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Comparative Analysis: Heat flow & drying performance in a dual Electric/gas convective dryer

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ABSTRACT

This study scrutinizes convective dryers at 45°C and 60°C, comparing the impact of electric and gas heat sources on heat flow and drying performance. By analyzing temperature changes within dryer compartments, we uncovered unique behaviors for each heat source. Gas showed faster moisture reduction compared to electric, achieving 9.81%wb and 9.39%wb at 45°C and 60°C in 33 and 21 hours, respectively, compared to 10.08%wb and 10.22%wb in 34 and 22 hours for electric. Effective diffusivity increased from 8.792 $\times 10^{-8}$ m^2/s to 1.22 $\times 10^{-7}$ m^2/s for electric and 8.9×10^{-8} m^2/s to 1.42×10^{-7} m^2/s for gas. Activation energy was 39.08kj/mol for electric and 42.59kj/mol for gas. The Page model demonstrated high accuracy (R^2 = 0.9968, RMSE = 0.0132, X^2 = 0.0002) across temperatures and heat sources for drying Clarias gariepinus. The findings suggest practical implications for industrial drying processes, highlighting the potential advantages of gas-based drying systems for faster and more efficient drying operations. Further exploration of these findings could lead to optimized drying methodologies, potentially enhancing efficiency in various drying applications within the industry.

1. Introduction

Drying, a crucial process in preserving food, relies on various methods like sun drying in regions like Nigeria. However, its susceptibility to contamination due to insects and weather conditions demands more reliable techniques. Despite the cost of the oven drying, it is more efficient than the conventional sun-drying due to the control over the drying atmosphere and better control of quality to reduce contamination [15]. Developed countries employ energy-intensive yet efficient methods such as convection, induction, and energy field processes for industrial drying [3]. Among these, hot air drying stands out for its efficiency in moisture removal and cost-effectiveness, often applied in food dehydration [13; 14, 16].

While multiple studies explore drying techniques using different heat sources, research specifically on African mud catfish drying using a dual-source (electric/gas) convective dryer is limited. Notably, previous investigations, like those by [4, 10, 12] have highlighted temperature and air velocity's influence on drying parameters. While studies have explored drying processes using electric and gas dryers, a comprehensive analysis specific to African mud catfish utilizing a dual-source (electric/gas) convective dryer still needs proper review. Therefore, this study aims to delve deeper into this specific context to comprehensively compare drying dynamics (rates, diffusivity, kinetics) between electric and gas heat sources in a convective dryer across varying temperatures for African mud catfish."

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2. Materials and Methods

2.1 Sample preparation

The African mud catfish (Clarias gariepinus) obtained from the local market in Anambra, Nigeria was used for this study. The specie is a popular delicacy among the low- and middle-income earners and vary in size, and relatively cheap and affordable. The fish was degutted, washed very well with clean water, brined and set for drying. The fish was then arranged in the mesh tray outside the drying chamber and left to drain for about 5-8 minutes

2.2 Experimental Setup

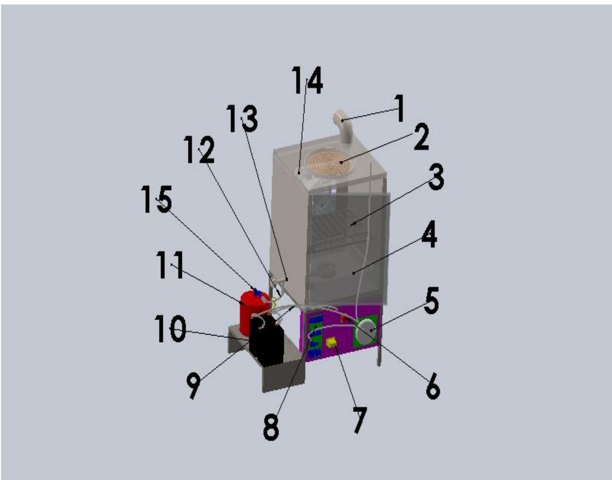
In this experiment, a 0.42m by 0.39m by 0.39m (HLB) hybrid gas/electric convective dryer made of stainless steel insulated with fibre glass, characterized by its capability to operate at various temperatures (range of 0 – 399K) and blower speeds (2m/s – 7m/s), was employed. The fundamental components of this dryer includes a STEL E5EM thermostat equipped with a sensor to regulate the temperature of the electric coil, a blower responsible for distributing heat from the source to the drying chamber, a mesh tray designated for sample placement, and a gas control system comprising a solenoid valve, igniter, and thermostat.

Electric control system

The electric system incorporates a heating element of 1.8kw and a distinct temperature regulator control mechanism. Here, the user inputs the desired control temperature, and the thermostat, upon sensing the temperature, transmits a signal to the contractor. The contractor then modulates the heater, cycling it on and off at predetermined intervals in accordance with the set temperature.

Gas control system

Conversely, the gas system encompasses a control section where the user inputs both the desired temperature and the ignition time. Subsequent to the temperature input, the thermostat dispatches a signal to the solenoid valve, prompting it to open. Following a specific duration, determined by the set ignition time (8 seconds, in this instance), the igniter activates, initiating combustion within the burner.



Number	Component Name
1	Exhaust
2	Heating Element
3	Fish Tray
4	Oil Tray
5	Gas Control
6	Power Button
7	Blower Control
8	Electric Control
9	Electric Cable
10	Battery
11	Gas Cylinder
12	Gas Hose
13	Burner
14	Blower
15	Solenoid Valve

Fig 1 Schematic view of the developed convective dryer

2.3 Drying Procedure

The study was carried out in Awka, Anambra state using a dual powered convective dryer (a gas powered and electrical powered kiln) at drying air temperatures of 45°C and 60°C, drying air velocity of 3m/s. The parameters selected were based on submissions from literatures [6, 9]. The dryer was powered and left for some time to attain the desired drying conditions, the pretreated fish was placed on the tray mesh and fed into the oven, the sample was extracted from the oven and weighed at time interval of 15mins for the first 1 hour and 30 mins for the remaining time to determine the weight loss and moisture content until a safe moisture content is attained. The weighing balance Virgo digital electronic lab weighing scale with accuracy of 0.1g and maximum capacity 2000g was kept very close to dryer and weighing period of 20s was maintained.

2.4 Drying kinetics

Moisture content determination:

The moisture content (Mc) on wet basis (% w.b) was determined according to AOAC as:

$$\mathrm{Mc} = \frac{\mathrm{W_i} - \mathrm{W_f}}{\mathrm{W_i}} \times 10 \qquad (1)$$

Where Mc is the moisture content (% w.b.); W_i the initial weight of the sample (g) and W_f the final weight of sample (g)

The Initial moisture content is determined by bone drying the fish at 150°C until there is no significant change in weight

The Moisture ratio (dimensionless variable) is calculated according to (12) and its given as;

$$MR = \frac{m_t - m_e}{m_0 - m_e} \qquad (2)$$

where m_t, m_o and m_e are the moisture content measured at time t, initial moisture content, and equilibrium moisture content respectively. The value of m_e is very small compared to m_t or m_o for long drying time. Thus eqn. (2) can be simplified according to (10)

$$MR = \frac{m_t}{m_0} \tag{3}$$

Drying rate:

Drying rate is defined as diffusion of moisture from the inside to the outside layer as its given as:

$$DR = \frac{m_t - m_{t+\Delta t}}{\Delta t} \tag{4}$$

Where $m_{t+\Delta t}$ is the moisture content (g water/g wet solid) at t + Δt, t is the drying time (mins) and Δt is change in time (mins).

Drying Kinetics model

Table 1 Drying kinetics models

Model Name	Equation
Lewis	$MR = e^{(-kt)}$
Page	$MR = e^{(-kt^n)}$
Wang and Singh	$MR = 1 + at + bt^2$
Logarithmic	$MR = ae^{(-kt)} + c$

The model parameters were determined by statistical methods using experimental time variation data of the fish samples moisture removal. Matlab was be used in analyzing the numerical values of the sample drying kinetics.

The validity or goodness of fit of the model was determined by the use of statistical parameters: coefficient of determination (R^2), Root mean square error (RSME), and reduced Chi-square (x^2). The model with the highest value of R^2 and lowest value of RSME and x^2.

The expression for the statistical parameters are given below:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}\left(MR_{pre} - MR_{\exp i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR_{pre}} - MR_{\exp i}\right)^2}\right] \tag{5}$$

$$x^2 = \sum_{i=1}^{n} \frac{\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - m} \tag{6}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \tag{7}$$

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

Effective moisture diffusivity

This is the general property of moist which involves liquid diffusion, vapour diffusion, hydrodynamic flow and other possible mass transfer mechanism. In this study the fish is assumed to be an approximated slab, so the Fick's second law of diffusion adopted to fit the experimental data for determining moisture diffusivity is expressed according to:

$$\frac{\partial M}{\partial t} = D_{eff}\Delta^2 \tag{8}$$

using the following assumptions: uniform initial moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage equ can be given as

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{2n-1} exp\left(\frac{(2n-1)^2\pi^2 D_{eff} t}{4L^2}\right) \tag{9}$$

where L is sample's half-thickness (m), t is the drying time (s), n is a positive integer and Deff is the moisture diffusivity. Linearizing eqn (9)

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 t\, D_{eff}}{4L^2}\right) \tag{10}$$

$where\ \frac{\pi^2 Deff}{4L^2}\ is\ the\ slope$ of the curve from the plots of ln MR data against time

The effective moisture diffusivity will be calculated using

$$D_{eff} = slope\ \times \frac{4L^2}{\pi^2} \tag{11}$$

Activation Energy

This is the minimum energy requirement for starting the drying process (1).

The Arrhenius equation is used in solving for the activation energy, it describes the relationship between the diffusion coefficient and the drying temperature. According to [6] is given as:

$$D_{eff} = D_o\ exp\left(-\frac{E_a}{RT}\right) \tag{12}$$

Where Ea is the activation energy (J mol^{-1}), R is the gas constant (J mol^{-1} K^{-1}), and T is the absolute temperature (K)
The equation can be linearized using natural logarithm into:

$$\ln D_{eff} = \ln D_o - \frac{Ea}{R}\frac{1}{T} \quad (13)$$

Then activation energy can be calculated by plotting the graph of ln D_{eff} against 1/T using:

$$S = \frac{E_a}{R} \quad (14)$$

Where S is the slope of the D_{eff} plot of 1 / T and R is the gas constant (J mol^{-1} K^{-1}).

3. Results and Discussion

3.1 Heat flow Analysis

The heat flow analysis in the convective dryer reveals a dynamic movement of heat within the system. This movement, visible in both gas and electric dryers, shifts temperatures from high (red) to lower (light blue) regions and vice versa. This transition is vital in initiating efficient moisture extraction during the drying process. The heat's dynamic movement creates an environment conducive to evaporation, facilitating effective moisture removal and maintaining an optimal drying setting.

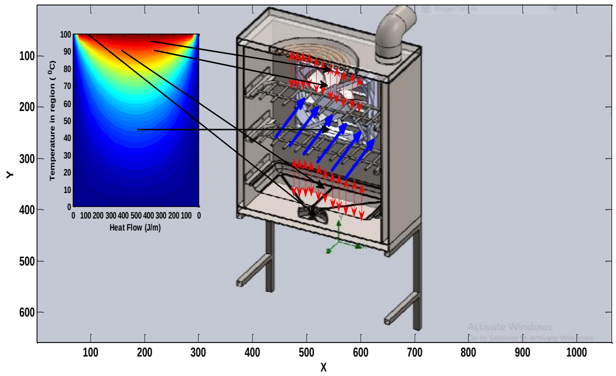


Fig 2 heat flow profile through the tray at set temperature

3.1.1 Elecctric dryer section

Figure 3 illustrates the electric dryer section view with temperature distribution ranging from 40°C to 60°C. The varying temperatures highlight zones that potentially impact drying efficiency, aiding in identifying optimal drying areas within the compartment. This distribution of temperatures in the dryer compartment is significant for the drying process. Lower temperatures at specific sections indicate areas where drying might be slower due to less heat, while moderate temperatures suggest regions conducive to efficient moisture removal. Understanding these temperature variations assists in identifying zones where the drying process might be more effective or require adjustments for optimal results.

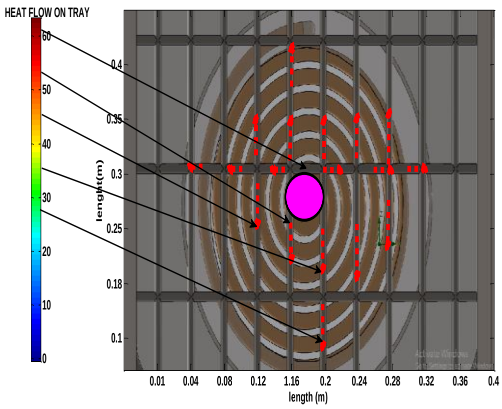


Fig 3: heat flow profile in electric section

3.1.2 Gas dryer section

Figure 4 depicts the lower section of the dryer compartment where the gas burner is located, showcasing heat distribution ranging from 40°C to above 60°C. The even heat dispersion throughout the lower tray indicates a balanced heating process, creating zones suitable for effective drying. The diverse temperature zones contribute to an environment conducive for moisture extraction and evaporation, essential for efficient drying procedures.

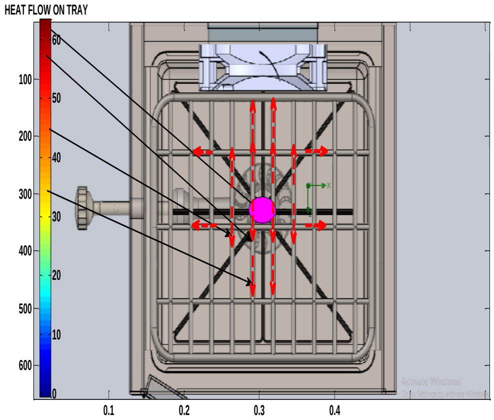


Fig 4: heat flow profile in the gas section

3.2 Heat flow plot

Figure 5 illustrates the heat flow plots in both dryer chambers at set temperatures of 45°C and 60°C, comparing them with the designated temperatures. At 45°C, both chambers display a rise in temperature exceeding the set value. However, the gas dryer shows a transient flow, while the electric dryer indicates a potentially steadier state around 60°C. Despite both chambers reaching a final steady state at 60°C, the electric dryer demonstrates a more consistent heat flow pattern. This suggests that the electric dryer might maintain a more stable and consistent drying environment compared to the gas dryer, which experiences fluctuations in heat flow.

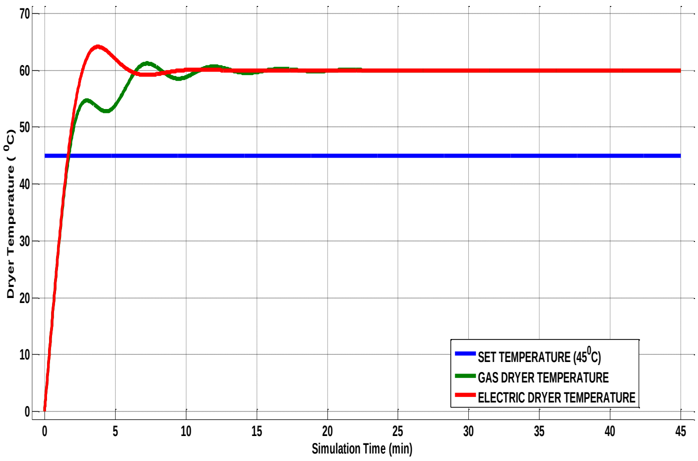


Fig 5: A graph of drying temperature against time for the heat flow at 45 ^{0}C.

At a set temperature of 60 ^{0}C, the heat flow at the different chambers exhibit a different behavior compared to a set temperature of 45^{0}C. Both flows shows transiency that lasted till 20 minutes of the simulation time. A steady temperature is achieved at 80 ^{0}C at 25 min of simulation time.

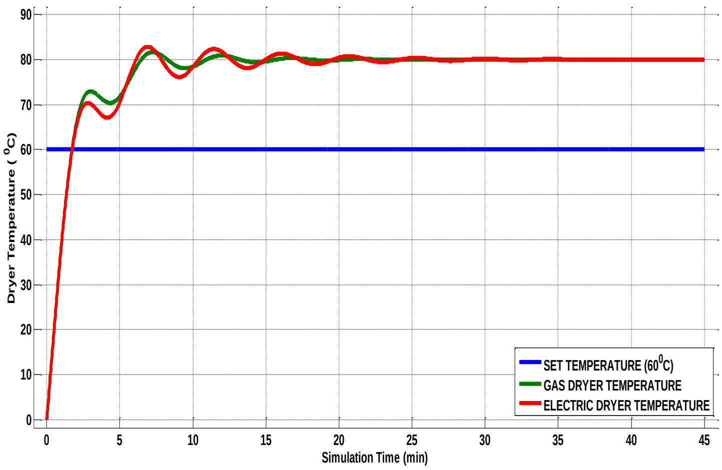
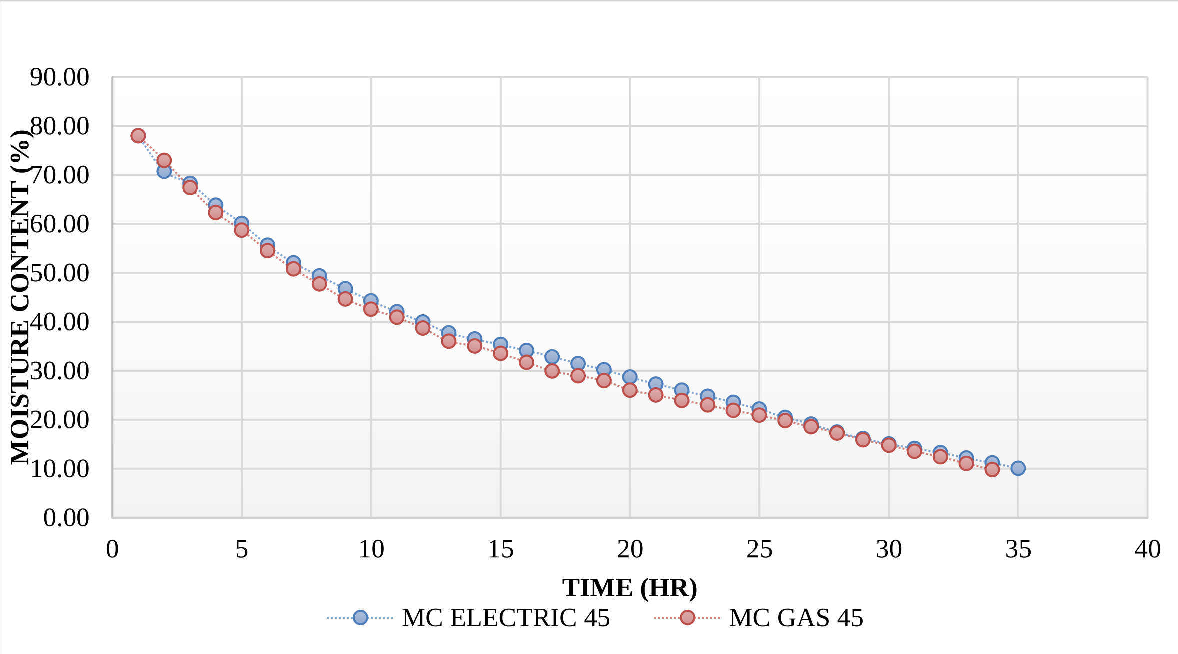
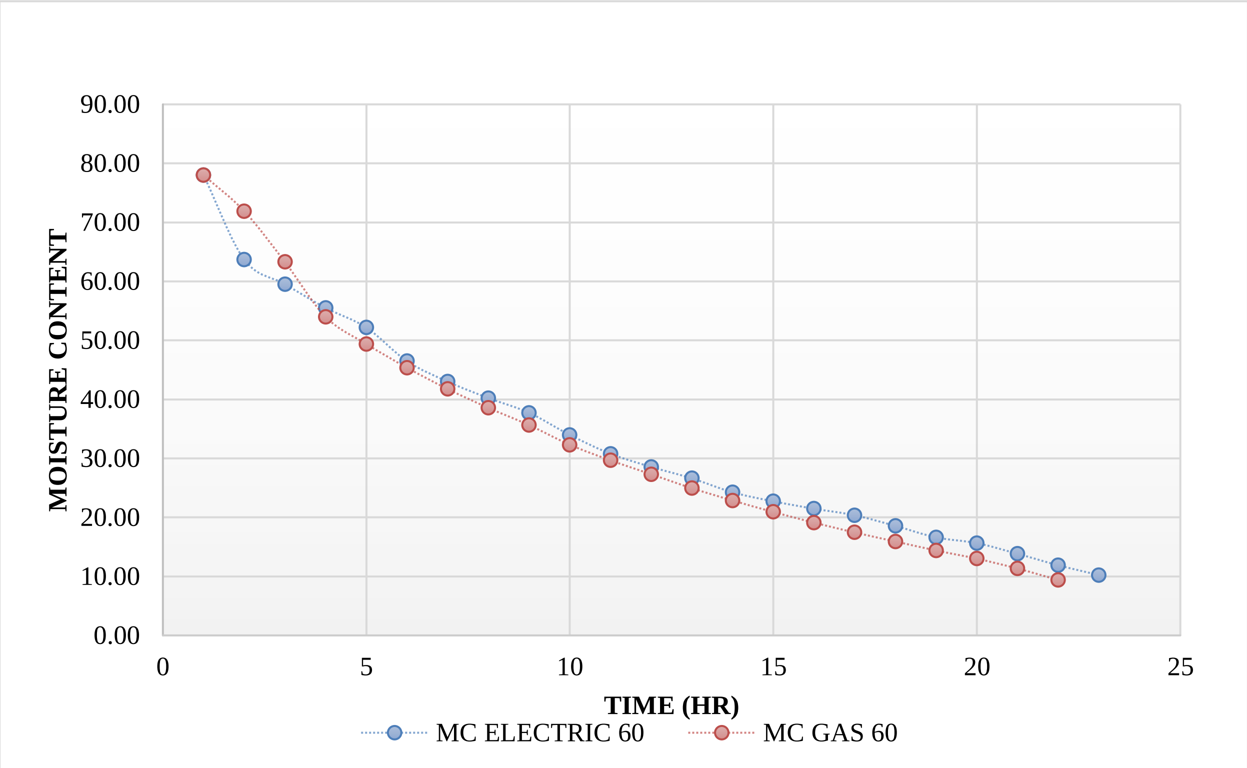


Fig 6: A graph of drying temperature against time for the heat flow at 60 ^{0}C.

3.3 Drying Performance

The moisture content result was gotten based on the data from the drying process by weighing the mass of the fish after 30 mins interval. The results gotten showed that at both temperatures 45°C and 60°C. the electric source had an initial higher moisture content reduction within the first hour but as the drying progressed the gas source resulted in a faster moisture content reduction. The MC curve in Fig 7 and 8 showed that the minimum moisture contents gotten at 45°C for the electric and gas after 34 and 33hours were 10.08%wb and 9.81%wb respectively. While for 60°C after 22 and 21hours were 10.22%wb and 9.39%wb. The results showed that MC reduces rapidly with increase in temperature and also with the use of gas as the heat source. Fig 9 and 10 shows the drying rate curves, which increases with increase in temperature for both heat sources. The electric source achieved a higher drying rate within the first hour but the gas source had a more consistent higher drying rate throughout the drying process leading to lesser drying time. This is in line with results found in previous studies [1, 4, 12].





Drying rate

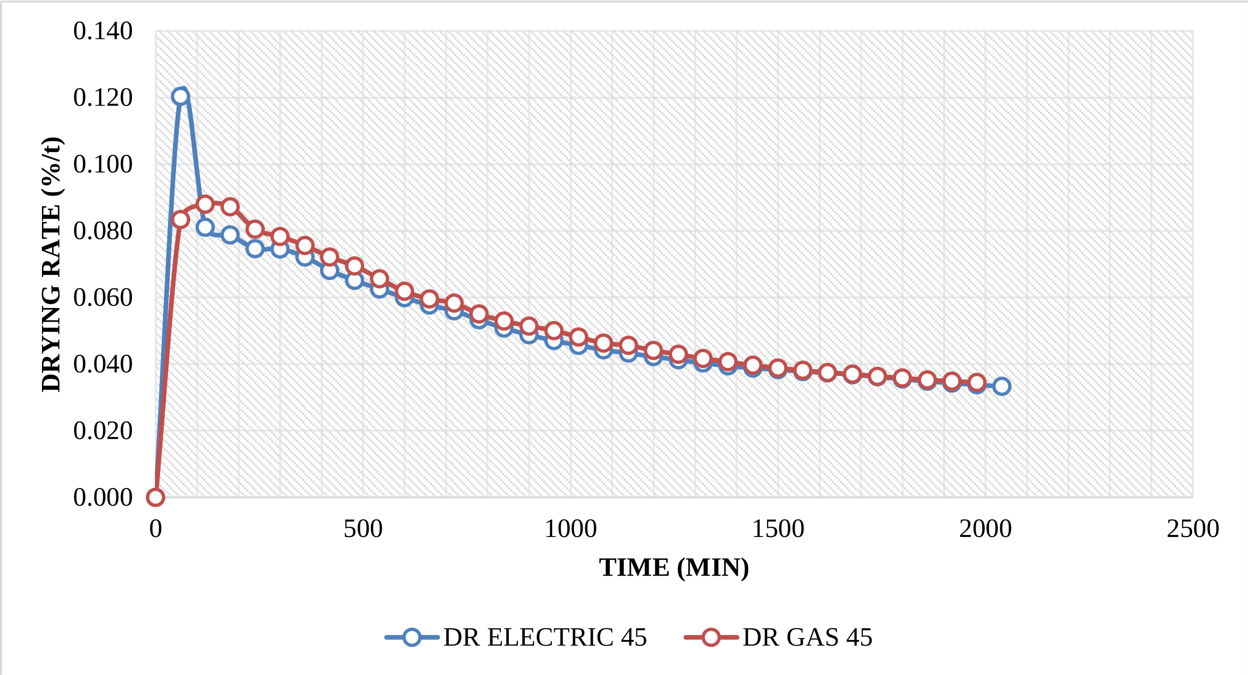


Fig 9: Drying rate vs Time at 45 ^{0}C drying temperature

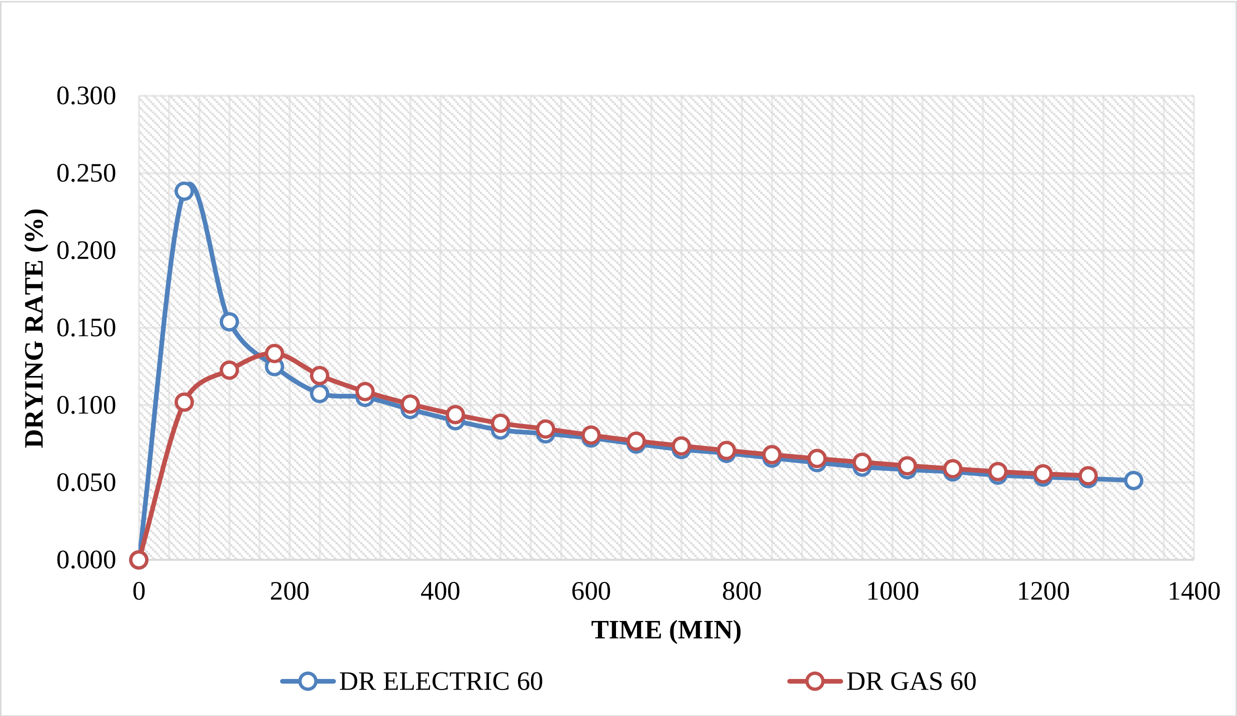


Fig 10: Drying rate vs Time at 60 ^{0}C drying temperature

Moisture Ratio

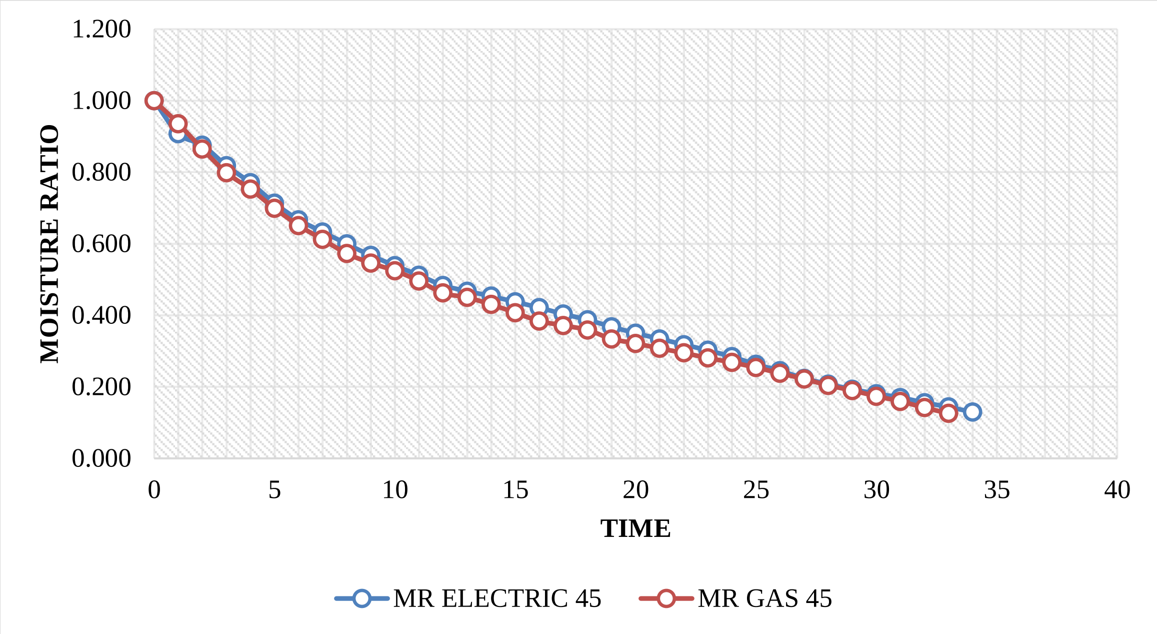


Fig 11 Moisture Ratio VS Time Graph at 45°C drying temperature

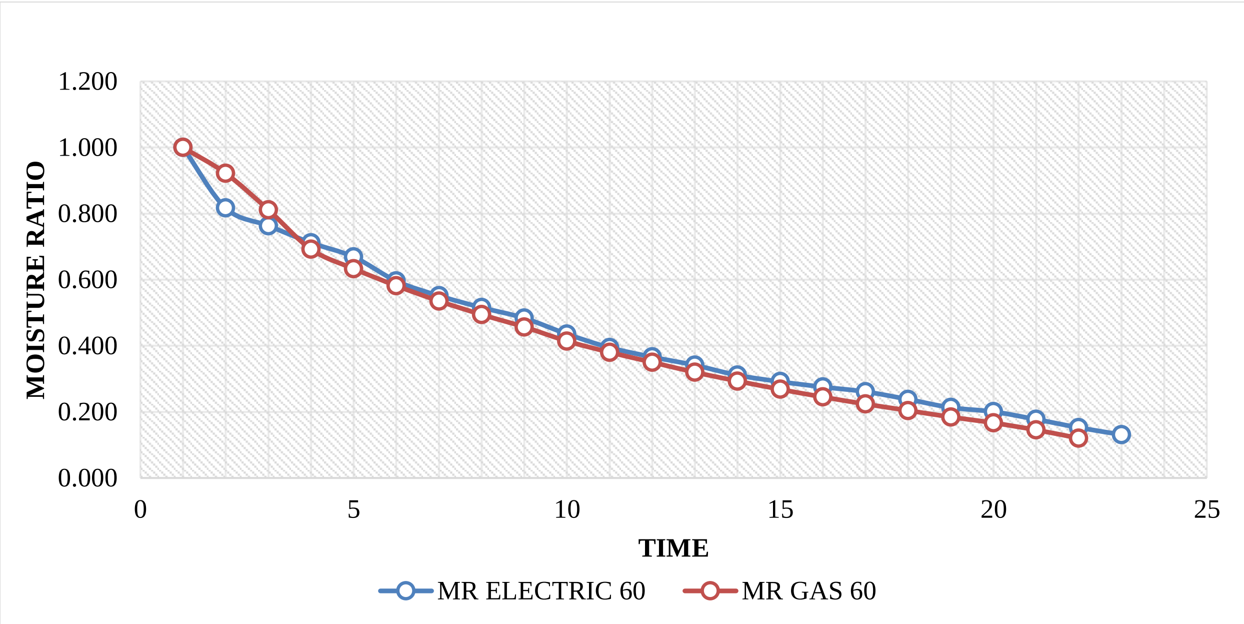


Fig 12 Moisture Ratio VS Time Graph at 60°C drying temperature

Effective Moisture Diffusivity and Activation Energy

From Fig 13 and 14 we can see that the effective diffusivity increased with increase in temperature. For the electric source at 45°C and 60°C the effective diffusivity increased from $8.792 \times 10^{-8} m^2/s$ to $1.22 \times 10^{-7} m^2/s$ respectively while for the gas it increased from $8.9 \times 10^{-8} m^2/s$ to $1.42 \times 10^{-7} m^2/s$ these fall in the range of acceptable effective diffusivity ($0.2–1 \times 10^{-9}$ m²/s). The gas source had a higher effective diffusivity. The Activation energy for the electric and gas heat source is 39.08kj/mol and 42.59kj/mol respectively, [19] reported a range of 2.67×10^{-10} and 8.17×10^{-10} $m^2 s^{-1}$ Effective diffusivity and The activation energy (Eα) varied between 36.99 and 42.59 kJ mol^{-1} for quince drying. [11] got a range of 7.821 x 10^{-11} to 4.591 x $10^{-10} m^2/s$ diffusivity and 20.32kj/mol - 33.318kj/mol activation energy for fish drying. [2] also reported an increase in effective diffusivity with increase in drying air temperature. Higher diffusivity implies that moisture moves more readily within the material during drying, allowing for faster moisture removal. This increased movement facilitates quicker drying and can be advantageous in reducing the overall drying time. On the other hand, higher activation energy signifies that more energy is needed to drive this moisture movement. While it might require more energy input, it could also imply that the drying process is more temperature-sensitive. Therefore, it could be more efficient at higher temperatures but less effective at lower ones.

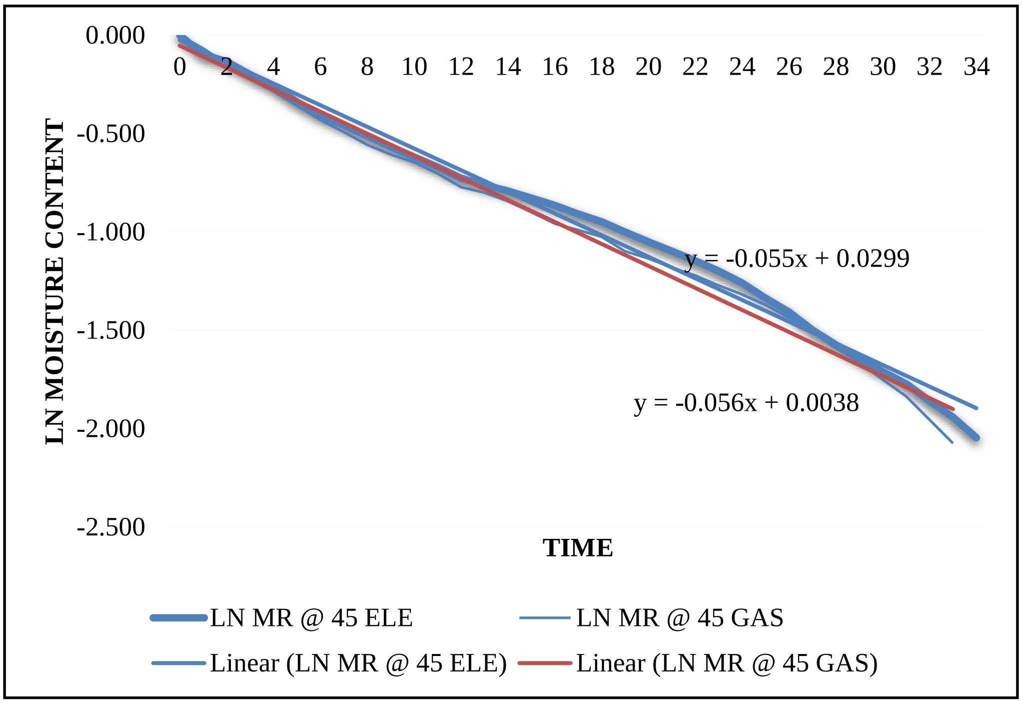


Fig 13 Ln MR against time at 45°C drying temperature

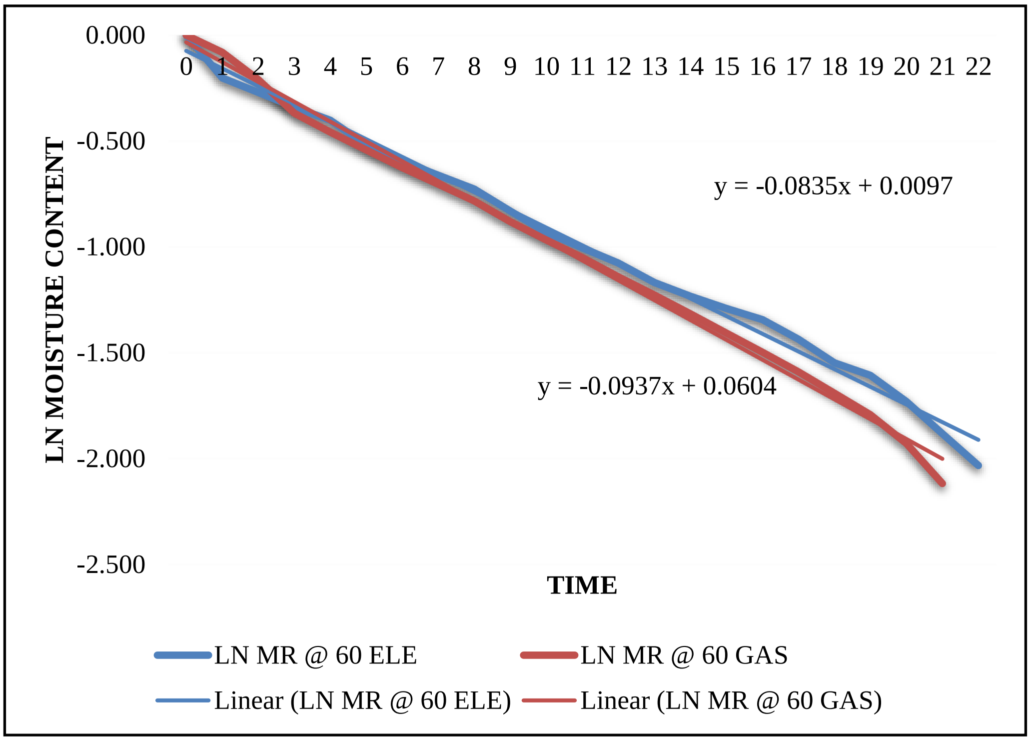


Fig 14 Ln MR against time at 60°C drying temperature

Fitting drying kinetic models

The MR was fitted into 4 different drying models with the aid of MATLAB. The results of kinetic modelling using four thin layer drying models are presented in Table 1 and 2 below. The best model was based on the statistical tools R^2, RMSE, and SSE values. The four models Lewis, logarithmic, Page, Wang and Singh all performed well, but Page was selected as the best model since it out-performed the other models used more frequently. The most correlation values were maximum coefficient of determination (R^2 = 0.9968), minimum root mean square error (RMSE = 0.0132), and reduced Chi-square (X^2 = 0.0002) for drying Clarias gariepinus. The Page model was also selected by [4] in drying onion slices and [12]

Table 2 The models correlation values for the heat sources at different temperatures

NO	MODEL	HEAT SOURCE	TEMPERATURE	R^2	RMSE	X^2
1	LEWIS	GAS	45	0.9884	0.0251	0.0007
			60	0.9940	0.0192	0.0004
		ELECTRIC	45	0.9893	0.0242	0.0006
			60	0.9815	0.0316	0.0010
2	PAGE	GAS	45	0.9968	0.0133	0.0002
			60	0.9972	0.0132	0.0002
		ELECTRIC	45	0.9945	0.0174	0.0003
			60	0.9944	0.0174	0.0003
3	WANG AND SINGH	GAS	45	0.9750	0.0370	0.0015
			60	0.9835	0.0320	0.0011
		ELECTRIC	45	0.9759	0.0364	0.0014
			60	0.9683	0.0413	0.0019
4	LOGARITHMIC	GAS	45	0.9945	0.0174	0.0003
			60	0.9961	0.0156	0.0003
		ELECTRIC	45	0.9936	0.0187	0.0004
			60	0.9933	0.0189	0.0004

Table 3 Model constants

No	Model	Heat Source	Temp (°C)	A	b	C	K	N
1	Wand & Singh	Gas	45	-0.0529	0.0009			
			60	-0.0847	0.0022			
		Electric	45	-0.0492	0.0007			
			60	-0.0807	0.0020			
2	Logarithmic	Gas	45	0.9101	-	0.0613	0.0659	
			60	0.9421	-	0.0470	0.1069	
		Electric	45	0.9543	-	0.0033	0.0540	
			60	0.9044	-	0.0353	0.0915	
3	Page	Gas	45				0.0856	34.0000
			60				0.1193	22.0000
		Electric	45				0.0758	35.0000
			60				0.1344	23.0000
4	Lewis	Gas	45				0.0600	
			60				0.0981	
		Electric	45				0.0566	
			60				0.0917	

6. Conclusions

This study explored convective drying using electric and gas heat sources, examining heat flow, drying rates, moisture diffusivity, and kinetics. The analysis revealed varied heat distribution patterns in both dryers, with the gas source showing more consistent heat dispersion. Although the electric dryer initially reduced moisture content more, the gas source demonstrated faster and more consistent moisture removal. Both sources exhibited increased diffusivity and activation energy at higher temperatures, with the gas source consistently showing higher values. The Page model emerged as the most reliable for representing drying kinetics.

Future research avenues may involve integrating a heat exchanger to boost system efficiency and refine the drying process. Additionally, in-depth analyses tailored to various fish types or materials could provide insights into specific drying behaviors, enabling process optimization with respect to a dual source convective dryer. Exploring renewable energy sources or hybrid systems presents opportunities to decrease energy usage and enhance the sustainability of drying procedures.

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