight of 259.50 g.

Modeling the Drying Curve and Drying Rate of the Degutted Herring Fish (Full)

Explicitly, Figure *2* shows the pattern of the obtained experimental data of samples (moisture ratio plotted against drying time). It was observed that each sectional sample followed a similar curve shape, which is non-linear in nature but can be effectively modeled exponentially. The drying curve of the observed moisture ratio for degutted herring fish exhibited the typical downward trend with drying time according to [25], indicating a continuous reduction in moisture content. A rapid decline in moisture ratio was observed at the initial stages of drying, followed by a slower rate of moisture removal as drying progressed. The shape of the drying curve suggests that moisture migration was initially dominated by surface evaporation, with internal diffusion becoming the control mechanism at later stages, and this is in alignment with reports from [25,26].

Table *2* presents the regression analysis generated using a regression-based machine learning model to evaluate the influence of drying time and temperature on the drying rate of degutted whole herring fish in the NSPRI smoking kiln. The model was applied to analyze and predict the relationship between the drying parameters and the drying rate.

The results show a joint significant effect of time and temperature on drying rate (F-cal = 298.5, P-value = 4.44×10^{-15}). However, the individual contribution of temperature to the drying rate was not statistically significant (t-value = 1.087, P-value = 0.291). In contrast, drying time showed a highly significant contribution to the model (t-value = -9.2220, P-value = 9.73×10^{-13}), indicating that time had a stronger influence on the drying process during the experimental period according to [26].

The regression model produced a RSE of 0.1812, indicating a relatively small deviation between the observed and predicted values. The Multiple R^2 value of 0.9692 shows that about 96.92% of the variability in drying rate is explained by the predictors, while the Adjusted R^2 value of 0.9659 confirms the strong explanatory power of the model after accounting for model complexity. Furthermore, the F-statistic (298.5; df = 2, 19; P-value = 4.44×10^{-15}) indicates that the overall regression model is highly significant.

The correlation coefficient between observed and predicted values (r = 0.9744) and the test R^2 value of 0.9494 further demonstrate the robustness and predictive reliability of the machine learning model.

The high coefficient of determination (R^2 = 0.9692) and correlation coefficient (r = 0.9744) obtained from the regression-based machine learning model demonstrate its strong predictive capability for estimating drying rate from drying time and temperature. This suggests that the machine learning approach can serve as a reliable tool for modeling and predicting the drying behavior of fish in the NSPRI smoking kiln.

Concisely, the rate of distribution of temperature in the compartment was not steady and evenly distributed across all sections simultaneously. Therefore, there is a need for modification because of the distribution of temperature across all parts of the drying chamber affect the capability of the NSPRI SK Model B in minimizing the time used in drying the herring fish, this necessitated the modification of the rotary smoking kiln according to [27]. The trained model further explained about 97.0% of the variation in the drying rate of the degutted herring fish. Notably, some factors for effective drying of fish are temperature, time, drying environment, and the butchering method used [28]. This implies that the unexplained 3.00% variation may be due to some of these factors not included in this study.

Furthermore, the training set and test set had a correlation of about 0.9845 and 0.9744, respectively, thus showing a strong direct relationship between the observed factors and the drying rate obtained in the experiment. Furthermore, the ability of the test set to explain about 95.0% of the variation in the drying rate of the herring fish using NSPRI SK justifies the level of accuracy obtained by applying machine learning. Similar results were achieved by [29].

Mainly, the four drying kinetics models were compared based on their respective RMSE, with the purpose of identifying an optimum model for the prediction of the drying rate of the herring fish using NSPRI SK. Table *3* shows the result of the modelling of the drying processing of Herring Fish (Degutted Whole) using NSPRI Smoking Kiln, it can be observed from the study that, the logarithmic model had the lowest RMSE value of 0.01826. The RMSE indicates the absolute fit of the model to the data points. It clearly shows the closeness of the observed data points to the predicted values. Thus, this implies that the lowest value (0.01826) of the RMSE in the logarithmic model indicated a good measure of how accurately the model predicted the drying rate of the degutted fish compared to its counterpart models. Similar results were obtained by [30,31].

Figure *2* shows the drying curves of degutted herring fish and the corresponding logarithmic model predictions. The close alignment between the experimental and predicted values demonstrates that the logarithmic model accurately describes the drying behavior. Physically, the model reflects the drying process where moisture is removed rapidly at the beginning (high surface moisture) and gradually slows as the fish approaches equilibrium moisture content, consistent with the typical falling rate period observed in food drying. This also indicates that drying time is the dominant factor influencing moisture loss, while temperature within the studied range has a smaller effect, supporting the regression and machine learning analysis presented in Table *2*.

Modeling the Drying Rate of the Degutted Head Part

The Regression Analysis in Machine Learning indicating the influence of drying time and temperature on drying rate of degutted Herring Fish (Head cut) is shown in Table *4*. Also, Figure *3* illustrates the Comparison of Experimental values and Logarithmic Model Predicted values for the Head part. It can be observed from the supervised learning that, a significant model (F-statistic: 95.06 on 2 and 19 DF, P-value: 1.271-10) was obtained and the two factors (Time; P-value = 1.41-7 and Temperature; P-value = 0.0397) understudied significantly contributed to the model capability in predicting the drying rate of the degutted head part of the herring fish using NSPRI SK. Furthermore, the ability of the test set to have a closely explained variation and correlation coefficient (Train set r = 0.856 and Test set r = 0.815) compared to the training set which made it plausible in predicting the outcome of NSPRI SK with more accuracy. The training model explained about 89.96% of the variation in the drying capability of NSPRI SK. The predictors jointly contributed meaningfully to explaining the variance in the response variable.

Pointedly, the four models were compared basically on their respective RMSE, with the purpose of identifying an optimum model for the prediction of the drying rate of the herring fish using NSPRI SK. It can be observed from the study that, the logarithmic model had the lowest RMSE value of 0.01811. The RMSE indicates the absolute fit of the model to the data point. It pointedly shows the closeness of the observed data points to the predicted values. Thus, this implies that the lowest value (0.01811) of the RMSE in logarithmic model indicated a good measure of how accurately the model predicted the drying rate of the degutted head compared to its counterpart models and this is in alignment with results obtained by [32] as shown in Figure *3* and Table *5*, respectively.

Modeling the Drying Rate of the Degutted Middle Part of Herring Fish

Exploring machine learning in explaining the variation in the capability of NSPRI SK in drying degutted middle part of the herring fish, the trained model was found to be significant in establishing the joint effect of time and temperature in drying (F-Stats = 73.21, P-value = 1.179-9). The model also explained about 87.31% variation in drying rate of degutted middle part of herring fish of an average initial weight of 99.0 g. Contrarily, it can be observed that, the individual contribution of temperature was not significant (Temp; P-value = 0.102). Expressly, this implies that temperature was not evenly and steadily distributed across the compartment simultaneously. Thus, the insignificant contribution of temperature in this model further reveals the cause of longer periods of drying time observed at the upper part of the kiln compared to the compartment closer to the combustion chamber during the usage of NSPRI SK.

Table *6* presents regression analysis evaluating the effects of drying time and drying temperature on the drying rate of degutted herring fish (middle part) using a machine-based learning approach. The model yielded a RSE of 0.2803, suggesting a low average deviation between observed and predicted drying rates. More importantly, the trained and test sets were found to have a high correlation coefficient of 0.9408 and 0.9600, respectively. An F-Statistic value of 73.21 with a corresponding p-value of 1.179×10^{-9} indicates that the regression model is highly significant, implying that drying time and temperature have a statistically meaningful joint effect on the drying rate. This is in accordance with similar results obtained by [32-34]. The trained set model explained about 88.51% variation and the test set model also explained about 92.17% variation. Thus, this implies that the test set was found to have a higher accuracy in explaining and predicting the capability of NSPRI SK in drying degutted middle part of the herring fish.

Among the four models under consideration, it can be seen from the result in Table *7*, and Figure *4*, the approximation of diffusion model had the lowest RMSE value of 0.01811. Thus indicating that, in comparison to the counterpart models, the approximation of diffusion model more subtly explained and predicted the capability of NSPRI SK in drying degutted middle part of herring fish. Additionally, Figure *4* visually represented the closeness of the predicted values obtained from approximation of diffusion model compared to the observed data.

Modeling the Drying Rate of the Degutted Tail Part of Herring Fish

Furthermore, in Table *8* and Figure *5*, the application of machine learning in explaining the variation in the capability of NSPRI SK during the drying of the degutted tail part showed a joint significant effect of the two factors (F-cal = 96.34, P-value = 2.426-10) on the drying rate. The model further explained about 91.0% variation in the drying rate of the degutted tail part.

More importantly, the training set and test set had a correlation of about 0.9563 and 0.9367 respectively showing a strong direct relationship between the two observed factor and the drying rate obtained. Lastly, the trained set explained about 91.5% variation in the drying rate using NSPRI SK. This indicates excellent agreement between observed and predicted values. Similarly, as the test set also explained an about 87.7% variation in its drying rate, this shows prediction to be more precise, which is in alignment with results obtained by [35].

From Table *9*, it can be observed that, the approximation of diffusion model had the lowest RMSE of 0.02800, thus indicating it as the most precise model that fit the data set more accurately among its counterpart models (page, logarithmic and two-term exponential models). This implies that the output of approximation of diffusion model had the minimum average distance between the predicted values and the actual values obtained in the dataset.

Drying of all Fish samples took place at the falling rate period, which is in accordance with results from [33-35].

The results of this study have practical implications for the drying of all fish cuts in the NSPRI smoking kiln. Specifically, the findings provide guidance on optimizing drying time, predicting moisture loss using the machine learning model, and ensuring uniform quality across different fish cuts, which can improve operational efficiency and reduce spoilage.

Result of Proximate Analysis of Herring Fish

The proximate composition of fresh, half-smoked, smoked, and conventionally smoked fish samples as shown in Table *10* indicates significant variation due to the effects of smoking and drying. The results showed a lower moisture content in the half-dried fish compared to the conventional half-dried fish, which is similar to the work reported by [33]. The decline in the fat content of the dried fish can also be seen as a factor that prevented microbial growth, which is similar to the work reported by [34], where decline in fat content prevents deterioration and microbial growth in Longneck croaker fish (*Pseudotolithus typus*).

Moisture content ranged from 77.35% in fresh fish to as low as 13.87% in smoked fish. This reduction is expected and desirable, as it enhances shelf life by inhibiting microbial growth. Values below 25% are generally acceptable for preserved fish products [36], thus the smoked and half-smoked samples are within acceptable range.

Ash content (1.40-2.77%) reflects the mineral content and is comparable with values reported by [37], who stated that fish ash content typically falls between 1% and 3%. All samples fall within this range.

Crude fat content varied widely. The conventional smoked (40.40%) and half-smoked (37.30%) fish had significantly higher fat content than the fresh (7.00%) and smoked fish (2.30%). While fat concentrations may increase due to water loss, excessively high fat may raise concerns for lipid oxidation and rancidity during storage. Nonetheless, the values are within acceptable nutritional limits and suggest good energy density [38].

Crude protein increased in smoked (15.00%) and half-smoked fish (14.37%) compared to fresh fish (9.00%), due to moisture loss. These values meet the FAO/WHO recommendation that fish protein content should range from 10% to 20%, indicating high nutritional quality [36].

Crude fiber remained low across all samples (0.09-0.99%), which is expected because fish are not a significant source of dietary fiber. These values are consistent with previous reports and are considered nutritionally negligible [39]. The low fiber content indicates that the drying process did not introduce any significant changes to the composition and confirms that protein and fat remain the dominant macronutrients in all fish cuts studied.

Carbohydrate content increased notably in smoked fish (65.83%), likely due to relative concentration effects. Although fish are not a primary source of carbohydrates, these values are not unusual when expressed on a dry weight basis [40,41]. All the values remain within a tolerable nutritional range.

All proximate values recorded are within acceptable nutritional ranges. Smoking improved the protein and reduced the moisture content, enhancing the nutritional value and shelf life of the fish. The fat and carbohydrate values varied, but none exceeded reported safe or functional limits. Thus, all processed fish types evaluated are suitable for human consumption and provide significant nutritional benefits.

Result of Bacteria count of Fish Samples After 24 and 48 Hours

The microbial count (Bacteria count) of the fish samples varied with the processing method and duration of storage as shown in the results in Table *11*.

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Fresh Fish showed a significant increase in microbial load, from 2.0×10^3 cfu/ml at 24 hours to 5.0×10^4 cfu/ml at 48 hours. This rapid growth is typical of fresh fish due to its high moisture content. The count at 48 hours exceeds the acceptable limit of 10^5 cfu/g for ready-to-eat fish products according to [42,43], which indicates the onset of spoilage.

Half-smoked fish had no detectable growth at 24 hours but developed a count of 1.0×10^3 cfu/ml at 48 hours. This value remains well within permissible limits and suggests that partial smoking delayed microbial growth, though not indefinitely according to [44].

Smoked fish had the lowest microbial load, with 1.0×10^1 cfu/ml at 24 hours and 1.0×10^3 cfu/ml at 48 hours. These counts are far below the critical threshold and indicate effective microbial control, primarily due to reduced water activity from thorough drying according to [45].

Conventional smoked fish showed Too Numerous To Count (TNTC) across all dilutions and time intervals, suggesting extremely high microbial contamination. This is far beyond permissible levels and poses a microbiological safety risk, which could likely be due to inadequate smoking, contamination, or poor handling practices according to [45].

According to the International Commission on Microbiological Specifications for Foods (ICMSF) and the FAO Codex Alimentarius, total viable counts in processed fish products should ideally be $\leq 10^5$ cfu/g. However, exceeding this limit indicates spoilage and potential health risks. Hence, the smoked fish using NSPRI smoking kiln is microbiologically safe and within permissible limits. The half-smoked fish is acceptable up to 48 hours post-processing. The fresh fish and conventional smoked fish exceeded safe microbial limits after 48 hours and may be considered unfit for consumption if they are not further processed or preserved.

Result of Mould Count of Fish Samples After 24 and 48 Hours

The result of Mould count of Fish Samples After 24 and 48 Hours is shown in Table *12*. Fresh Fish indicated no detectable microbial growth up to 48 hours; however, by 72 hours, microbial colonies were Too Numerous To Count (TNTC), indicating severe spoilage. This value exceeds the permissible microbial limit of 10^5 cfu/g according to [42,43], making the fish unsafe for consumption at this point.

Half-smoked fish had no detectable growth until 72 hours, when it developed a count of 5.0×10^4 cfu/ml. This count remains within the acceptable limit ($\leq 10^5$ cfu/g as per ICMSF/FAO standards) [42,43], suggesting that partial smoking effectively delayed microbial growth and extended shelf life up to 72 hours under controlled conditions.

Smoked fish using the NSPRI smoking kiln showed moderate microbial growth only at 48 hours (1.0×10^3 cfu/ml), and no further growth was detected at 72 hours. These values are well below the critical limit according to [45], indicating that proper smoking provided excellent microbial stability.

Conventional half-smoked fish remained TNTC throughout all drying period, indicating very high and uncontrolled microbial contamination according to [45]. This points to poor preservation or unsanitary conditions during or after smoking. The microbial levels exceed safe consumption thresholds at every stage.

Smoked fish using NSPRI smoking kiln remained safe throughout the 72-hour period. Half-smoked fish remained within acceptable limits up to 72 hours. Fresh fish and conventional half-smoked fish exceeded permissible microbial limits by 72 hours and are considered microbiologically unsafe. Hence, according to ICMSF (2002) and FAO Codex Alimentarius (2007), total viable counts in ready-to-eat or processed fish products should not exceed 10^5 cfu/g [42,43]. Exceeding this threshold indicates microbial spoilage and potential health risks.

Conclusions

Smoke drying of herring fish using the NSPRI smoking kiln effectively retained the nutritive value of the fish, and drying of all fish samples took place primarily at the falling rate period. All models gave good prediction of the drying kinetics of Herring fish with RMSE values tending toward 0 (zero). However, the best model behaved differently for all fish-cut samples. Additionally, among the models used in this study, the logarithmic model and the approximation of diffusion model were found to be the optimum models for predicting the drying kinetics of degutted herring fish.

All proximate values recorded are within acceptable nutritional ranges. Moisture content ranged from 77.35% in fresh fish to as low as 13.87% in smoked fish. Smoking improved the protein and reduced the moisture content, thereby, enhancing the nutritional value and shelf life of the fish. The fat and carbohydrate values varied, but none exceeded reported safe or functional limits. Thus, all processed fish-cut types evaluated are suitable for human consumption and provide significant nutritional benefits. Microbiological analysis showed that the smoked fish was safe and within permissible limits recommended by ICMSF and the FAO Codex Alimentarius.

The half-smoked fish is acceptable up to 48 hours post-processing while fresh and conventionally smoked fish exceeded safe microbial limits after this period. The results of this study demonstrate that the NSPRI smoking kiln performed effectively, achieving controlled drying primarily in the falling rate period, retaining nutritional quality, ensuring microbiological safety within permissible limits ($\leq 10^5$ cfu/g), and producing consistent drying across all fish cuts at a batch capacity of 25 kg.

Hence, the results of this study prove that NSPRI Smoking Kiln performed well for the smoking of Herring fish.

Limitations: While the study focused on the functional capability of the NSPRI smoking kiln and the drying kinetics of fish cuts, parameters such as dryer efficiency, thermal performance, and detailed quality assessment were not included. These aspects represent important areas for future investigation but do not affect the validity of the current findings

Future Prospects: The results provide a basis for further studies on dryer performance optimization, quality assessment, and predictive control of drying using machine learning, applicable to all fish cuts processed in the NSPRI smoking kiln.

Building on the current findings, future studies should focus on comprehensive performance evaluation, optimization of drying parameters, quality assessment across fish cuts, and the broader application of machine learning for predictive control in postharvest drying systems.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Taiwo Oluwatoyin AJAO, Adedolapo Shotonwa, Popoola ST, Oluwatosin A OJO, Olayiwola A, Jimoh AA, Akeju BM, Solomon I, Dauda A. Dikko, JO Famakinwa

Acquisition, analysis, or interpretation of data: Taiwo Oluwatoyin AJAO, Adedolapo Shotonwa, Popoola ST, Oluwatosin A OJO, Olayiwola A, Jimoh AA, Akeju BM, Solomon I, Dauda A. Dikko, JO Famakinwa

Drafting of the manuscript: Taiwo Oluwatoyin AJAO, Adedolapo Shotonwa, Popoola ST, Oluwatosin A OJO, Olayiwola A, Jimoh AA, Akeju BM, Solomon I, Dauda A. Dikko, JO Famakinwa

Critical review of the manuscript for important intellectual content: Taiwo Oluwatoyin AJAO, Adedolapo Shotonwa, Popoola ST, Oluwatosin A OJO, Olayiwola A, Jimoh AA, Akeju BM, Solomon I, Dauda A. Dikko, JO Famakinwa

Supervision: Taiwo Oluwatoyin AJAO, Adedolapo Shotonwa, Popoola ST, Akeju BM, JO Famakinwa

Disclosures

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