RESEARCH ARTICLE

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Development and Sustainability Assessment of a Fish-drying Kiln: Eco-thermodynamic Insights

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Abstract

The demand for sustainable and viable drying technologies has risen continuously in response to the growing energy costs and emerging environmental decline. The study designed and evaluated the operational efficiency of a counter-flow heat recovery fish drying kiln at a uniform temperature (55 °C), varying air velocities (1.0, 1.5, and 2.0m/s), and batch sizes (15, 20, and 25kg) of catfish using an eco-thermodynamic approach embodying energy, exergy, environmental, and economic assessments. The findings indicate that heat transfer was greatly improved with higher air speeds and batch sizes, which also reduced charcoal consumption from 22.18kg to 18.85kg and shortened the drying duration from 330 to 180 minutes. The drying rate varied between 0.041 $\leq \mathcal{X}_d \leq$ 0.083kg/min, with a rehydration ratio of 1.71 $\leq \zeta_R \leq$ 1.74 and shrinkage of 20 $\leq \phi_s \leq$ 30.54% (± 2.25%). Specific energy utilization dropped from 42.88 $\times 10^3$ to 21.87$\times 10^3$ kJ/kg, and exergy efficiency increased from 42.88 $\leq \eta_{ex} \leq$ 49.75% (± 0.48%). The sustainability index and improvement potential were obtained as 1.68 and 457.48MJ, respectively. Environmental assessment enhanced as carbon credits rose to ₦532.33 and CO_2 emissions dropped from 62.77 kg to 53.35 kg/cycle. The kiln exhibited unique economic feasibility, as evidenced by the reduction in drying costs from ₦26.13 to ₦15.68/kg, and an increase in yearly savings from ₦3.88 million to ₦6.86 million. The benefit-cost ratio rose from 1.98 to 3.59, and the payback time was shortened to 0.27 years. These findings support the kiln's potential as an inexpensive, ecologically friendly, and thermally productive solution for drying fish products. Future research directions were proposed.

Keywords: catfish, specific energy utilization, exergy efficiency, sustainability metrics, charcoal-powered dryer, psychrometry.

1 Introduction

The growing global demand for premium dried fish, especially in less developed countries, has spurred advancements in drying technology intended to

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increase sustainability and energy efficiency. Due to its very perishable nature, fish preservation continues to be a major concern for many people in these nations who depend on it as a source of protein and micronutrients. Postharvest loss of fish frequently surpasses 30% in sub-Saharan Africa, especially in coastal and riverine areas [1]. This is mostly because of insufficient processing and storage facilities [2]. Conventional techniques for smoking and drying fish, which usually include open fire or crude kiln systems, are labour-intensive, ineffective, and lead to significant waste of energy, uneven product quality, and environmental contamination [3]. These methods are not only expensive but also lack technical expertise or have limited access to sustainable designs, even though there are better drying methods available. In Nigeria and other low-income economies, biomass-powered fish-smoking kilns continue to be an essential part of the conventional processing of fish. These technologies provide heat for drying and storage using locally accessible resources like firewood, agricultural waste, and charcoal, especially hardwood charcoal. However, the majority of conventional kilns are marked by excessive fuel consumption, erratic drying, and substantial thermal loss, all of which lead to inferior product quality and environmental damage [3]. As a result, current research has concentrated on creating better biomass-fuelled kilns that are highly combustion efficient, control airflow, and increase thermal resistance. Although many designs currently lack the methodical assessment of energy and exergy performance parameters required to determine the real efficiency of these dryers, these improvements have enhanced homogeneity in drying and lowered emission levels [4].

In recent times, energy and exergy assessments have become popular as reliable techniques for assessing the thermodynamic outcome of biomass-powered food dryers. Whereas energy assessment measures the overall energy utilization and production, exergy assessment emphasizes determining the percentage of energy that may be transformed into productive activity, hence revealing system irreversibilities and possible sections for enhancement that the conventional energy balances frequently ignore [2]. These methods have been used in a few recent studies to assess fish drying kilns, showing that ineffective heat transfer and inadequate combustion regulation are frequently linked to substantial exergy losses. A handful of research efforts also tried to combine exergy-based parameters with thermal performance measures, such as drying rate, fuel economy, and smoking efficiency [5]. Alfiya et al. [6] developed a biomass-based dryer and evaluated its performance using the 4E analysis concept with anchovy and shrimp fish products. Other researchers have developed and analyzed the thermal performance of different fish dryers using solar, liquefied petroleum gas (LPG), electricity, and their combined heat sources [7–10]. Nevertheless, there is still a scarcity of comprehensive studies that integrate thermodynamic concepts with kiln design characteristics, particularly as it applies to charcoal-fuelled kilns with an active counter-flow heat exchanger and sensor-controlled temperature and airflow units intended for rural use. This gap emphasizes the necessity of more development and evaluation of biomass-powered fish-drying kilns utilizing both energetic and exergetic mechanisms. Previous studies of this dryer design ignored the combined assessment of energy, exergy, environmental, and economic variables in such regulated systems.

The present study bridges this gap through the development of a fish-drying kiln incorporated with a counter-flow heat exchanger and sensor-based control units to adjust the airflow, temperature, and relative humidity. From the foregoing, it is imperative to design, fabricate, and thermodynamically assess a reliable, reasonably priced fish-drying kiln that can maximize energy use while sustaining high drying efficiency and product quality. The evaluation of the designed fish-drying kiln is conducted through an extensive eco-thermodynamic (4E) evaluation technique, which includes energy and exergy assessments, environmental impact (greenhouse gas emissions, carbon credits), and economic performance indices (payback period, life span, annualized capital cost, etc.). This method facilitates an in-depth understanding of energy consumption, waste production, and environmental consequences, prompting the development of heat-efficient systems that are more sustainable. The specific objectives of this study are to develop a counter-flow fish drying kiln with automated temperature control, analyse its fuel use, drying duration, and thermal behaviour, evaluate its energy and sustainability metrics at varying airflow rates and batch sizes, and benchmark its efficiency with widely used crop dryers reported in the literature. The study focuses on data-driven design improvements that boost total process sustainability, minimize the usage of charcoal, and encourage efficient use of energy. This study

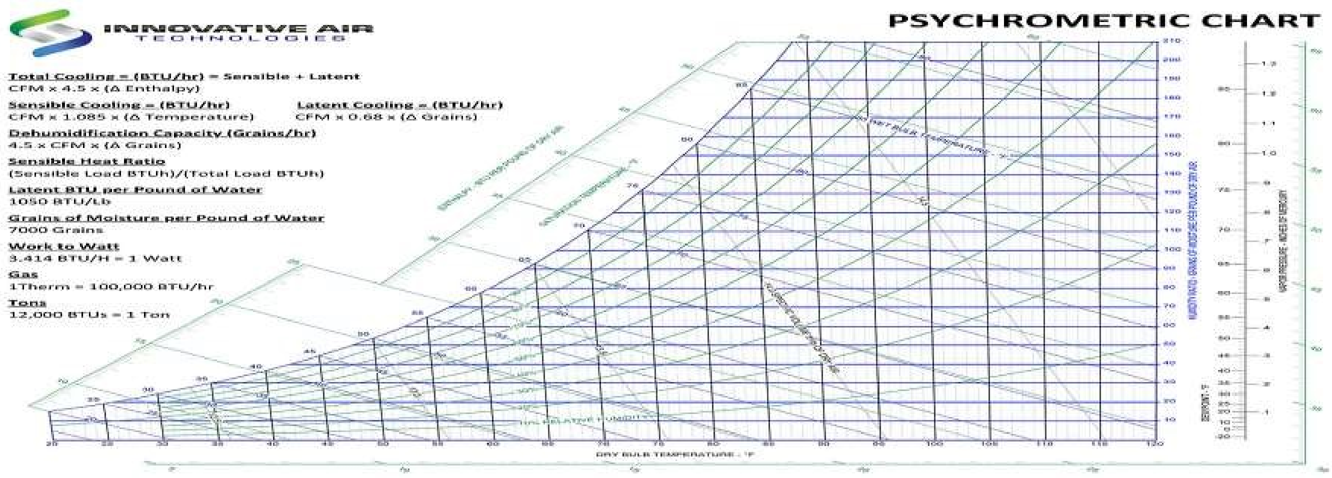


Figure 1. Psychrometrics of the drying air properties.

lays the groundwork for enhancing fish preservation equipment in regions with limited resources, which can potentially boost economic prospects, encouraging resilience in the ecosystem.

2 Methodology

The experimental method consists of 4 basic stages: kiln development (design & fabrication), sample preparation, drying tests, and data collection.

2.1 Test samples

Fresh catfish samples (*Clarias gariepinus*) were purchased from a rural fish farm in Owerri West, Imo State, Nigeria. This species, which varies in size and is reasonably priced and accessible, is a common delicacy for households with low and intermediate incomes. The axial dimensions (length, width, and thickness) of the samples were 40.2 ± 1.5 mm, 6.5 ± 0.5 mm, and 2.7 ± 1.0 mm, respectively. An electronic scale was used to determine the mass of each trial batch (15, 20, and 25 ± 0.01 kg). After a clean water wash with salt solution, the degutted samples were allowed to drain. The brine solution helped reduce the initial moisture content of the samples, suppressing the growth and development of microorganisms and enhancing flavour and texture. The initial moisture content (60% w.b.) was obtained gravimetrically at 105±1.1 °C for 24h [11]. The gutted, brined catfish samples were allowed to drain out saltwater, ready for convective drying.

2.2 Design considerations and assumptions

This research work was intended to develop the markets for dried fish by small-scale fish farmers and processors in Owerri-West, Imo State, the southeastern region of Nigeria. The prototype design requirements were to dry 25 kg (batch size) of dry catfish samples (*Clarias gariepinus*) in 5 to 6 hours using the biomass heat unit. However, the following design conditions applied:

1. Charcoal (from a hardwood) is the main fuel source, given its abundance in the region. For easy manoeuvrability, the kiln's combustion chamber and drying chamber were constructed as separate units, assembled with the aid of bolts and nuts and gaskets; rollers were attached to their frame support.
2. An indirect fish drying process using a heat exchanger.
3. Control and monitoring of temperature and humidity are accomplished by a sensor system based on a microcontroller.
4. A DC centrifugal blower with variable speed adaptability was used to adjust airflow.
5. Stainless steel material was used for the interior unit of the drying kiln, as well as for the drying racks and oil collection pan, to avoid product contamination.
6. Ease of loading and unloading of solid fuel and fish samples in their respective chambers; a mechanism for producing, storing, and transferring heat, as well as a moisture transfer that occurs throughout the drying process.
7. Adequate power was provided through the solid fuel and accumulator to operate the DC blower, generating the optimum air enthalpy to overcome the back pressure from the drying chamber

(drying racks) and maintain the desired drying temperature.

8. Mean ambient daytime air conditions: 29.6 °C and 62.67 per cent relative humidity (RH).
9. Moisture content after brining: 60% wet basis (w.b); final (desired) moisture content of fish: 15% w.b [12]; maximum drying temperature (to avoid casehardening): 55 °C [13].
10. The psychometric chart was used to estimate the quantity of fuel required per batch, the size of the blower needed, and the drying time, allowing for the calculation of production costs to be made.
11. Other considerations include: initial moisture content of fish at harvest = 75±1.2% w.b, density of air (ρ_a) = 1.225 kg/m^3, latent heat of vaporization of water (h_{fg}) = 2260 kJ/kg, specific heat of water = 4.186 kJ/kg °C, air velocity = 1.0, 1.5, and 2.0 m/s, specific heat capacity of air, c_p = 1.005 kJ/kg °C.

2.3 Design fundamentals

1. Mass of desorbed moisture, M_m

   The brined fish samples have a moisture content of 60%, so a 25 kg batch of brined fish contains 15 kg of moisture computed using the expression provided in the Appendix (Eq. (A1)).

2. Estimation of the quantity of air needed to extract the given mass of moisture, Q_a

   Using the psychometric chart (Figure 1) to determine the humidity ratios and properties of the drying air, with dry-bulb temperature, T_{ab} = 29.6°C, RH = 62.67%, this yields a value of 0.0174 kg of moisture per kg of air. This is the theoretical quantity of moisture extracted by drying the air, and a reasonable assumed pick-up factor for fish drying = 0.2 [13].

3. Blower size:

   The mass flow rate is converted to volumetric flow rate, Q_v. Using the psychometric chart to determine the specific volume of air, V_{sp} = 0.878 m^3/kg.

4. Estimation of heat energy from burning charcoal:

   The thermal requirement, Q for batch drying of the fish samples is shown in Appendix A (Eq. (A8)).

5. Quantity of charcoal required for burning

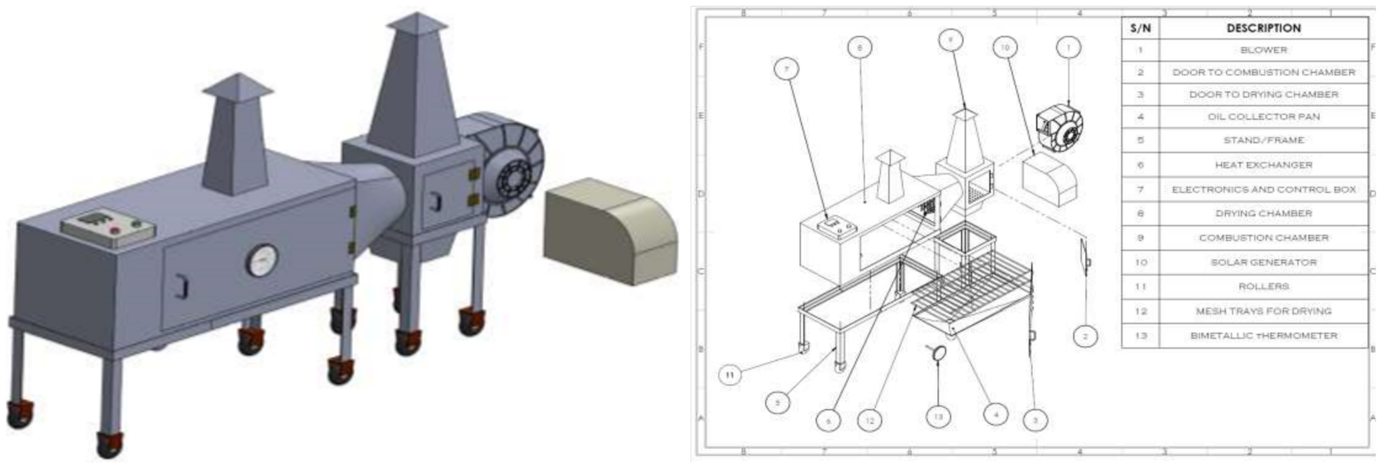
   Equation ((A9)) was used to calculate the amount of charcoal needed, m_c, to burn in the charcoal furnace (combustion unit).

6. Kiln capacity, V_k

   The volumetric kiln capacity was computed based on the mass and bulk density of the fish sample in the kiln, provided in Appendix ((A13)).

2.4 Key components and specifications

1. Combustion unit: This is a chamber that houses the charcoal chamber (in the shape of a frustum of a pyramid) used to generate heat for fish drying, specifically from solid fuel, such as charcoal. It is fabricated from a 1 mm-thick mild steel metal sheet, measuring 270 × 150 × 200 mm^3. A tapered-shaped chimney, 650 mm in height, was mounted on the combustion chamber (charcoal furnace) to ensure proper buoyancy and combustion. This unit is insulated/lagged with 20 mm-thick kaolin refractory material to minimize heat loss via conduction.
2. Drying chamber: This unit measures 1000 mm x 500 mm x 750 mm and houses the gutted fish undergoing drying. It contains wire-mesh trays and an oil collection pan. The interior of the drying chamber and its units were made of stainless steel. A chimney and an auxiliary exhaust fan are mounted on the top and side of the drying chamber, respectively. The drying chamber is insulated with a 20 mm-thick thermosetting polymeric material.
3. Blower: A direct current (DC) centrifugal blower of 5 blades, 0.5 hp, and 1 mm thickness was selected to be powered by an accumulator or solar generator. The blower draws in ambient air, which conveys heat into the heat exchanger unit.
4. Heat exchanger: A 2 mm thick mild steel material was constructed in-between the combustion chamber and the drying chamber to provide indirect heating, which prevents the deleterious effects of biomass smoke on food products, thus increasing the energy efficiency of the kiln.
5. Control unit: This is a microprocessor-controlled electronic box that regulates the temperatures and relative humidity of the drying kiln by switching off the DC blower when the drying chamber attains the optimum drying temperature of 60°C.
6. Castor wheel: This is a roller device mounted



(a) (b)

Figure 2. (a) Isometric view of the developed fish-drying kiln; (b) exploded view of the kiln.

on the base of the frame support of the entire fish-drying kiln for easy maneuverability.

7. Bolts and nuts: Hexagonal nuts and bolts of 10 and 14 mm size, respectively, are used to assemble the combusting and drying chambers for easy transportation.

8. Power generator: A 300 W solar generator to power the centrifugal DC blower.

2.5 Kiln description and drying experiments

2.5.1 Description of the developed kiln

The developed charcoal-fired fish-drying kiln was designed to handle a maximum batch size of 25 kg of fresh fish (Figure 2). The major components and technical descriptions of the drying kiln are as stated in the previous section. Heat of combustion is generated in the charcoal/combustion chamber and transferred to the drying chamber through the counter-flow heat exchanger that preheats the inlet air. The ambient air is sucked in through the DC centrifugal blower at varying speeds and preheated in the combustion chamber, and transferred through the heat exchanger (to avoid sample contamination—the carcinogenic effect of carbon) to the drying chamber and exits through the chimney. The drying chamber temperature and relative humidity are monitored and measured by an Arduino microprocessor unit and a bimetallic thermometer. An oil-collector pan is placed under the drying racks to capture natural oils and fats dripping from the fish samples during drying. It serves to improve the kiln's cleanliness, safety, and simplicity of upkeep. The DC blower is powered by a solar generator or a 75-amp-hour accumulator. The uniqueness of the kiln design lies in the incorporation of the counter-flow heat exchanger, oil collector pan, and heat flux control using the microprocessor.

2.5.2 Drying trials

The combustion chamber was loaded with 22.18 kg of hardwood charcoal and ignited. The preset drying temperature and air velocity were selected using the electronic control. The kiln, having attained a steady-state condition, was loaded with the drained, gutted samples with an initial moisture content of 60% w.b. The drying process was subjected to a uniform drying temperature of 55 °C, varying air velocities of 1.0, 1.5, and 2.0 m/s (64.8, 97.2, and 129.6 m^3/h), and batch sizes of 15, 20, and 25 kg. The constant drying temperature was used to avoid the case-hardening phenomenon typical for fish drying [13]. Drying tests were run in three replications for each air velocity-batch size treatment combination. The drying temperature is maintained by the Arduino microprocessor within a threshold of ±1°C by turning off/on the blower. The bimetallic thermometer and electronic-controlled thermistor sensors measure the temperature (55 ± 1 °C), and the relative humidity of the drying air varied between 82.4 ± 1.3% and 36.2 ± 5.1%. The drying chamber relative humidity (36.2 ± 5.08%) varies with batch size due to varying vapour pressure gradient. Moisture content and per cent weight loss, and drying time were measured at 10-minute intervals per drying cycle. The final desired moisture content (15% w.b — a safe level for sustained preservation) was determined when no discernible change was recorded between two consecutive mass measurements. The mass of charcoal in the burning chamber was measured and recorded. Energy and exergy evaluations were then conducted from these measured values. Additionally, drying rate, energy efficiency, percentage shrinkage, rehydration ratio, and eco-thermodynamic metrics were determined. All drying tests were conducted in triplicate to guarantee repeatability, and the average data were utilized for analysis.

2.6 Moisture content determination

The amount of desired moisture contained in the dried fish samples (m_t) was estimated using the standard expression (Appendix A Eq. (A14)).

2.7 Drying rate, $\|_d$

This refers to the amount of desorbed moisture from the fish samples per unit drying time, estimated using Appendix A (Eq. (A15)).

2.8 Rehydration capacity, ζ_R

This is the ability of a dried fish sample to absorb water and return to its initial size or texture after being soaked in water. It shows the efficiency with which the drying process is done and its degree of reversibility. ζ_R aids in determining if the conditions were excessively severe, as well as how drying impacted the interior structure. It is calculated using the standard technique reported by Doymaz and Ismail [14] , expressed in Appendix A (Eq. (A16)).

2.9 Shrinkage determination, ϕ_s

The estimation of percentage shrinkage in the dried fish samples measures the dimensional variations brought on by moisture desorption during the drying process. With the use of a digital vernier calliper, the geometric mean diameter of the samples is calculated before and after drying, and Equation ((A17)) was used to compute shrinkage (Appendix A, Eq. (A17)).

2.10 Useful energy for drying, Q_u

The energy utilized for moisture evaporation from fish samples is expressed as given in Appendix A (Eq. (A18)).

2.11 Energy efficiency

The energy efficiency of the kiln, η_e, which is the ratio of the useful energy consumed for drying to the overall energy supplied to the kiln, is provided in the appendix (Eq. (A19)) [15].

2.12 Specific energy

Specific energy (Q_{sp}), which is the energy consumption per kg of desorbed moisture, is calculated using Appendix A (Eq. (A20)).

2.13 Exergy analysis

The quality and efficiency of energy use in a fish-drying kiln fuelled by charcoal are evaluated using exergy analysis. Exergy analysis accounts for irreversibilities and losses from combustion, heat transfer, and drying inefficiencies, in contrast to energy analysis, which focuses on the amount. In a charcoal kiln, the fuel's chemical energy is transformed into heat energy to remove product moisture. However, environmental interactions, temperature gradients, and wasted exhaust heat all contribute to considerable exergy degradation. By measuring energy intake, output, and losses, this study helps identify deficiencies in the kiln system and recommends improvements, such as optimising airflow, integrating heat recovery, or enhancing insulation. Additionally, the determination of exergy is crucial when evaluating a system's capacity to provide productive work. Therefore, the exergy of the drying kiln is evaluated under the following headings:

1. Exergy inflow (from combustion of charcoal): This characterizes the optimum productive application of the heat obtained from the chemical potential of the charcoal fuel during combustion as the charcoal adjusts for atmospheric conditions. It is expressed using the empirical correlation as stated in Appendix (Eq. (A21) to (A23)) [16, 17].
2. Exergy destroyed (Ex_{des}): refers to the energy loss associated with a particular unit process, such as fish drying. This is expressed using Appendix A (Eq. (A24)).
3. Exergy efficiency (η_{ex}) of the fish-drying chamber is estimated using Appendix A (Eq. (A25)).

2.14 Sustainability impact evaluation (SIE)

Evaluating the sustainability impact of the charcoal-fired fish-drying kiln entails determining its effects on the environment, the economy, and energy. Although charcoal is an easily accessible biomass fuel, burning it emits greenhouse gases and particles that may adversely impact human health. To ascertain the long-term environmental impact of the kiln, the following essential metrics offer a multifaceted perspective on the sustainability of the fish-drying kiln:

1. Energy payback period (E_{pbp}): The energy payback period determines the duration taken by the kiln's usable energy production to repay the energy used in its development and operation. Greater energy sustainability is indicated by a

lower E_{pbp} value, estimated as Appendix A (Eq. (A26)) [18, 19].

2. Carbon emission (ϵ_{CO_2}): indicates the overall amount of CO_2 generated during the burning of charcoal. It is calculated using the expression provided in Appendix A (Eq. (A27)) [21].

3. Earned carbon credit (E_{CC}): Appendix A (Eq. (A28)) calculates the amount of carbon saved as a result of increased efficiency or the usage of renewable energy [21].

4. Sustainability index (I_s): It represents the total sustainability of the system based on exergy efficiency. Greater SI values signify improved conformity to environmentally friendly standards [14, 21]. This is given in Appendix A (Eq. (A29)).

5. Coefficient of environmental destruction (Y_{ed}): This metric (Appendix A, Eq. (A30)) measures the percentage of exergy intake that results in environmental deterioration [6].

6. Waste exergy ratio (χ_{we}): This is a measure of the percentage of total energy input that is wasted, provided in Appendix A (Eq. (A31)) [21].

7. Environmental impact factor (k_{ei}): This establishes a single-impact index by combining indicators for exergy destruction (loss) and emissions [6]. It was computed using the standard expression (Appendix A, Eq. (A32)).

8. Improvement potential (I_p): Measures the extent to which recovered energy remains usable to improve the system's performance and get it closer to optimal (reversible) performance. That is, it indicates the potential thermodynamic improvement that can be achieved in the drying kiln, given by Appendix A (Eq. (A33)) [6, 15].

The application of these sustainability parameters improved the performance of the fish-drying kiln with the aid of the heat exchanger unit, which considerably reduced or circumvented carbon deposition on the fish samples and CO_2 release compared to conventional versions. The kiln's lower environmental impact is confirmed by metrics like low χ_{we}, short E_{pbp}, and high I_s. Furthermore, possible financial incentives through carbon trading schemes are highlighted by E_{CC}. Therefore, the kiln's potential for sustainable fish drying is firmly established by these multi-criteria evaluations.

2.15 Economic evaluation

In this work, the developed charcoal-fired fish-drying kiln was evaluated for commercial sustainability and economic feasibility at varying batch sizes and airflow rates. According to the method described by Lehmad et al. [20] and Hadibi et al. [23] , economic variables such as annual savings, life span of the kiln, payback period, yearly capital and maintenance costs, benefit-cost ratio, etc., were calculated.

2.16 Uncertainty assessment

Evaluating the accuracy of variables used in drying research requires the use of uncertainty assessment. The uncertainties associated with the drying variables include the amount of charcoal consumed, temperature, airflow rate, relative humidity, drying rate, energy efficiency, etc., as summarized in Table 1. According to Alfiya et al. [6] and Lakshmi et al. [24] , experimental uncertainties can be caused by a range of factors, including choice, calibration, reading, observation, techniques, and location. Uncertainty is represented by Appendix A (Eq. (A34)). The total uncertainty of ±4.66% is within the widely recognized range of ±3 to 7% for heat drying tests, suggesting that measurement differences are negligible and acceptable from a scientific standpoint. This negligible margin guarantees that the reported drying and energy characteristics can be consistently replicated under comparable conditions of operation.

Table 1. Uncertainties of the drying kiln experimental factors.

Experimental variables	Unit	Uncertainty (%)
Drying chamber temperature	°C	±0.50
Volumetric airflow rate	m^3/h	±0.33
Relative humidity	%	±1.35
Mass loss	kg	±0.42
Moisture content	% w.b	±0.17
Drying rate	g/g	±0.08
Drying efficiency	%	±1.81
Total	%	±4.66

From Table 1, the experimental measurements in this present work revealed a ± 4.66% uncertainty rate, suggesting an acceptable level of reliability in the collected experimental results. This V_y value, which is in line with literature values [6, 20], compensates for possible mistakes caused by instruments, environmental fluctuations, and methodological constraints, thus validating the performance of the drying kiln.

2.17 Justification of selected parameters

Since air velocity and batch size have the most effect on the flow of heat, combustion efficiency, and moisture desorption characteristics in charcoal-fuelled dryers, they were selected as the main experimental factors. The homogeneity of hot air distribution within the drying chamber, the intensity of combustion in the furnace, and the convective heat flux that reaches the fish are all directly influenced by air velocity. Air velocity is a technically crucial element since even slight variations can have a substantial impact on drying time, specific energy consumption, and exergy efficiency. Conversely, batch size influences fuel requirements and heat recovery efficiency, regulates the thermal load on the fish drying kiln, and determines the residence period of food materials in the drying domain. Larger loads usually affect the kiln's gross thermodynamic behaviour by increasing moisture load, decreasing drying rate, and changing airflow resistance. For analyzing dryer performance and guaranteeing substantial optimization under actual micro-scale fish processing situations, these metrics thus constitute the most useful, sensitive, and industry-relevant variables.

The developed fish kiln has a number of novel attributes that set it apart from traditional charcoal-based dryers, in addition to the relevance of the chosen test variables. By rerouting exhaust heat back into the drying stream, the counter-flow heat exchanger improves thermal recovery and lowers charcoal-fuel losses. Constant drying conditions are ensured by a microprocessor-based control system that automatically controls airflow and enhances combustion stability. Additionally, an extensive performance outlook that is seldom employed in small-scale local dryers is provided by the combined energy-exergy-environmental-economic assessment scheme. Collectively, these innovative features increase productivity, lower operating expenses while rendering the kiln more suitable for contemporary, sustainable fishing operations.

3 Results and Discussion

Each drying test was carried out in triplicate, and the accompanying standard deviations (mean $\pm$ SD) have been incorporated in the average values provided in the tables. These variance estimates increase the statistical reliability and reproducibility of the findings by reflecting the inherent variations evident among replicated runs. However, error bars were taken into consideration for the graphical illustrations, but they were removed since they created too much visual clutter. For clearer interpretation, the variability is instead shown openly as standard deviations in the relevant tables. More so, the root-sum-square method was used to assess uncertainty propagation for all derived variables (such as specific energy, exergy, and performance indices); however, the resulting intervals were expressed numerically instead of plotted because the addition of shaded confidence bands made the graphs visually dense and challenging to interpret.

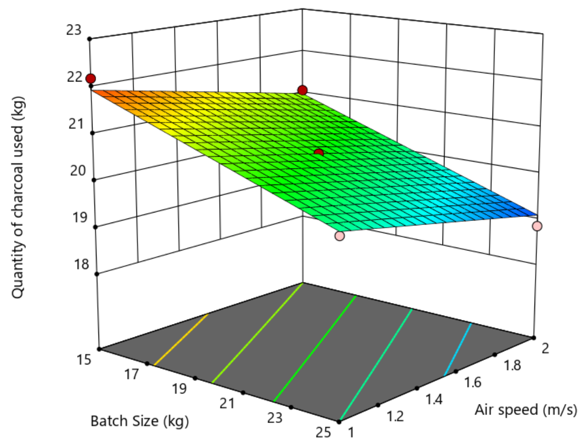


Figure 3. A 3D plot of charcoal usage at varying operational conditions.

3.1 Fuel consumption analysis

The amount of charcoal fuel consumed in drying the catfish samples in varying batches and air speeds is shown in Figure 3. The quantity of charcoal fuel used reduces as batch size and air speed increase. At a reduced air speed of 1.0 m/s and a small batch size of 15 kg, the maximum charcoal consumption of 22.18 kg was observed, whereas with an elevated air speed (2.0 m/s) and a larger batch size (25 kg), the lowest charcoal usage of 18.85 kg was noted. This observable pattern is technically imperative, as the transfer of heat is less productive at minimal air velocity, which results in prolonged drying durations and higher consumption of charcoal. This observation is substantiated by the findings of EL-Mesery et al. [19]. Also, lower batch sizes lead

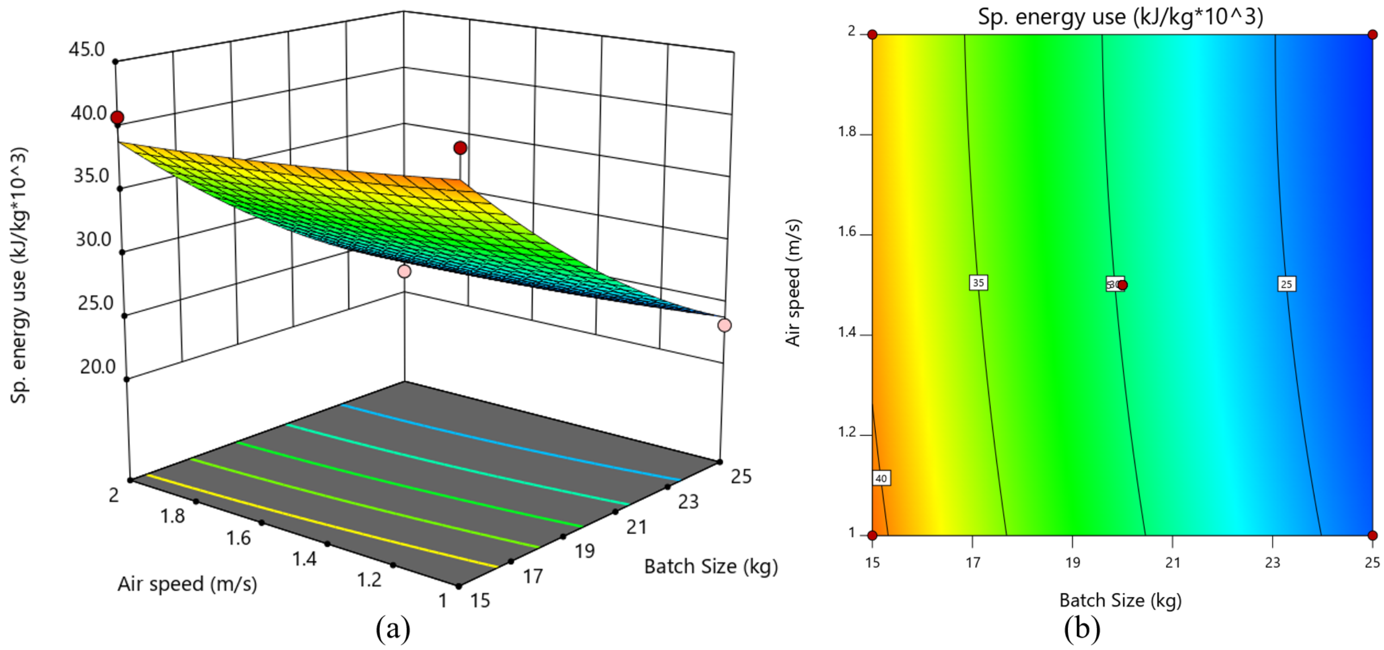


Figure 4. 3D response surface and contour plots of the influence of batch size and air speed on the specific energy use.

to underutilization of the heat produced, requiring more charcoal consumption per kg of dried fish sample. In contrast, increased batch sizes maximize heat dispersion (from the combustion chamber to the drying chamber through the heat exchanger unit), and greater airspeeds improve convective drying, which lowers charcoal-fuel consumption and increases thermal economy. This declining tendency in the use of charcoal is confirmed by the gradient colour variation from orange to blue. These results lend credence to better energy management and cost-cutting techniques in conventional fish dryers.

3.2 Specific energy use

The sustainability study of the developed charcoal-fired fish-drying kiln incorporated with a heat exchanger was carried out at varying batch sizes and airflow rates. The energy performance of the system at these process conditions is shown in Figure 4. The 3-dimensional surface plot shows a distinct pattern: the specific energy consumption (Q_{sp}) is greatly decreased by increasing the batch size and air speed. This behaviour is explained by increased convective heat transfer at greater air velocities, which facilitates quicker moisture extraction and enhanced thermal efficiency when heat use is maximized by greater batch sizes. The largest batch size (25 kg) and air velocity (2.0 m/s) resulted in the lowest SEC of 21.87×10^3 kJ/kg, whereas the lowest air velocity (1.0 m/s) and small batch size (15 kg) resulted in the most elevated Q_{sp} of 42.88×10^3 kJ/kg. These results support previous research by Mugi et al. [17] and Kumar et al. [22] , which found that proper loading and increased airflow enhance drying kinetics and energy efficiency by lowering passive heat loss. The predicted Q_{sp} values are shown by the colour bands in the 3D plot, which go from blue (low Q_{sp}) to red (high Q_{sp}). Whereas warmer hues (yellow-red) denote less effective regions, cooler hues (blue-green) emphasize effective process conditions. The actual experimental findings in comparison to the Q_{sp} model's predictions are indicated by the red and pink design points superimposed over the surface. Notably, pink hollow spots indicate situations where measured values were lower, signifying better-than-expected energy performance, while red solid regions indicate situations where the experimental Q_{sp} was greater than predicted, indicating localized inefficiencies or thermal loss. By emphasizing locations where actual performance deviates from predicted outcomes, these design locations improve the model's accuracy. Mujumdar [25] supports this strategy in assessments of thermal dryers. The quadratic regression model (Equation 1) describes the statistical correlation between the experimental parameters and Q_{sp}:

$$Q_{sp} = 29.75 - 8.24b - 0.71v + 0.21bv + 1.51b^2 + 0.3v^2 \quad [R^2 = 0.9677] \tag{1}$$

where b and v represent the batch size (kg) and air velocity (m/s), respectively.

The Q_{sp} model's strong coefficient of determination ($R^2 = 0.9677$) signifies that the regression model accounts for around 96.77% of the variation in specific energy use. It also illustrates an impressive correlation between the specific energy of moisture desorption and process conditions. This implies that the model has a very high degree of fit and prediction potential, as indicated by the predicted versus actual (close clustering) and normal residual plots (Figure 5), which further demonstrate that the proportion of normal and anomalous data in the study did not introduce any discrepancies. Also, the Q_{sp} model is statistically significant ($p < 0.05$). The results of the analysis of variance indicates that air speed and batch size had considerable influence on the specific energy utilization ($F = 11.72$, $P = 0.0019$), i.e., a function of the sample load processed by the kiln. The negative linear coefficients substantiate that raising the batch size and airflow rate diminishes Q_{sp} initially. Nevertheless, the positive quadratic factors, b^2 and v^2, imply a curvature in the energy response, suggesting that, at a certain point, any rise in these parameters could not result in appreciable reduced energy costs [21]. The positive interaction term bv suggests a synergistic impact. A mild increase in b and v variables jointly improves energy efficiency more than raising one independently. This energy model aligns well with the experimental outcomes and provides a solid foundation for optimizing drying kiln operation.

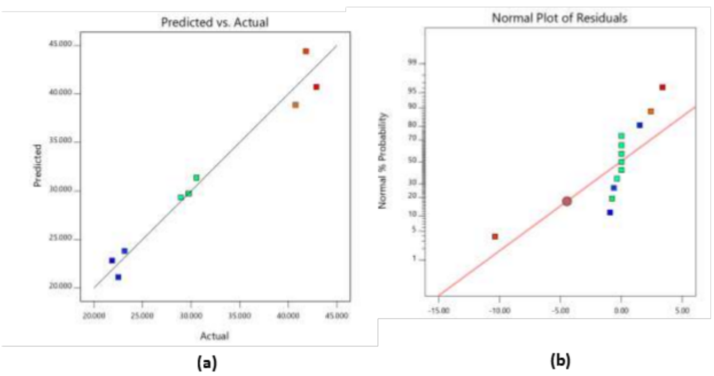


Figure 5. Statistical plots of (a) the predicted versus measured specific energy use of the fish drying kiln; (b) normal % probability plot of specific energy use residuals.

Model validation: A multi-stage validation procedure was used to confirm the reliability of the developed models. When compared to the relevant experimental observations, the predicted values of specific energy consumption, drying rate, exergy efficiency, and other pertinent responses showed close agreement with marginal variability. The distribution and randomness of errors were assessed using residual analysis, which verified that there was no systematic bias in the model fits. The reproducibility of the data showed consistent patterns throughout repeated trials, and all drying tests were carried out in triplicate. To ensure uniform airflow, temperature, and combustion factors before taking measurements, thermal steady-state inspections were also performed during each test. This extensive validation process improves the reported performance of the constructed fish kiln's credibility and reproducibility.

3.3 Energy efficiency, η_e

As illustrated in Figure 6, the interaction between air speed and batch size on η_e of the fish-drying kiln. It reveals that increasing air speed and batch size improve the kiln's η_e. This development is due to improved heat transfer via convection at greater air velocities and increased heat usage with greater batch weights, which reduces heat loss per unit of mass. The energy efficiency of the drying kiln was obtained in the range of $25 \leq \eta_e \leq 30.5$ ($\pm$ 1.25%), with corresponding air speeds and batch sizes of 1.0 m/s, 15 kg, and 1.5 m/s, 25 kg, respectively. This, however, indicates a better thermal utilization potential of the developed fish drying kiln in comparison with the reports of Alfiya et al. [6] and Dhanushkodi et al. [26] , which yielded maximum η_e values of 24.15% and 9.0%, respectively.

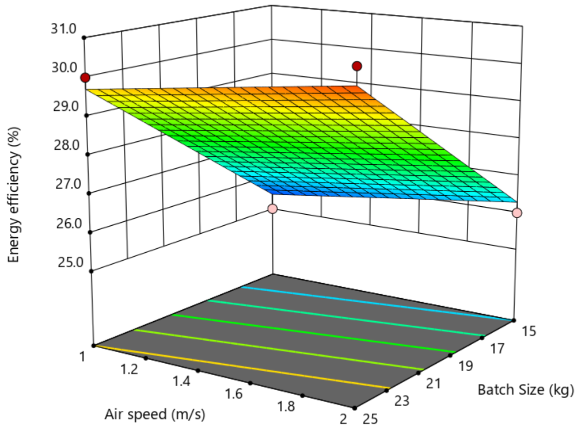


Figure 6. Energy efficiency of the drying kiln as affected by air speed and batch size.

3.4 Catfish drying dynamics

The drying responses of the catfish samples in the three studied batch sizes (15, 20, and 25 kg) are shown in Figure 7, illustrating the percentage of loss of mass with drying time. According to the results, the 25 kg batch required about 330 minutes (5½ h) to attain a comparable moisture decrease (15% w.b) with 52.72% weight loss, whereas the smaller batch sizes (15 kg) exhibited more rapid and larger moisture extraction, achieving over 52% weight loss in 180 minutes. This behaviour is explained by resistance to airflow and the dispersion of heat loads. A greater surface area is exposed per unit mass in smaller batches, which improves mass transfer and convective heat while accelerating interior moisture mobility. On the contrary, the other hand, greater airflow resistance caused by larger batch sizes results in thermal stratification and longer drying times. This is consistent with research by Darvishi et al. [27], which found that due to restricted permeation of heat and vapour diffusion, higher material thickness or load lowers drying rate. It follows that although larger batch sizes enhance charcoal-fuel consumption and energy efficiency (as shown in previous graphical plots), they could also decrease drying rate and consistency, requiring process optimization or trade-offs to guarantee high-quality dried samples without using a large amount of energy.

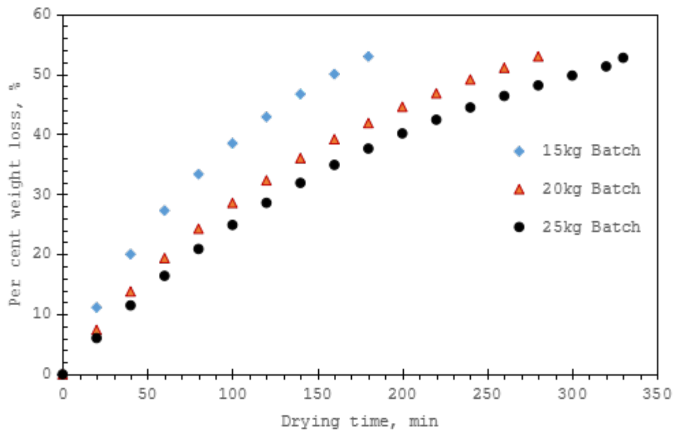


Figure 7. Variation of percentage weight loss of catfish with time of drying at different batch sizes.

The drying rate curves for three batch sizes (15, 20, and 25 kg) over time are shown in Figure 8. Following an initial surface evaporation phase, the drying rate shows a typical falling-rate pattern, suggesting that interior diffusion is predominantly responsible for controlling moisture diffusion. While the 25 kg batch had a more constant drying rate, but lower initially, the 15 kg batch had the highest kicking-off drying rate (~0.083 kg/min) but dropped more quickly. For all batch sizes, air speed had a major impact on the drying dynamics. The maximum air speed (2.0 m/s) among the three air speeds under study consistently increased the drying rate, particularly in the early phases. This is explained by quicker extraction of moisture made possible by enhanced convective heat flow and a larger moisture concentration difference at the fish's exterior. Given the decreased boundary layer interference and a drop in air momentum, which impeded moisture transfer from the fish exterior, drying rates were continually decreased at 1.0 m/s. At 1.5 m/s, an intermediate drying response was noted, providing a compromise between drying homogeneity and energy intake. These outcomes are consistent with the observations of Erdem et al. [2] and Doymaz et al. [14], who reported that during convective drying, raising air velocity speeds up the movement of moisture and boosts mass transfer coefficients. Consequently, an economic benefit in attaining quicker, more energy-efficient, and consistent drying may be obtained by combining greater airflow with suitable batch loading.

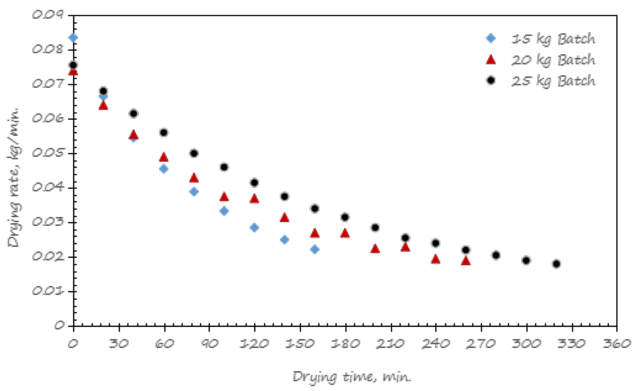


Figure 8. Effect of drying time on the drying rate of catfish of varying batch sizes.

3.5 Rehydration behaviour

Rehydration is an essential quality metric for dried fish as it shows the degree of physicochemical and structural alterations that take place after drying. The rehydration ratio rose steadily with immersion duration, demonstrating that the dried catfish preserved an appropriate porosity structure to permit water absorption. A swift rehydration in the first phase was followed by a prolonged absorption phase that occurred as the fish samples reached optimum moisture content. This dual-phase trend is in line with the diffusion-driven moisture transport typically observed in dried plant-based materials. The result of the rehydration attributes of the dried catfish samples from the various batch sizes at a constant drying temperature (55°C) and air velocity (1.5 m/s) is displayed in Figure 9. For all batch sizes, the rehydration ratio, ζ_R rose with drying time and showed the usual sigmoidal rehydration trend. The mass of the rehydrated 15, 20, and 25 kg batch fish samples was 11.08, 14.49, and 17.85 kg, respectively, with ζ_R values of 1.57, 1.54, and 1.51 at 100 minutes. The substantial moisture differential between the soaking solution and the dried fish samples caused a quick water absorption period during the first 100 minutes, which aided capillary absorption into intercellular spaces [6, 17]. The rehydration rate steadily dropped after 100 minutes, reaching equilibrium between 240 and 300 minutes, when the ζ_R values for the three batch sizes remained stable at 1.74, 1.72, and 1.71, respectively. This plateau is ascribed to structural constraints brought on by irreversible shrinkage and protein degradation during drying, as well as saturation of water-binding pores. Significantly, the bigger batch (25 kg) continuously showed somewhat lower ζ_R values than the smaller batches. This is probably because the larger batch experienced more noticeable structural collapse during drying, which made it more difficult for the water to be absorbed during rehydration. These results are consistent with earlier findings by Ruan et al. [29] , who found that the water absorption capacity of denser, more compacted dried fish tissues from higher drying batches is decreased. Additionally, the constant trend for the batches implies that the microscopic makeup and rehydration processes of dried catfish are influenced by batch size. This knowledge is crucial for enhancing rehydration procedures and evaluating the quality of the final fish product to ensure consumer acceptability.

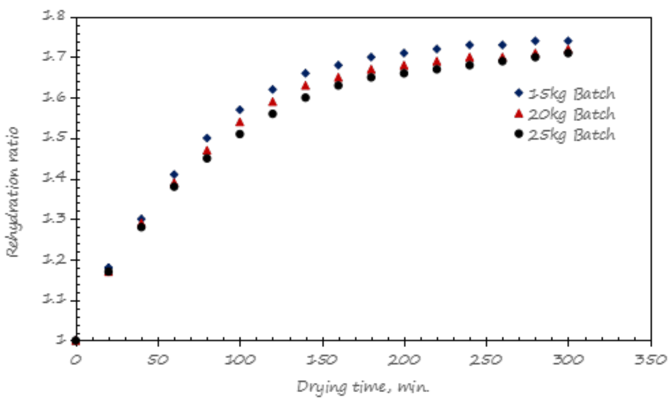


Figure 9. Rehydration behaviour of the dried catfish samples from different batch sizes at a constant drying temperature and air velocity.

However, moisture uptake attributes were quantitatively established by fitting the experimental rehydration data with the Peleg model, which is often utilized to predict water absorbance in dried food products due to its ease of use and high empirical outcome. The model is stated as follows:

$$M(t) = M_0 + \frac{t}{k_1 + k_2 t} \tag{2}$$

where $M(t)$ is the moisture content at time t, M_0 is the initial moisture content, k_1 is the Peleg rate constant (associated with the initial rehydration rate), and k_2 is the Peleg capacity constant (associated with the highest achievable moisture).

The calculated values of k_1, k_2, and the determination coefficient (R^2) are reported in Table 2. While the moderate k_2 values suggest that the dried fish samples have considerable water-holding capacity, the relatively low k_1 values show a quick initial rehydration rate. The considerable R^2 values (> 0.96) suggest that the Peleg model offered an outstanding fit to the data from the experiments. In all, the Peleg model adequately represented the rehydration response of the kiln-dried fish products, indicating that the drying technique retained adequate microstructural quality for satisfactory water absorption. This additionally validates the appropriateness of the developed kiln for the production of dried fish of desirable reconstitution standard.

Table 2. Parameters of the Peleg model for rehydration of dried catfish.

Parameter	Value	Interpretation
k_1 (min · kg/kg)	0.85 ± 0.04	Higher initial water absorption is indicated by lower k_1 values.
k_2 (kg^{-1})	0.07 ± 0.01	Controls the optimum moisture absorption potential.
R^2	0.97	Shows strong correlation between model and data.

3.6 Shrinkage

The result of the shrinkage characteristics of the varying batch sizes of the dried catfish samples at a constant drying temperature (55°C) and air velocity (1.5 m/s) is shown in Table 3. The findings indicate that shrinkage increases with batch size, ranging from 20 $\leq \phi_s \leq$ 30.54% (± 2.25). This observed pattern implies that the heat differential and structural stresses inside the fish substrate may exacerbate with increasing batch size, resulting in more noticeable tissue shrinkage and deformation. Greater drying loads may enhance intracellular resistance to moisture movement, resulting in tighter packing of muscle fibers and structural collapse [29]. Fitri et al. [31] noted that geometric shrinkage is a crucial sign of physical deterioration in dried fishery products, and the shrinkage proportions also fell within normal limits. Despite the mild variations across batches, the pattern highlights how crucial it is to regulate product thickness and load configuration during fish drying in order to reduce textural loss and guarantee rehydration capability [24]. The shrinkage result of this present study is within the range of the findings of Anieszani et al. [32] , who obtained ϕ_s values in the range of 17.02–32.61% for anchovy fish samples and at par with the report of Wincy et al. [33] for dried shrimps (21.47%).

Table 3. Geometric mean diameter-based shrinkage of dried catfish samples.

Batch size (kg)	x_1 (cm)	x_2 (cm)	Shrinkage, ϕ_s (%)
15	35.00	28.00	20.00
20	37.00	27.20	26.49
25	39.00	27.10	30.54

3.7 Exergy analysis

Exergy assessment quantifies usable energy, losses, and inefficiency of the system to offer insights into the sustainability and quality of the energy utilized in the fish-drying kiln. Figure 10 shows the major exergy indicators considered to estimate the influence of air velocity at a uniform batch size of 20 kg. The exergy efficiency improved in the range of $42.88 \leq \eta_{ex} \leq 49.75\%$ ($\pm$ 0.48) when air velocity was raised from 1.0 to 2.0 m/s, but exergy inflow dropped from 302.5 MJ to 288 MJ, thus showing improved thermodynamic performance. According to this pattern, faster air speeds improve heat and mass transfer, which lowers the energy requirement for moisture desorption and boosts the kiln's overall efficiency. As airspeed increased, energy loss, a fundamental measure of the kiln's irreversibility, decreased, suggesting improved energy efficiency and less entropy development. As a result, at 1.0 m/s, the coefficient of environmental damage (Y_{ed}) decreased from 2.0 to 1.64. This suggests more sustainable use of energy at greater airflow rates and less environmental impact. These outcomes are consistent with study results by Valencia-Ochoa et al. [34] and Ndukwu et al. [35] , which found that increased airflow reduces environmental impact while increasing drying energy efficiency. According to Wincy et al. [33] , crop dryers that are more efficient and have less exergy loss are also more ecologically friendly. Additionally, Sturm et al. [36] stressed how crucial it is to optimize drying settings to accomplish thermally sustainable processes. These findings highlight the need to regulate air velocity appropriately to enhance the energy and sustainability performance of fish-drying operations.

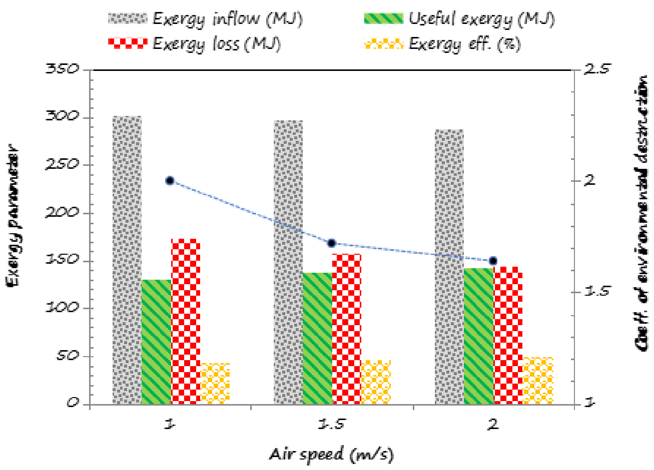


Figure 10. Exergy and sustainability performance metrics of the charcoal-fired fish-drying kiln.

3.8 Sustainability impact evaluation (SIE)

The sustainability of thermal agricultural dryers generally hinges on their energy outcomes, ecological footprints, and thermodynamic viability [21]. A comprehensive analysis of energy consumption, energy flow, and environmental indicators provides key insights into the ecological suitability and operational performance of the drying kiln. The mean sustainability index of the drying kiln (I_s) was obtained as 1.68, indicating high thermodynamic sustainability and low environmental effect [21, 36], whereas the average payback period (E_{pbp}) is 0.3 years (3 months and 6 days), which, in turn, confirms that the drying kiln is sustainable and economically viable, as well as demonstrating incredibly quick capital return, considerably faster than that of conventional West African small-scale farmers' fish dryers [37]. According to Alfiya et al. [6] , solar dryers have E_{pbp} of 0.78 years. The results of other SIEs are given in Table 4. The amount of carbon emitted per drying cycle (ϵ_{CO_2}) dropped from 62.77 to 53.35 kg CO_2 due to enhanced heat transfer at greater air velocity and improved efficiency of batch loading. This treatment combination lessened the quantity of fuel used for each kg of dried catfish, thus boosting ecological

Table 4. Sustainability indicators of the charcoal-powered fish-drying kiln at varying process factors.

Velocity (m/s)	Batch Size (kg)	ϵ_{CO_2} (kg CO_2)	E_{CC} (₦)	χ_{we} ($\pm$ 0.21)	k_{ei} ($\pm$ 0.25)	I_p ($\pm$ 0.41MJ)
1.0	15	62.77	244.75	0.85	226.22	579.54
1.0	20	59.63	339.59	0.83	189.63	534.37
1.0	25	56.49	435.96	0.80	159.69	490.91
1.5	15	61.20	292.17	0.85	214.97	561.73
1.5	20	58.06	388.54	0.82	180.24	517.16
1.5	25	54.92	484.91	0.79	151.75	474.29
2.0	15	59.63	339.59	0.84	204.21	544.09
2.0	20	56.49	435.96	0.81	171.24	500.11
2.0	25	53.35	532.33	0.79	144.12	457.84

ϵ_{CO_2} = Carbon emission, E_{CC} = Earned carbon credit, χ_{we} = Waste exergy ratio,
k_{ei} = Environmental impact factor, I_p = improvement potential.

sustainability. With a rise in air speed and batch size, combustion of charcoal improves, resulting in reduced ϵ_{CO_2} for each dried catfish sample. This increases the earned carbon credit (E_{CC}) from ₦ 244.75 (at 1.0 m/s, 15 kg) to ₦ 532.33 (at 2.0 m/s, 25 kg), indicating that optimal operating conditions result in higher carbon savings for the kiln. The observed trend suggests that while bigger batch sizes minimize emissions per unit of output and increase carbon credits, increased velocity improves the combustibility of charcoal and drying efficiency. The waste exergy ratio, χ_{we} from 0.850 to 0.790 ($\pm$ 0.21) when air velocity rises from 1.0 to 2.0 m/s and batch size extends from 15 to 25 kg, suggesting a drop in exergy loss with regard to input. This demonstrates that the kiln's thermodynamic performance is increasing as greater amounts of the energy inflow are transformed into productive work. A comparable decrease in the environmental load for each drying cycle is reflected in the environmental impact factor (k_{ei}), which drops from 226.22 to 144.12 ($\pm$ 0.25). This trend demonstrates how operational optimization may reduce waste heat discharge and CO_2 emissions. This trend demonstrates the beneficial impact of process optimization in reducing ϵ_{CO_2} and thermal waste discharge. Additionally, as the air speed and batch size rise, the improvement potential (I_p) decreases dramatically from 579.54 to 457.84 ($\pm$ 0.41MJ), indicating that less energy is lost and the kiln gets more efficient, reaching a more sustainable and optimum level under enhanced process conditions. The designed kiln performs within comparable limits for specific energy consumption, drying time, and exergy efficiency, according to a comparison with comparable biomass, solar-biomass, and conventional charcoal-fired dryers documented in the literature, as well as with FAO-recommended drying settings for small-scale industrial kilns. These benchmarks show that the system's performance is appropriate for replication and scale-up under normal small-scale fish processing settings, in addition to being compatible with well-established drying methods.

3.9 Economic evaluation

The primary goal of the economic evaluation of the developed charcoal-powered fish-drying kiln is to ascertain that it can operate profitably. The economic assessment of this work was carried out based on the methodology described in the works of Lehmad et al. [20] , Nwakuba et al. [21] , and Hadibi et al. [23]. A few relevant factors were taken into account, considering the current status of the Nigerian economy and the kiln's estimated cost implications, which are shown in Table 5. Varying the batch size from 15 to 25 kg considerably boosts the financial outcome across all critical parameters, according to the economic assessment of the fish-drying kiln at uniform air temperature and speed. Due to the distribution of fixed costs like labour, electricity, and capital loss over greater quantities, the per-unit cost of drying decreases from ₦26.13/kg at a 15 kg batch to ₦15.68/kg at a 25 kg batch, demonstrating improved cost efficiency.

With 250 drying days, the savings increase from ₦15,500 to ₦27,450 each batch as a result of this increased efficiency, increasing the annual savings from ₦3.88 million to ₦6.86 million. Profitability is directly boosted by a rise in throughput, while capital and maintenance costs remain constant. In addition, the payback period decreases from 0.33 years (3 months and 29 days) at 15 kg to 0.27 years (3 months and 7 days) at 25 kg, indicating a higher return on the capital cost and a lower level of financial uncertainty. Additionally, the benefit-cost

Table 5. Comparative economic assessment of the charcoal-powered fish-drying kiln at varying batch sizes.

Economic Factor	15 kg	20 kg	25 kg
Batch size (kg)	15	20	25
Maintenance cost (% yearly capital cost)	10	10	10
Cost of fresh catfish (₦/kg)	1,800	1,800	1,800
Selling price of dried catfish (₦/kg)	5,500	5,500	5,500
Yearly operation (days)	250	250	250
Capital cost (₦)	500,000	500,000	500,000
Dryer max. capacity (kg/day)	50	50	50
Life span (years)	19.68	19.68	19.68
Electricity cost (₦/year)	20,000	20,000	20,000
Yearly capital cost (₦)	27,989	27,989	27,989
Labour cost (₦/batch)	3,000	3,000	3,000
Yearly maintenance cost (₦/year)	50,000	50,000	50,000
Total yearly cost (₦)	97,989	97,989	97,989
Unit cost of drying (₦/kg)	26.13	19.60	15.68
Savings per batch (₦)	15,500	21,750	27,450
Yearly savings (₦)	3,875,000	5,437,000	6,862,500
Payback period (years)	0.33	0.3	0.27
Benefit-cost ratio	1.98	2.78	3.59

1 USD = ₦ 1,529.68 (as of July 5, 2025).

Table 6. Comparative benchmarking of current results against previous dryers.

Study	Dryer Type	Product	Drying duration (h)	Thermal efficiency (%)	Fuel consumption (kg/batch)	Remarks
Ezurike et al. [4]	Modified smoking kiln	Tilapia	$4 \leq t \leq 6$	$21 \leq \eta_{th} \leq 29$	$3 - 4.2$	Enhanced airflow for combustion.
Asamoah [5]	Charcoal-fired fish kiln	Catfish	$5 \leq t \leq 7$	$15 \leq \eta_{th} \leq 22$	$4.5 - 6$	Conventional Ghanaian kiln
Alfiya et al. [6]	Biomass-solar hybrid dryer	Yam	$6 \leq t \leq 8$	$19 \leq \eta_{th} \leq 27$	$3.2 - 4.8$	Manual operation in mixed-mode.
Present study (2025)	Counter-flow heat recovery fish kiln	Catfish	$180 \leq t \leq 330(\pm 4.5)$ min	$25 \leq \eta_e \leq 30.5(\pm 1.25)$, $42.88 \leq \eta_{ex} \leq 49.75(\pm 0.48)$	$18.85 - 22.18$	Microprocessor-controlled with heat recovery.

ratio increases considerably with batch size, ranging from 1.98 at 15 kg to 3.59 at 25 kg, confirming the improved return on investment and economic viability at larger batch sizes. Even with economic factors like interest rate (15%), inflation rate (24%), and salvage and maintenance expenses (10%), the kiln's lengthy life expectancy of 19.68 years keeps the annual capital cost stable at ₦27,989. Due to this stability, the cost structure is predictable, making batch size the primary control mechanism for profitability. The 25 kg batch is the most economically viable choice for long-term drying operations because, in basic terms, processing bigger batch sizes maximizes the kiln's 50 kg/day capability and produces noticeably superior economic results. The results of the economic assessment are comparable to the findings of Alfiya et al. [6] for shrimp and anchovy samples in a biomass dryer.

3.10 Comparative benchmarking with present dryers

Table 6 presents a benchmarking comparison with published performance indices from comparable dryers in the literature, providing context for the performance of the developed kiln. The findings demonstrate that the amount of fuel used, drying time, and thermal efficiencies attained in the present study either match or surpass the ranges documented by Ezurike et al. [4] , Asamoah et al. [5] , and Alfiya et al. [6].

4 Conclusion

The development and sustainability analysis of a charcoal-powered fish-drying kiln incorporating a heat exchanger was successfully carried out. The dryer demonstrated exceptional thermal and operational performance at different air flow rates and batch sizes. The results showed that higher batch size and air velocity enhanced thermal efficiency. The highest charcoal utilization (22.18 kg) was recorded at a 15 kg batch size and 1.0 m/s air velocity, whereas the lowest consumption (18.85 kg) was recorded at 25 kg and 2.0 m/s. The drying period varied from $180 \leq t \leq 330$ ($\pm$ 4.5) minutes for 15 and 25 kg batch sizes, respectively, and in each case, the weight loss was in excess of 52%. These findings confirm that convective drying is improved by optimal airflow, whereas larger batch sizes boost fuel efficiency but can marginally impede the drying rate. The drying rate varied between $0.041 \leq \mathcal{K}_d \leq 0.083$ ($\pm$ 0.0035) kg/min, at process conditions of 25 kg batch size and 1.0 m/s air velocity, and 15 kg batch size and 2.0 m/s air velocity, respectively. The rehydration ratio (ζ_R) varied with time and ranged between $1.71 \leq \zeta_R \leq 1.74$ ($\pm$ 0.15), for the 25 and 15 kg batches, respectively, with a minimal per cent sample shrinkage of $20 \leq \phi_s \leq 30.54$ ($\pm$ 2.25%) range.

Batch size and air velocity considerably reduced the specific energy consumption, which dropped from 42.88×10^3 kJ/kg (15 kg, 1.0 m/s) to 21.87×10^3 kJ/kg (25 kg, 2.0 m/s), demonstrating the synergistic impact of both airflow and heat loading on drying efficiency, and exergy efficiency increased from $42.88 \leq \eta_{ex} \leq 49.75\%$ ($\pm$ 0.48), suggesting improved thermal usage with increased airflow and loads. Environmental metrics affirmed the drying kiln's eco-sustainability with decreasing emissions of carbon dioxide (from 62.77 to 53.35 kg CO_2 per batch), a lower waste exergy ratio (from 0.850 to 0.790), and a greater carbon credit of ₦ 532.33 when the batch size and air velocity are increased. The sustainability metrics, such as I_s (1.68) and I_p (457.84 MJ), confirmed the environmental sustainability of the kiln. Economically, the kiln proved to be highly profitable. Increasing batch sizes from 15 to 25 kg reduced drying costs from ₦26.13 to ₦15.68, resulting in yearly savings of ₦3.88 million to ₦6.86 million. The payback period declined from 0.33 to 0.27 years (approximately 3 months), but the benefit-cost ratio grew from 1.98 to 3.59, indicating quick capital recovery and long-term financial viability.

Notable technical, environmental, and economic benefits are demonstrated by the kiln's performance, notably at operational settings of 25 kg batch size and 2.0 m/s. These findings place the kiln as a viable, energy-efficient, and cost-efficient appealing option for enhancing conventional fish-drying techniques in sub-Saharan Africa and beyond. Future studies may consider incorporating the kiln with solar energy sources and a heat recovery unit, adopting real-time smart controls for airflow and drying temperature, and performing a life cycle sustainability analysis (LCSA) and emission modelling to improve energy efficiency and extend the application to other food products.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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Appendix A: Mathematical Formulations

Mass of desorbed moisture, M_m:

$$M_m = \frac{M_b M_i}{100} = 15\,\text{kg} \tag{A1}$$

where M_b and M_i are the mass per batch of fish (25 kg) and the initial moisture content of brined fish (60% w.b). This implies that a 25 kg batch sample at 60% M_i has 15 kg of moisture.

Therefore, after drying, the samples' M_i will be reduced to 15% w.b, and the mass of the dry matter, M_d, at the desired moisture level will be:

$$M_d = (M_b - M_m) = 10\,\text{kg}. \tag{A2}$$

Thus, the overall mass of dried fish samples, M_s at 15% w.b, becomes:

$$M_s = \frac{M_d}{(100 - 15)\%} = 11.76\,\text{kg} \tag{A3}$$

Mass of moisture present in the dried fish samples, M_{ds} becomes:

$$M_m = M_s - M_d = 1.76\,\text{kg} \tag{A4}$$

The overall mass of desorbed moisture during drying, M_{dm}, is given as:

$$M_{dm} = M_m - M_{ds} = 13.24\,\text{kg} \tag{A5}$$

The theoretical mass of moisture held by the heated air (at $T_{db} = 55°\text{C}$) = 0.0281 kg moisture/kg_{da}.

The moisture pick-up potential of the drying air, $\varphi = 0.0281 - 0.0174 = 0.0107$ kg moisture per kg dry air.

This is the theoretical quantity of moisture extracted by drying the air, and a reasonable assumed pick-up factor for fish drying = 0.2 [13].

Hence, the actual mass of moisture expected to be removed per kg of air is calculated as:

$$m_r = 0.0107 \times 0.2 = 0.00214\,\text{kg} \quad \text{moisture per kg air.}$$

The overall quantity of air needed to dry the 25 kg batch of catfish, Q_a:

$$Q_a = \frac{M_{dm}}{m_r} = 6186.92\,\text{kg moisture per kg air.}$$

The volumetric flow rate, Q_v is expressed using:

$$Q_v = m_a * V_{sp} = 987.65\,\text{m}^3/\text{h}. \tag{A6}$$

This indicates that a moderately-sized blower will be required to dry a 25 kg batch in 5½ hours. Therefore, a DC centrifugal blower of varying speed ratings was selected to suit the design, and the drying time can be increased to 6 hours without lowering the dried fish quality.

$\therefore$ The mass flow rate per hour with a 5½ drying time, t is:

$$m_a = \frac{Q_a}{t} \tag{A7}$$

$$m_a = 1124.89 \,\text{kg of air per hour (or 0.312 kg/s)}$$

The revised volumetric flow rate (Q_{vr}) is calculated thus: $Q_{vr} = m_a * V_{sp} = 987.65\,\text{m}^3/\text{h}$. This quantity of air could be supplied by the selected DC centrifugal blower, given its variable speed and power ratings.

$$Q = m_a * (h_2 - h_1)\,\text{kJ/s} \tag{A8}$$

where h_1, h_2 are the specific enthalpies of the inlet air and air at drying temperature (kJ/kg), respectively, with values obtained from the psychrometric chart with ambient conditions (29.6°C, 62.67% RH): $h_1 =$ 74.7 kJ/kg of air. For h_2 of the heated air (55°C, 62.67% RH) = 99.3 kJ/kg air.

$$\therefore Q = 7.68\,\text{kJ/s} \sim 7.7\,\text{kW}$$

$$m_c = \frac{Q}{Q_c} \tag{A9}$$

where Q_c is the calorific heat value of charcoal (7600 kJ/kg); hence $m_c = 0.00112$ kg/s.

Since 0.00112 kg of charcoal is needed per second, in 5½ hours ($t = 19,800$ s), 22.18 kg of charcoal is needed $= m_x$.

$\therefore$ Heat generated (Q_g) by burning 22.18 kg of charcoal fuel is calculated as:

$$Q_g = m_t * Q_c = 168568\,\text{kJ} \approx 0.169\,\text{MJ}. \tag{A10}$$

$\therefore$ The overall estimated heat generated, Q_T (kJ/h), is given by:

$$Q_T = \frac{Q_g}{t} = \frac{168568}{5½} = 30648.73\,\text{kJ/h}. \tag{A11}$$

The overall heat generated by the charcoal is transmitted by the centrifugal blower to the drying chamber through a heat exchanger. The amount of energy utilized by the DC blower (E_b) was obtained by:

$$E_b = P_b * t \tag{A12}$$

where P_b is the power of the DC blower (hp).

The volumetric kiln capacity is given as:

$$V_f = \frac{M_b}{\rho_f} \tag{A13}$$

where V_f, ρ_f are the volume of fish (0.02315 m^3) and the density of the fish sample = 1080 kg/m^3, respectively.

Volume of the kiln, $V_k = L * W * H = (1.0 * 0.5 * 0.75)\,\text{m}^3 = 0.375\,\text{m}^3$.

$\therefore V_k \gg V_i$. This implies that the fish samples, drying racks, and the collector pan occupy $\sim$ 15% of the kiln's volume. This indicates that there is adequate space for drying air to circulate, which boosts the drying efficiency of the kiln.

$$m_f(\%_{\text{w.b}}) = \left(\frac{m_1 - m_2}{m_1}\right) * 100 \tag{A14}$$

where m_1, m_2 are the masses of the initial brined and dried fish samples (kg), respectively.

$$\mathcal{K}_d = \frac{m_r}{t} = \frac{\mathcal{M}_t - \mathcal{M}_{t+dt}}{dt} \tag{A15}$$

where $\mathcal{M}_t$ is the moisture content at any time, t(%w.b.); $\mathcal{M}_{t+dt}$ is the moisture content at time, $t + \Delta t$(%w.b.).

$$\zeta_R = \frac{m_x}{m_b} \tag{A16}$$

where m_x, m_b are the mass of the rehydrated fish sample (g) and the mass of the dried fish sample (g), respectively.

$$\phi_s = \frac{x_1 - x_2}{x_1} * 100\% \tag{A17}$$

where x_1 and x_2 are the geometric mean diameters of the samples before and after drying, respectively.

$$Q_u = M_m * h_{fg} \tag{A18}$$

$$\eta_e = \frac{Q_u}{Q_T} * 100\% \tag{A19}$$

η_e gives an idea of the quantity of heat energy that is truly utilized to dry the fish as opposed to the heat energy wasted to the ambient, kiln walls, or exhaust.

$$Q_{sp} = \frac{Q_T}{\mathcal{K}_d}\left(\frac{\text{kJ}}{\text{kg}}\right) \tag{A20}$$

$$Ex_{\text{chem}} \approx \beta * Q_{\text{hhv}} \tag{A21}$$

$\therefore$ The overall exergy input, $Ex_i = m_{\text{ch}} * Ex_{\text{chem}}$ (A22)

Exergy outflow, Ex_o (i.e., energy of hot drying air, Ex_{air}) is given as:

$$Ex_{\text{air}} = m_a c_p \left[(T_o - T_a) - T_a \ln \left(\frac{T_o}{T_a} \right) \right] \quad \text{(A22)}$$

However, the exergy balance of the kiln is expressed as [15] :

$$\sum Ex_{\text{in}} - \sum Ex_o = \sum Ex_{\text{des}} \tag{A23}$$

$$Ex_{\text{des}} = Ex_{\text{loss}} = Ex_{\text{in}} - Ex_o \tag{A24}$$

$$\eta_{ex} = \frac{Ex_o}{Ex_i} * 100\% \tag{A25}$$

where Ex_{chem} and Q_{hhv} are the chemical exergy of charcoal (kJ/kg) and higher heating value of charcoal (30,000 kJ/kg), respectively; β is the exergy-to-energy ratio, typically $1.04 - 1.10$ (commonly 1.06 for charcoal); m_{ch} is the mass of charcoal burnt (kg); T_o is the air temperature entering the drying chamber (°C); and T_a is the ambient temperature (°C).

$$E_{\text{pbp}} = \frac{E_{\text{embodied}}}{E_{\text{saved}}} \tag{A26}$$

where E_{pbp} is the overall energy requirement for the kiln construction and installation (kJ), E_{saved} is the yearly useful energy output from the kiln (kJ).

$$\epsilon_{CO_2} = m_x \epsilon_{\text{ch}} \tag{A27}$$

where m_x is the mass of charcoal burnt per batch of drying (kg), ϵ_{ch} is the emission factor (~ 2.83 kg CO_2/kg charcoal).

$$E_{CC} = (\epsilon_{\text{ref}} - \epsilon_{CO_2}) * \mathcal{P}_c \tag{A28}$$

where ϵ_{ref} is the baseline or reference emissions from a conventional or less effective system, the carbon price (market price per ton of CO_2 emitted, USD/ton).

$$I_s = \frac{1}{1 - \eta_{ex}} \tag{A29}$$

$$Y_{ed} = 1 - \eta_{ex} \tag{A30}$$

$$\chi_{we} = \frac{Ex_{\text{loss}}}{Ex_{\text{in}}} \tag{A31}$$

$$k_{ei} = \frac{\epsilon_{CO_2} \cdot Ex_{\text{loss}}}{E_{\text{saved}}} \tag{A32}$$

$$I_p = Ex_l(1 - \eta_{ex}) \tag{A33}$$

$$V_y = \sqrt{\left(\frac{\partial y}{\partial x_1} v_1\right)^2 + \left(\frac{\partial y}{\partial x_2} v_2\right)^2 + \left(\frac{\partial y}{\partial x_3} v_3\right)^2 + \cdots + \left(\frac{\partial y}{\partial x_n} v_n\right)^2} \tag{A34}$$

where V_y is the uncertainty of the experimental outcome; v_1, v_2, and $v_3 \ldots v_n$ are the experimental uncertainty values in the input variables; and y denotes a variable, which is a function of input factors.

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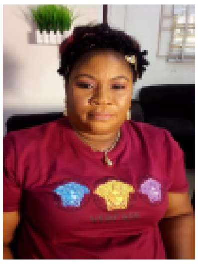

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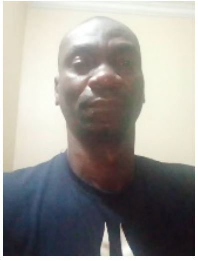

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