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Research Paper

Design and Fabrication of a 300kg Capacity Fish Oven

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ABSTRACT

It is widely assumed that simply scaling up existing fish oven designs meets the drying efficiency, quality and safety requirements of the growing demands of fish products. However, this may not be the most effective solution for large scale fish growers due to various logistical and operational challenges. The existing empirical support for the construction and performance evaluation of large sized ovens remains insufficient. An electric-gas powered fish oven was developed as part of a project to enhance fish smoking methods and solve energy consumption, and scalability issues faced by large scale fish growers. According to performance assessments, the drying chamber receives a noteworthy heat input from the electric source. The efficiency of the gas source was 63%, that of the electric source was 79%, and the efficiency of the gas-electric mode was 84%. The drying pace and the percentage weight loss of the fish samples were found to be significantly influenced by the heat source and the kind of fish. Because of its functional status, this study found that Tilapia fish dried more quickly than Catfish. However, compared to utilizing solely the electric source, it was found that employing the gas dryer shortened the drying time by one hour. These improvements have the potential to improve the efficiency of fish processing and decrease losses that occur after harvest. The oven was constructed using locally available materials. After testing, it was determined that the constructed oven operates with high performance and effectiveness.

Keywords: electric oven; gas oven; heating element; large oven; Design.

INTRODUCTION

Decades of research have focused on improving fish processing techniques to meet the demands of growing populations and maintain the nutritional quality of fish products. There has been a long-standing interest in developing ovens capable of handling large volumes of fish while maintaining quality and safety standards, which are crucial for the economic viability and environmental sustainability of the fishing industry, particularly in regions where fish serve as a primary protein source. Traditional preservation methods, such as sun-drying and smoking, have been widely used but are often inefficient and labor-intensive. In contrast, modern techniques, such as electric fish ovens, offer potential solutions to these challenges by providing a more reliable and efficient means of preserving fish. Despite advancements in preservation technology, there remains a need to develop cost-effective and scalable solutions to meet the growing demand for fish products while minimizing environmental impact.

Several studies have demonstrated the importance of proper fish preservation methods in reducing post-harvest losses and improving food security. While traditional methods like sun-drying and smoking are commonly used, they are often inefficient and can lead to product contamination and spoilage. In contrast, modern techniques such as electric fish ovens and gas powered ovens offer advantages in terms of efficiency, quality, and safety. However, there is still ongoing research to optimize these technologies and address challenges such as energy consumption and scalability.

Ezurike et. al [1] presented a detailed design and analysis of a Liquefied Petroleum Gas (LPG)-powered fish drying machine, a modification to conventional dryers that use charcoal, electric, or solar energy. The gas-powered fish dryer reduces fish moisture content and uses natural gas as heat energy. Thermal analysis was conducted on the system, using conduction and convection energy equations and numerical computational software. The machine was found to have peak drying energy and exergy efficiencies of 90% and 10%, respectively, after evaluation and testing.

Immanuel & Genitha [2] conducted a study on designing, fabricating, and evaluating a domestic gas oven. The oven, made of stainless steel and aluminum, had dimensions of 450 mm in outer dimensions and 380 mm in inner dimensions. The gas burner was placed on a stand for baking, and a bimetallic thermometer was placed in the oven. The oven's effectiveness was tested by baking cakes, cookies, and muffins, revealing higher energy efficiency and reduced baking time.

Stephen et. al [3], compared energy and exergy performance of PCM augmented Trombe walls, considering PCM compositions and wall thickness. Results show peak daily stored energy, stored exergy, room temperature, and efficiency for concrete and clay-based systems. The desired room temperature range is achieved with a 600W/m2 insolation, 60% fired brick composition, and 0.35m wall thickness.

Adegbola, & Adeyinka.[4] discussed the design and construction of a domestic electric basic oven, aiming to improve the existing oven by incorporating a blower and interlock switch. The design, detailed in an AUTOCAD design, was tested on food items, revealing higher efficiency and faster baking compared to the existing model.

However, the efficiency of the large fish oven as well as the working condition to minimize energy consumption has not been well researched and hence need further research.

The goal of the present article is to explore the design and fabrication of a 250kg capacity fish oven and its potential impact on meeting fish product demands. We hypothesize that implementing such an oven design will lead to increased processing efficiency and profitability for fish processing facilities. To test the oven , we conducted a series of experiments to evaluate the performance of the new oven design compared to traditional methods. We predict that the new oven will significantly reduce processing time and labor costs while maintaining or improving the quality of the processed fish products. By providing a detailed analysis of the design process and performance outcomes, this study aims to contribute to the advancement of fish preservation technology and enhance food security in regions reliant on fish as a primary protein source.

MATERIALS & METHODS

2.1 Material Selection

The material index is used as criteria to filter materials to obtain material suitable for the design of the oven casing.

2.2 Design Analysis

2.2.1 Design Consideration

In the design considerations for a kiln used in the drying of items, various factors come into play. These include the quantity and variability of the items to be dried within a specific timeframe. The initial moisture level of fresh products and the designated safe final moisture content of dried products are also key parameters. The functionality of the drying system involves the ability to efficiently load and unload fresh items into the drying chamber. This requires attention to heat generation, conservation, and transfer methods, along with the incorporation of effective mass transfer techniques during the drying process. Furthermore, the materials used in the fabrication of the kiln must possess the capability to withstand the heat necessary for drying the items, considering both the weight of the dryer and the quantity of smoked fish to be processed. The overall design also takes into account various aspects such as the airflow and heat distribution system. This includes considerations for spacing, total product weight, ease of loading and unloading, vapour condensation, hygiene, smoking (drying) temperature, and the longevity of the materials employed in the kiln. Each of these factors contributes to the effectiveness and safety of the drying process.

2.2.2 Energy Requirements of the Gas Oven

Methane is used as a cooking gas in the oven. Methane is a chemical compound with the formula (one atom of carbon and four hydrogen atoms). It is the most basic alkane. It is the primary component of natural gas. Methane has a lower carbon footprint than other hydrocarbon fuels, producing less carbon dioxide per unit of energy heat being released.

The following equation describes the methane combustion reaction:

$$CH_4\,(g) + 2(O_2\,(g) + 3.76\,N_2\,(g)) -> CO_2\,(g) + 2\,H_2O\,(g) + 7.5\,N_2\,(g) + KJ\,Heat \quad (7)$$

The heat responsible for the formation of water vapour:

Hydrogen and oxygen are the main components. The reaction's chemical equation is as follows:

$$H_2\,(g) + 0.5\,O_2\,(g) --- H_2O\,(g) \quad ?H = -241.8\,KJ \qquad (1)$$

The enthalpy of formation of water vapour ($\Delta H°f$) is -241.8KJ/mol, a reaction that is exothermic. Because heat is emitted into the environment, this value is negative [5]. The essential constituents of Carbon IV oxide are Oxygen and Carbon (graphite), both of which are solids. The reaction's chemical equation is as follows:

$$O_2\,(g) + C\,(s) --- CO_2\,(g) \quad ?H = -393.5\,KJ \qquad (2)$$

The enthalpy of formation of Carbon dioxide at 298.15k ($\Delta H°f$) is -393.5KJ/mol

Also, heat of formation of methane (CH_4) at standard conditions (298.15k, 1 atm) is -74.8KJ.

We may compute the total heat of combustion for methane using (7). As a result, the total heat involved in the methane combustion reaction is:

$$[Heat\,of\,formation\,of\,CO2\,(g) + 2 \times Heat\,of\,formation\,of\,H2O\,(g) + 7.5 \times Heat\,of\,formation\,of\,N2\,(g)]\,minus\,[Heat\,of\,formation\,of\,CH4\,(g) + 2 \times Heat\,of\,formation\,of\,O2\,(g) + 7.5 \times Heat\,of\,formation\,of\,N2\,(g)]$$

Total heat

Thus, total heat involved in the combustion reaction of methane in the oven is -**802.3kJ/mol** (Note that the negative sign implies that the reaction emits (gives off) heat to the environment, as one would anticipate from a combustion reaction, i.e. an exothermic reaction.) [5].

2.2.3 Weight of Water to be removed.

The dryer was designed to dry a maximum number of 300kg (200 pieces) fresh fishes per batch (African catfish usually takes an average of 5 months to reach table size, at which its weight ranges from about 0.3kg – 1.5kg [6] depending on quality of fingerlings used, quality of feeds, water management quality, absence of disease, stocking density etc.).

Taken a batch weight of 300 kg at 75 percent moisture content [7] after brining, thus the total weight of water present is:

$$M1 = 300kg\,x\,\frac{75}{100} = 225kg$$

i.e. 225 kg of water, which means that the dry matter with no moisture content will be:

$$Wd = 300kg - 225kg = 75kg$$

After drying, it is desired that the final weight of the fish contains about 8% of moisture (safe moisture content) [8] showed that the gutted, dried and smoked African catfish had moisture content as 6.27% - 10.92%) for quality taste and long shelf life.

Which means that the dry matter will correspond to (100-8) % of the final weight

$$\frac{92}{100} \times Wf \;=\; 75kg$$

$$Wf \;=\; 75kg \times \frac{100}{92}$$

$$Wf \;=\; 81.52kg$$

i.e. 81.52kg of dry matter and 16 kg of water (i.e. 81.52kg – 75kg)

This means that the weight of water that has to be removed is:

$$Wwater \;=\; Mtotal \;-\; Wf \;=\; 300 - 81.52 \;=\; 218.48kg\ per\ batch\ of\ 300kg$$

2.2.4 Quantity of air needed to remove the required Moisture from the Fish

Using the following local ambient circumstances, as provided by a local weather station (weather base): average ambient temperature of 28.25°C and relative humidity of 78 percent, respectively. The moisture content of the air is 0.0182kg moisture per kg of dry air, according to the psychrometric chart. Using the psychrometric table, the potential weight of moisture that heated air can contain when heated to 65°C is 0.0282kg. It is worth noting that, after heating, the air still has the same amount of moisture, but the relative humidity has dropped from 78 percent to around 10%. To put it another way, it can absorb more moisture from the product. The potential for heated air to absorb moisture is calculated as follows: 0.0282 - 0.0182 = 0.01kg moisture per kg of air = theoretical wt. of moisture that each gram of heated air can absorb. A pick-up factor of 0.2 was assumed to be suitable for drying fish [9]. As a result, the actual moisture weight loss per kilogram of air is: 0.01 x 0.2 = 0.002kg moisture per kilogram of air. The total amount of air (in kilograms) necessary to dry the 300 kg batch of fish is as follows:

Total amount of moisture to be removed / real potential for moisture to be picked up by air = 218.48kg / 0.002 = 109240kg

2.2.5 Converting Weight of the Air to Volume of Air

Volume flow rate (m^3/hr) = mass flow rate (kg/hr) x specific volume (m^3/kg).

For specific volume, using the psychrometric chart (28°C, 78% Rh), it yields.

0.877 m^3/kg. For a maximum drying time of 6hrs, the mass flow rate (kg/hr) gives:

$$Mair = \; 109240kg \;/\; 6hrs.$$

$$= \; 18206\; kg/hr.$$

Therefore,

volume flow rate = $18206\; kg/hr\ x\ 0.877 m^3/kg\ or\ 15967 m^3/hr.\ Or\ 9397\ CFM$;

Therefore, it behoves the use of a-10cm diameter inlet hole for the ambient drying air [10].

2.2.6 Estimating the Energy required from Gas to heat the Oven.

The heat needed to dry the product is given by [11] as:

$$Q \;=\; M_{air}\ x\ (h_2 - h_1) \qquad (10)$$

Where:

Q = heat required (kW)

$M_{air} \;=\; air\ mass\ flow\ rate\ (kg/sec) \;=\; 18206\,/3600 \;=\; 5.06\ kg/s$

H_2 and h_1 = specific enthalpy of air at drying and inlet temperatures respectively.

From the psychrometric chart,

$h_1 \;=\; 36.1\ kJ\ per\ kg\ of\ dry\ air\ at\ 68°F$;

$h_2 \;=\; 117.95\ kJ\ per\ kg\ of\ dry\ air\ at\ 150°F$

Therefore,

$Q \;=\; 5.06kg/sec\ x\ (117.95 - 36.1)$

Q= $414.161\ kJ/s\ or\ 414kW.$

Assuming a calorific value of methane to be 55.4MJ/kg (Obi et al, 2001), then:

$414.161\ kJ/s \;\div\; 55.4 \;\times\; 1000kJ/kg \;=\; 0.0074kg/sec.$

2.2.7 Estimating the Energy required from Electric Heater to heat the Oven

Oven useful heat energy required is given by:

$$E \;=\; E_1 + \; E_2 \qquad (11)\ [12]$$

$$E \;=\; W\, C_p\, (\,T_2 - T_1) \;+\; L_v\, W_t \qquad (12)$$

In which,

$$E_1 \;=\; W_m\, C_p\, (\,T_2 - T_1) \qquad (13)$$

$$E_2 = \; L_v\, W_t \qquad (14)$$

Where: E = Oven useful heat energy gain, kJ.
E_1 = sensible heat added to the material (fish)
W_m = weight of fish, kg
C = specific heat of fish, kJ/kg°C.
T_2 = temperature of air outside the dryer, °C.
T_1 = Oven inlet temperature, °C.
W_t= weight of water to be removed, kg.

If T_2 is assumed to be 65°C, then heat of vaporisation, L_v at 65°C is given as 42.25kJ/mol = 2345.4 kJ/kg

Specific heat of fresh fish is given as 0.8kJ/kg [13].

From (13),

$$E_1 = 300kg\ x\ 0.8\ (65 - 28.25) = 8820\ kJ$$

And,

$$E_2 = L_v\,W_t = 2345.4\ x\ 218.48\ kg = 512422.992\ kJ \quad ;$$

From (12)

$$E = E_1 + E_2 = 8820 + 512422.992 = 521242.992\ kJ$$

Assuming 6hrs of cooking, the required heat energy per hour would be:

$$521242.992\ kJ \div 5hrs. = 86873.832\ kJ/hr \quad ,$$

or $24.13\ kJ/s = 24.13\ kW$

2.2.8 Drying Chamber Volume

The volume of the drying chamber is determined by:

A cat fish of 3 kg, cleaned and prepared for drying, occupies a space of 15 x 15 x 10 cm^3 = 2250 cm^3 [6] thus,

The volume of 300kg cat fishes will occupy = 100 x 2250 cm^3 = 225,000 cm^3. Assuming the space between the fish (for manoeuvrability) space occupied by the racks is half of the fish space, then, the total volume of the drying chamber is 1.5 x 225,000 = 337,500 cm^3. Fixing the rows in the drying chamber to be (ten), talking about 10 catfishes per row,

The height of the chamber is estimated to be 1.5 x 15 x 10 (rows) cm = 225 cm.

A fish pin takes five fishes; thus, the depth of the chamber is 1.5 x 15 x 5 = 112 cm.

The width of the drying chamber is therefore, 337500/225/112 = 13 cm.

The final width of the oven = 13 × 2 = 26 cm.

For aesthetic purpose, evenness and operation convenience, the volume for the chamber was taken as 225 x 112 x 60 cm^3.

Determination of the thickness of insulation was based on the recommendation of [12,13]. Thus, fiberglass of 2 inches (5.08 cm) thickness was used to lag the dryer chamber.

2.2.9 Ball Bearings and Rack Sizing

The ball bearings however, were selected in preference to journal and roller bearings. This is because ball bearings are known for their less noisy operation, reduced rate of wear, and durability. In addition, their selection was made based on the recommendation of the Antifriction Bearing Manufacturers Association (AFBMA). The bearing used had outer and inner diameters of 4cm and 1.5cm respectively. Racks were arranged, one above the other at a distance of 20cm in the drying chamber. The dimensions of the racks were taken as 112cm x 20cm x 26cm. This is in line with the recommendation of [14] that dryer racks should be optimally loaded to 7-12% of their volumes.

2.2.10 Heating Element

The heating element will have the following configuration

$$P = I \times V \qquad (15)$$

$$24.13KW = I \times 220$$

$$I = 110A$$

$$P = I^2 \times R$$

$$24.13KW = 110^2 \times R$$

$$R = 2O$$

Figure 1 3- D model of the designed oven

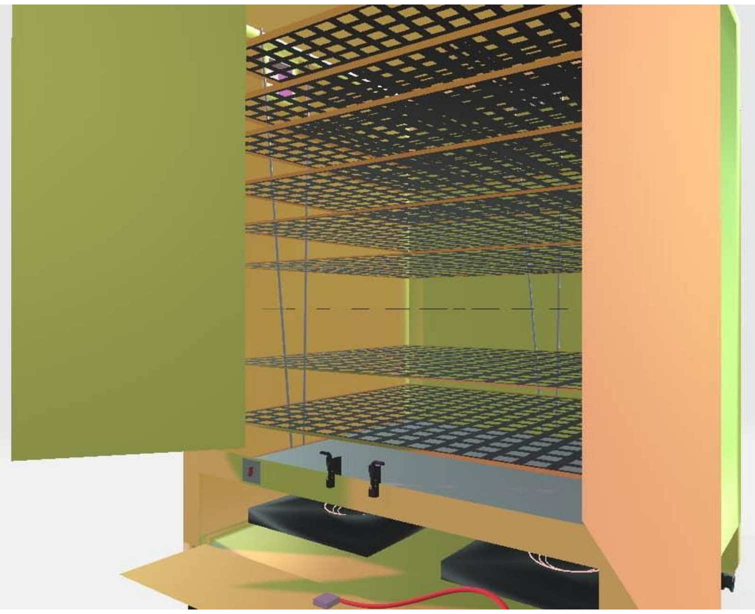

Figure 2 3- D model of the designed oven

RESULT

The fish oven throughput capacity—the greatest number of fish samples that can be dried in a batch, as well as sensory evaluations (such as product moisture content, colour, and taste), drying rates, drying efficiency, fuel efficiency, rate of fuel consumption, and drying times were used to assess the dryer's performance.

Table 2 (a): Technical Performance of the electric-dryer heat on the dried Fish

	CATFISH				TILAPIA		
Time (hrs)	**Wt. of fish (kg)**	**Moisture content (% wb)**	**% wt. loss**	**Chamber Temp. (ºC)**	**Wt. of fish (kg)**	**Moisture content (% wb)**	**% wt. loss**
1	300.00	54.2	---	120.6	300.00	60.6	---
2	270.45	48.6	9.85	100.4	253.62	51.9	15.46
3	220.90	43.8	26.36	92.2	203.37	40.4	32.21
4	132.10	21.6	55.97	75.6	128.16	20.4	57.28
5	107.50	1.42	64.17	58.2	97.11	1.08	67.63
6	96.26	0.00	67.91	52.4	89.19	0.00	70.27

Table 2 (b): Technical Performance of the dryer on the dried Fish using gas source alone

	CATFISH				TILAPIA		
Time (hrs)	Wt. of fish (kg)	Moisture content (% wb)	% Wt loss	Chamber Temp. (ºC)	Wt. of fish (kg)	Moisture content (% wb)	% Wt. loss
1	300.00	56.2	---	90.6	300.00	62.8	---
2	275.28	52.4	8.24	146.2	260.28	55.6	13.24
3	240.38	44.6	19.87	100.4	211.74	46.3	29.42
4	209.25	31.7	30.25	70	179.85	30.6	40.05
5	168.54	19.2	43.82	64	153.84	20.6	48.72
6	137.28	4.56	54.24	59.6	120.47	6.66	59.84
7	126.48	0.00	57.84	42.4	111.81	0.00	62.73

Table 2 (c): Technical Performance of the dryer on the dried Fish using gas and electric source combine

	CATFISH				TILAPIA		
Time (hrs)	Wt. of fish (kg)	Moisture content (% wb)	% Wt loss	Chamber Temp. (ºC)	Wt. of fish (kg)	Moisture content (% wb)	% Wt. loss
1	300	60.50	---	100.4	300	56.0	---
2	238.73	56.13	20.42	128.6	234.39	49.4	21.87
3	187.05	45.50	37.65	99.8	175.98	32.4	41.34
4	166.73	24.40	44.42	64.5	160.43	18.6	46.52
5	124.19	0.00	58.60	42.3	112.74	0.00	62.42

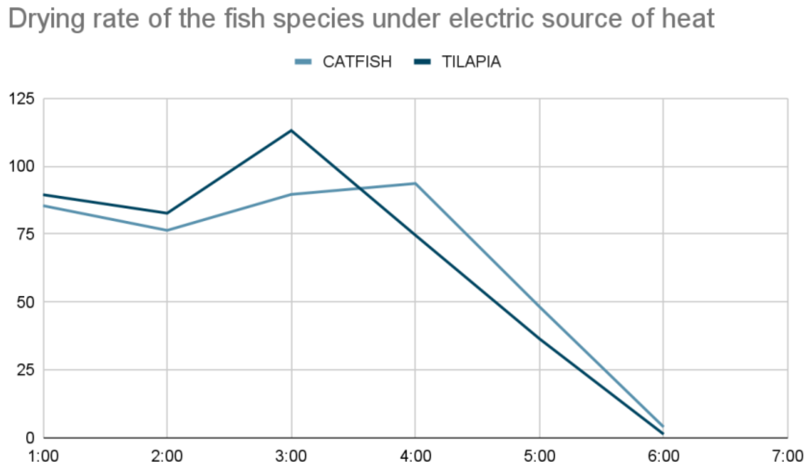

Figure 3: The drying rate of catfish and tilapia under electric source of heat

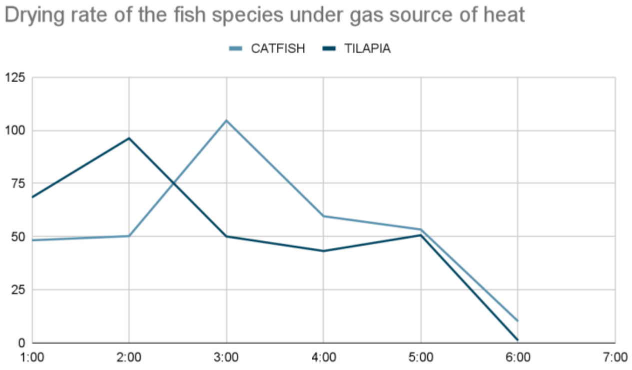

Figure 4: The drying rate of catfish and tilapia under gas source of heat

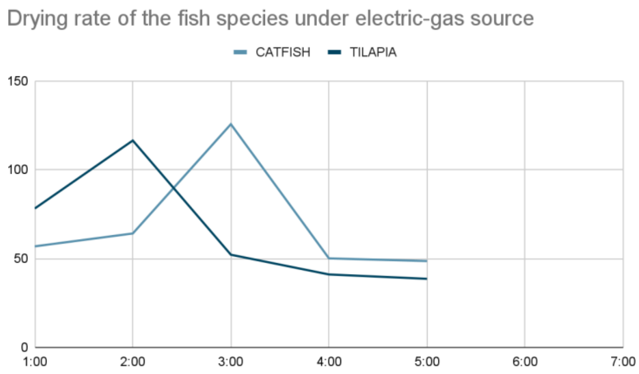

Figure 5: The drying rate of catfish and tilapia under electric-gas source of heat

DISCUSSION

In the present study, we investigated the drying rates of two species of fish and their processing efficiency using different heat sources. The findings reveal significant differences in the drying rates of Catfish and Tilapia fish species when subjected to various heat sources. The results suggest that the type of heat source, such as gas, electric, or gas-electric combinations, affects the moisture loss rates and final moisture content differently for each fish species.

According to statistical assessments, the drying chamber receives a noteworthy heat input from the electric source.The efficiency of the gas source was 63%, that of the electric source was 79%, and the efficiency of the gas-electric mode was 84%. The drying pace and the percentage weight loss of the fish samples were found to be significantly influenced by the energy/heat source and the kind of fish. Because of its functional status, this study found that Tilapia fish dried more quickly than Catfish (the thicker skin of Catfish impacts heat penetration and moisture loss rates). However, compared to utilizing solely the electric source, it was found that employing the gas dryer shortened the drying time by one hour.

This finding is inline with previous research and highlights the importance of considering both heat source and fish species in fish drying processes. Additionally, these findings offer valuable insights for industries involved in fish processing and preservation. By understanding how different heat sources and fish species interact during the drying process, producers can optimize drying techniques to yield fish products with desirable qualities.

Our study has limitations that should be acknowledged. Firstly, the specific conditions of our study may limit the generalization of our findings to broader contexts. However, despite these limitations, the consistent patterns observed in our data support the reliability of our results.

CONCLUSION

An oven that runs on gas and electricity has been designed and built. Fresh catfish and tilapia fish were used in three distinct operating modes of the system's testing: gas, electric, and gas-electric. The fish oven might be utilized in agricultural engineering workshops as laboratory demonstration equipment or as a prototype model of a commercial fish smoking kiln used in fish processing companies.

In conclusion, our study sheds light on the complex interactions between heat sources and fish species during the drying process. By uncovering novel insights into fish drying kinetics, we contribute to the optimization of fish preservation techniques and advance our understanding of food preservation science. Future research may further explore the underlying mechanisms driving these interactions and investigate additional factors influencing fish drying kinetics to refine drying techniques and improve the quality of dried fish products.

Declaration by Authors

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Conflict of Interest: The authors declare no conflict of interest.

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