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Performance Evaluation of a Solar Dryer for Silver Cyprinid (Omena): Enhancing Food Security through Sustainable Preservation

Garison Kiprotich [a*], Stephen K. Kimutai [b] and Hesborn R. Ayub [c]

[a] Department of Mechanical Engineering, Murang'a University of Technology, P.O Box 75 -10200, Kenya.
[b] Department of Mechanical, Production & Energy Engineering, Moi University, P.O Box 3900-30100, Kenya.
[c] Department of Industrial and Energy Engineering, Egerton University, P.O Box 536-20115 Egerton, Kenya.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aim: The aim of this study was to design, construct, and assess a small-scale solar drying unit for drying Silver Cyprinid *(Omena)* fish. The rationale was to develop an effective, cheap and sustainable way to help local fishermen in Kenya, especially those around Lake Victoria, to advance the methods of drying fish and, hence, increasing the focus on preservation of nutrients.

**Corresponding author: E-mail: garisonkip@gmail.com, gkiprotich@mut.ac.ke;*

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Methodology: A solar drying unit was designed and constructed to harness solar energy as its primary heat source for drying fish. Performance evaluations were conducted at Egerton University, Kenya, where 5 kg of *Omena* fish were distributed across three tray decks (2 kg on the lowest, 2 kg on the middle, and 1 kg on the top tray). Temperature fluctuations within the dryer, including the inlet chamber, chamber entrance, and chimney, were monitored during sunlight exposure. The operational efficiency and drying time of the unit were also evaluated.

Results: Temperature variation in the dryer was between 25 0C and 37 0C, average temperature of 37 0C, 35 0C, 40 0C and 42 0C was observed for the product, ambient, collector and drying chamber respectively. From the study it was found that the dryer was able to dry approximately 12 kg of freshly harvested *Omena* during a day under 8 hours of sunlight with an efficiency of 51.94%. This confirmed that the drying process enhanced the quality attributes of the fish in terms of texture, flavor, smell and color, with an overall acceptance score of 4.125 of the dried fish on hedonic scale.

Conclusion: The study concluded that; utilizing technology of solar dryers in the drying of Omena fish improves on the hygiene level, the performance on the nutrient quality of the fish is not affected negatively by this technology and therefore, the way forward in producing food in a sustainable manner is adopted by applying this technology. This developed small scale solar dryer provided efficient and effective solution to the conventional open sun drying and smoking system. The study thus calls for more cost-outcome studies that will compare the above solar dryers with the conventional methods of drying in Kenya.

Keywords: Fish; omena; performance; solar dryer; sustainable; silver cyprinid.

1. INTRODUCTION

The need for sustainable food preservation techniques has grown in response to global issues like population expansion, climate change, and food scarcity (Mrabet, 2023, Wijerathna-Yapa, 2022, Obahiagbon, 2024). Solar drying is one of the numerous approaches being investigated, and it seems like a viable option ((Goel et al., 2024), especially for perishable items like Omena, a small fish species that is common in Kenya and essential to the food security of the region (Omukoto, Graham, & Hicks, 2024). Omena meets the nutritional requirements of millions of people globally by providing an important source of protein and other key elements (Omagor et al., 2020). More importantly, insufficient drying methods greatly increase the risk of aflatoxin contamination, which is a major public health and food safety issue in Sub-Saharan Africa. Small-scale farmers might potentially reduce post-harvest losses, improve food quality, increase revenue, and provide potential for employment by using suitable drying technology. In Kenya, farmers, food wholesalers, processors, and exporters have all suffered financial losses as a result of inadequate drying techniques used across the food value chain (Omega, 2023).Utilizing solar as a green source of energy to preserve Omena and other comparable has proven to be sustainable and eco-friendly method. This study evaluates the performance of a solar dryer specifically to preserve Omena. The effectiveness of solar drying as approach to increase food security and reduce post-harvest losses in Kenya. Key aspects such as product quality, energy consumption, drying efficiency, and economic viability are investigated.

Traditional fish drying techniques like smoking, open-air drying often prove unreliable, leading to compromised quality of dried fish (Hall, 2011). Open-air sun drying has been the most commonly used method among smallholder farmers in tropical regions due to its affordability. However, the method is more susceptible to environmental factors such as exposure to birds, pest, rain, wind, pests and rodents which eventually lead into post-harvest losses, as highlighted by Reza (Reza, 2024). Also, numerous dryer designs have been developed to tackle these challenges, including the utilization of hybrid solar dryers (Natarajan et al., 2022, Richa et al., 2022, Osodo, Nyaanga, & Kiplagat, 2019) and the adoption of greenhouse dryers explored by (Baidhe et al., 2024) and the recent work of (Ahmad et al., 2022).These innovative designs have significantly led to reduction in post-harvest losses as opposed to air sun drying methods. Solar drying is an excellent alternative to sun drying due to its increased efficiency, environmental sustainability, and cost-effectiveness (Mohana et al., 2020, Srivastava et al., 2022).

According to a 2011 report by the FAO, it is estimated that one-third of all food produced worldwide is either lost or wasted (Boiteau & Pingali, 2023). The bulk of this food loss happens early in the value chain, especially during post-harvest handling and processing, (Gyan et al., 2020). In less economically developed nations, the primary drivers of food loss are concentrated at the consumption stage. This distressing trend of excessive food loss, (Munesue, Masui, & Fushima, 2015) results in dire consequences, leaving millions in low-income countries malnourished. The Food and Agricultural Organization anticipates that by 2050, the global population will exceed 9 billion, demanding nearly a 70% surge in agricultural production (Béné et al., 2015). Further, research on global protein demand suggests that aquaculture production would need to rise from 82,087 Kilotonnes (kt) in 2018 to 129,000 kt by 2050 in order to meet the needs of a growing population (Boyd, McNevin, & Davis, 2022). In Africa, the human population is projected to grow by 2 billion by 2050, yet global food production has been on the decline, resulting in 690 million people suffering from severe hunger ((Mumuni & Aleer, 2023). The effects of climate variability and change on food security are increasingly evident, highlighting the urgent need to reduce post-harvest losses in fish drying to ensure a more sustainable food supply (Kigozi et al., 2020, Kabahenda, Omony, & Hüsken, 2009). Kenya's problems with food insecurity may be eased by addressing the widespread problem of food loss and waste globally, especially post-harvest loss, across various production and supply chains (Kimiywe, 2015).

Fish preservation employs various techniques to prevent spoilage and ensure food safety. Traditional methods like smoking, sun drying, and salting have been used for centuries, while more modern approaches, such as canning, have further enhanced the preservation process. However, managing the preservation of the small, abundant silver fish known as "*Omena*" remains challenging due to large-scale harvesting and the need to maintain strict hygiene standards during handling and processing (Echessa, 2024). In addition, spoilage risks increase with the presence of filamentous fungi, which can produce aflatoxin, a highly toxic compound. Mold growth, which thrives at temperatures between 10°C and 40°C and humidity levels around 70%, exacerbates the risk of aflatoxin contamination. Aflatoxin poisoning can manifest with symptoms ranging from vomiting and abdominal pain to more severe outcomes like convulsions, coma, or even death. Properly drying food helps inhibit fungal growth, creating safer storage conditions. In line with this, the Kenya Bureau of Standards (KEBS) emphasizes the importance of maintaining quality standards in fish preservation. It recommends that Silver Cyprinid fish should have a moisture content between 5% and 7% to minimize spoilage and reduce the risk of aflatoxin contamination (Kigozi et al., 2020, Owaga, 2011).

Significant strides have been made in developing cost-effective solar drying systems (Deef et al., 2023). Key considerations include the affordability and accessibility of materials such as bamboo, repurposed wood, and low-cost metals, which help to reduce construction expenses. To optimize the absorption of solar energy and its conversion into heat, efficient solar collectors, including evacuated tube and flat-plate designs, are employed. Enhanced air circulation, essential for uniform drying, is facilitated by low-power fans or ventilation systems powered by solar energy. In colder climates, effective insulation such as cellulose derived from recycled paper minimizes heat loss. The system's modular and scalable design offers flexibility, allowing for adjustments to the drying capacity based on demand. Additionally, integrated temperature and humidity sensors ensure precise control of drying conditions. Built to endure harsh environments, the systems are durable and resistant to weather, particularly in coastal regions where salt air can cause corrosion. Furthermore, a solar tracking mechanism is incorporated to ensure optimal energy efficiency throughout the day and across seasons. Given the vital role that fish plays in local diets and economies, particularly in coastal communities, the use of solar energy for fish drying presents a sustainable and cost-effective solution to preserve fish and enhance food security.

The need for solar drying has proved to be a long-term way to enhance fish preservation (Wu et al., 2024). By promoting solar drying initiatives, Kenya can achieve a great milestone in enhancing food safety, reduction in post-harvest losses and increase in revenue generation activities of fishing communities ((Mhango, 2024, Kibet, 2023).

However, while notable progress has been achieved, there is a pressing need for further research into optimizing these systems. Investigating ways to improve efficiency, scalability, and adaptability to various climates and locations will ensure that solar fish drying becomes a more reliable and widespread technology. Such research is essential to address the unique challenges of fish preservation and to meet the growing demand for sustainable food processing methods

(Kamarulzaman, Hasanuzzaman, & Rahim, 2021, Jha & Tripathy, 2021).

Therefore, this study aims to explore the use of solar drying techniques for dehydrating Silver Cyprinid, commonly known as '*Omena*,' in Kenya and across Africa. The goal is to generate essential knowledge that will contribute to building a sustainable food system, benefiting both present and future generations.

1.1 An Overview of Traditional vs Modern Fish Drying Techniques in Kenya

Fish is dried by taking out the moisture in order to stop microbes from growing and to keep the fish from spoiling, thereby extending its shelf life (Fitri et al., 2022). In Kenya, fish drying is a common traditional preservation technique, particularly in coastal areas and around freshwater basins like Lake Victoria. Among the various techniques used to preserve fish, sun drying is one of the most traditional and frequently applied.

a) Sun drying

Sun drying is the most common fish preservation technique in Kenya, where fish are spread on mats or drying racks under direct sunlight. This method is typically practiced in open areas such as beaches, riverbanks, and rooftops, where fishermen and processors dry their catch. However, the quality of the dried fish can vary greatly depending on the strength and duration of sunlight. While sun drying is simple and cost-effective, it is highly weather-dependent, which can lead to inconsistencies in the final product's quality and safety. One major drawback of this method is its exposure to microorganisms (Rasul et al., 2022). In open-air drying, fish are susceptible to contamination by bacteria, fungi, and other harmful microorganisms, which thrive in the uncontrolled conditions of fluctuating temperatures and humidity. This increases the risk of spoilage and compromises food safety. In contrast, solar drying, which uses enclosed systems with regulated heat and airflow, provides better protection from these contaminants, producing higher-quality, safer, and more hygienically dried fish.

b) Smoking

Smoking is a common fish preservation method in Kenya, where fish are exposed to smoke from burning wood or biomass using kilns or drums. This process not only dehydrates the fish but also imparts a distinctive flavor and aroma. However, traditional smoking methods often result in uneven drying and can pose health risks due to harmful compounds like polycyclic aromatic hydrocarbons (PAHs) in the smoke. Despite its benefits such as extending shelf life, enhancing flavor, and increasing fish use in soups and sauces, smoking has several drawbacks. While it helps reduce waste during peak fishing seasons and allows storage for leaner periods, it falls short compared to solar drying. Issues such as handling damage, inconsistent drying, limited smoker capacity, and the time-intensive nature of the process, which requires constant monitoring of flame intensity and tray rotation, make smoking less efficient (Adeyeye, 2019).

c) Brine or salt drying

Salted dried fish is preserved through a curing process in which fish processors immerse the fish in brine or salt solutions before drying. This method works by drawing out moisture and preventing bacterial growth, making it a popular technique for preserving small fish species like Omena, which are dried whole after being treated with salt.In some circumstances,however,fish may be cut into portions or fillets before drying, depending on the type or intended purpose.However, despite the extended shelf life provided by this method, there are notable health risks associated with it. High salt intake from consuming salted fish can contribute to various health issues, such as hypertension, cardiovascular diseases, and kidney problems (Nagendra et al., 2020). Additionally, the uneven absorption of salt, particularly in larger fish, can lead to insufficient preservation and create potential risks of spoilage or bacterial contamination (Gupta et al., 2024), which may cause foodborne illnesses.

d) Solar dryers

With increasing concerns about post-harvest losses and food safety, solar drying technology is gaining traction (Deepak & Behura, 2023, Saha et al., 2024). Fish solar dryers play a crucial role in efficiently reducing fish moisture levels in less time while preserving high quality. Unlike traditional sun drying, which exposes fish to contaminants, solar dryers provide a controlled environment, ensuring faster and more consistent drying. Tests comparing hybrid solar dryers with regular solar dryers and sun drying demonstrate superior drying rates, which improve food safety, retain nutrients, and enhance the overall quality of dried fish (Reza & Hossain, 2023). However, despite these advantages, the adoption of solar dryers in Kenya remains limited due to poverty and low capital income. High initial costs and the need for technical expertise are significant barriers to wider implementation.

e) Fish drying best practices

To improve the quality and safety of dried fish products in Kenya, there is an urgent need to design and evaluate affordable solar fish dryers (Rasul et al., 2019). Traditional drying methods like sun drying and smoking, while widely used due to their simplicity and low cost, are weather-dependent and pose health risks, compromising the overall safety and nutritional value of the dried fish. In contrast, modern techniques such as solar drying offer significant benefits, including reduced drying times, enhanced efficiency, and better product quality. However, the widespread adoption of solar dryers faces challenges, particularly due to economic constraints and limited access to technology (George et al., 2019). These efforts will help raise product standards and ensure competitiveness in the market.

Ongoing research into affordable small-scale solar dryers is crucial for ensuring the sustainability of Kenya's fish drying industry, particularly in regions like Lake Victoria, where smoking is the dominant drying method. Solar dryers not only retain more of the fish's high-quality proteins and heart-healthy lipids but also reduce the nutritional losses typically associated with traditional smoking techniques. By addressing economic limitations, increasing awareness, and investing in affordable drying technologies, Kenya can enhance the safety, quality, and marketability of its dried fish products.

1.2 *Omena*'s Contribution to Livelihood Improvement

The small silver fish known as the Silver Cyprinid, or *Omena*, is found in the drainage basins of Lake Victoria, Lake Kyoga, Lake Nabugabo, and nearby water bodies. It is highly valued for its rich nutritional content, providing essential vitamins (A, B, and D), proteins, and minerals such as iron and calcium (Omukoto et al., 2024). *Omena* accounts for approximately 35% of Kenya's total fish consumption, making it a vital food source. When properly dried, it can last up to two years, serving as an affordable and reliable source of protein, which significantly contributes to food security (Omukoto, Graham, & Hicks, 2024). Moreover, the fishing and trading of *Omena* play a crucial role in boosting local economies by creating jobs and generating economic opportunities throughout the supply chain.

In Kenya, particularly in regions around Lake Victoria and Lake Kyoga, the fish industry has a direct impact on improving livelihoods (Natugonza et al., 2021). Utilizing efficient drying methods, such as solar drying, ensures the production of high-quality, long-lasting fish products that are marketable both locally and internationally (Abraha et al., 2017). This enhances the incomes of fishermen and traders while reducing post-harvest losses. Proper drying techniques also improve hygiene and nutritional value, allowing small-scale fishers to access broader markets and diversify their revenue streams. Ultimately, these advancements contribute to economic growth, poverty reduction, and sustainable livelihoods for communities reliant on fishing (Béné et al., 2016). The variation in appearance of freshly harvested and fully dried *Omena* is evident as shown below in Figs. 1 and 2, respectively.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Omena fish samples were purchased from five independent establishments in Kisumu, Kenya, primarily along the shore of Lake Victoria. The independent sources included the Kisumu main

Fig. 1. Freshly harvested *Omena*

Fig. 2. Fully dried *Omena*.

fish market, Dunga beach landing site, Umoja fish traders sacco, Nyamasaria open market, and Kiboko bay beachfront stalls. The selected sources were chosen using a random sampling technique.10 kg of freshly harvested *Omena* were used for the study.

2.2 Construction of the Dryer

The construction of a solar dryer, and evaluation of drying and sensory properties of dried Silver Cyprinid was done at Egerton University, Kenya. The solar dryer utilized solar energy as its main heat source, effectively drying fish during sunny periods. The experimental model consisted of major components such as the solar collector, the dryer chambers, cabinets, solar panel powered fan mini ventilator 20 W solar panel 6-in exhaust fan, and drying trays, all with designed specifications. For measurement purposes, Thing Speak software connected to and temperature (DHT22; range -40 to 100%) and humidity (DHT11; range 0% to 100%) sensor. The solar radiation was measured using a pyranometer (model SP-Lite2).

The solar dryer frame was prepared with a size of 2 m height and 1.4 m length frame based on the 10 kg *Omena* required to be dried per session. Wooden poles are completely covered with plywood on the sides and a Perspex material on the top section to protect from direct sunlight, dust, and flies and to dry the product quickly since the Perspex material is a good absorber of heat. The solar collector fixed in a wooden frame of (0.14 m height x 1.5 m length and 0.75 m width) was used to harness the solar radiation incident to it. Four dryer racks of equal dimensions (3 cm height x 0.58 m length and 0.84 m width) were made using rectangular wooden poles covered by galvanized mesh wire (16 cm × 2 holes) upon which *Omena* samples spreads as shown in Figs. 3 and 4 while Table 1 shows the equipment used for the experiment.

2.3 Experimental Procedure

Throughout performance evaluations, 5 kg of fish were evenly distributed across three tray decks: 2 kg on the lowest, 2 kg on the middle tray, and 1 kg on the top tray. This configuration enabled the lower and the middle tray to benefit from the absorption of solar radiation from the black-coloured solar collector. The top tray was loaded 1kg in order to avoid overcrowding and ensure proper circulation of air throughout the drying chamber. With these arrangements efficient evaporation was achieved, promoting uniform drying and enhancing ultimate drying performance.

The incident solar radiation on the solar collector fluctuated over time, leading to noticeable variations in temperature recordings. Drying cycles were observed at 30-minute intervals from 8:00 AM to 5:00 PM. Environmental conditions, including temperature and relative humidity, exhibited significant variability due to prevailing weather conditions. Freshly obtained Silver Cyprinid samples were weighed using a weighing scale (Reshly BTt457A). To reduce load and improve drying days, the weighed samples were divided among the three dryer racks with a 4 cm gap between each one. To guarantee consistent drying, the samples were hygienically turned over in each rack every two hours. Since the area is glossy between 8:00 am and 5:00 pm, the *Omena* samples were dried during these hours. The procedure was repeated twice to obtain better results. After the final weight at 5.00 pm was recorded, the *Omena* pieces in the dryers were gathered and wrapped in polyethylene to prevent moisture absorption.

2.4 Sensory Evaluation

The sensory evaluation of the dried fish's color, texture, and general acceptability was assessed by experts from Egerton University's Department of Dairy, Food Science, and Technology (Table 2). They paid close attention to the color, looking for any differences and consistency. The acceptability test was used to assess sensory qualities (Omagor et al., 2020). Color, flavor, taste, and general acceptability of the test were assessed using a five-point hedonic scale, with 1-denoting extreme dislike, 3-neither like nor disliking, and 5-denoting extreme like. The more popular method of identifying samples with a three-digit identifier was applied. The sensory assessors were given product samples on white plates, which were arranged in a random sequence. Before the test, the judges received orientation on the process of sensory evaluation.

2.5 Important Design and Analysis Equations

2.5.1 The inclination angle of the solar collector

The formula for calculating the tilt angle (β) of the solar collector, as presented by Kumar (Kumar et al., 2024), is given.

Table 1. Equipment used for the experiment

#	Name	Model	Manufacturer	Description
1	Solar panel powered fan mini ventilator	Luqeeq7a034pr0h1	Mission Solar (United States)	Power source: Solar powered Wattage: 20 watts Special feature: Water proof Brand: Luqeeq Electric fan design: Exhaust fan
2	Humidity sensor	DHT11	Kuong shun Electronic	Range: 0% to 100%
3	Temperature sensor	DHT22	Kuongshun Electronic	Range: -40°C to 100°C
4	ThingSpeak-Matlab Extension	Version 4.0	Math Works (2020)	Software for ThingSpeak (version 4.0,software)
5	Pyranometer	SP-Lite2	TekBox Digital Solutions Pte.Ltd	Expected signal range: 0–120 Mv Nominal impedance :> 1MΩ Response Time: < 1 second (at 95%)
6	Weighing balance	(BT457A)	Reshy	Brand: RESHY Weight: Limit 10 Kg Material: Stainless steel/ABS

Fig. 3. Experimental dryer

Fig. 4. Dryer assembly and tray decks

Table 2. Five-point hedonic scale of sensory evaluation

		Organoleptic quality			
Score	**Colour**	**Oduor**	**Texture**	**Taste**	**General acceptability**
1	Dark	Dislike	Very poor	Very poor	Dislike
2	Slight dark	Neither like	Poor	Poor	Neither like
3	Moderate	Like slightly	Fair	Fair	Like slightly
4	Pale	Like moderately	Good	Good	Like moderately
5	Very pale	Like very much	Very good	Very good	Like very much

Adapted from Berdos, Aquino (Berdos et al., 2020)

$$\beta = 10^{\circ} + lat\ \emptyset \qquad (2.1)$$

$Where;\ lat\ \phi\ represents\ the\ latitude\ of\ the\ collector\ location$

2.5.2 Moisture content

Moisture content (%) (Lawrence et al., 2011)

$$MC = \frac{(M_{L-}\ M_F)100}{M_L} \qquad (2.2)$$

$Where; M_{L\,=}\ Sample\ mass\ before\ drying(kg)$

$M_{F\,=}\ Sample\ mass\ after\ drying(kg)$

2.5.3 Average drying rate

According to (Bolawa et al., 2011) the expression is given by,

$$d_A = \frac{M_W}{t_d} \qquad (2.3)$$

$Where; M_W = Mass\ of moisture\ content,$
$t_d = drying\ time\ (hrs)$

2.5.4 Mass of air needed for drying

$$M_a = \frac{d_A}{(W_f - W_l)} \tag{2.4}$$

$Where; d_A = Average\ rate\ of\ drying$,
$= initial\ humidity(kgH_2o\ kg\ dry\ air),$
$W_f = final\ humidity(kgH_2o\ kg\ dry\ air)$

2.5.5 Equilibrium relative humidity

This was calculated from the following isotherms.

$$a_w = 1 - exp[0.194 + 0.5639 ln M_d] \tag{2.5}$$

$$M_d = \frac{M_f}{(100 - M_f)} \tag{2.6}$$

$$ERH = 100a_W \tag{2.7}$$

$Where; ERH = equilibrium\ relative\ humidity,$
$a_w = water\ activity,$
$M_f = final\ moisture\ content\ (\%)\ wet\ basis,$
$M_d = moisture\ content\ dry\ basis(kg\ water, kg\ solids)$

2.5.6 Required pressure

The density difference between the hot air within the dryer and the surrounding air caused the necessary pressure differential over the food bed.

As per (Bolawa et al., 2011) the expression for Air pressure is;

$$P = 0.00308g(T_c - T_a)_H \tag{2.8}$$

$where\ \ H = pressure\ head,$ pressure head,
$P = Air\ pressure\ (Pascals),$
$g =$ Acceleration due to gravity $(9.81ms^{-2})$
$T_a = Ambient\ temperature$ (℃)

2.5.7 The Energy balance equation

$Total\ heat\ gained = Total\ heat\ lost\ by\ the\ absorber\ of\ solar\ collector.$

$$IA_C = Q_u + Q_{cond} + Q_{conv} + Q_R + Q_P \tag{2.9}$$

$Where;$
$IA_C = Rate\ of\ all\ radiation\ incident\ energy\ on\ the\ surface\ of\ absorbers\ (Wm^{-2})$
$Q_u = Rate\ of\ usable\ energy\ gained\ by\ dry\ air\ (W),$
$Q_{cond} = Rate\ of\ the\ absorber's\ conductive\ losses\ (W),$
$Q_{conv} = Convective\ loss\ rate\ from\ the\ absorber\ (W),$
$Q_R = The\ absorber's\ rate\ of\ long\ wave\ re-radiation\ (W),$
$Q_P = Rate\ at\ which\ the\ absorber\ loses\ long\ wave\ reflection\ energy\ (W),$

On combining heat losses terms equation (2.9) reduces to;

$$Q_L = Q_{cond} + Q_{conv} + Q_R \tag{2.10}$$

Therefore; reflected energy of the absorber is given by;

$$Q_L = U_L A_0 [T_c - T_a] \tag{2.11}$$

$where; U_L = Total\ heat\ transfer\ efficiency\ of\ the\ absorber\ material\ (Wm^{-2}K^{-1})$
$T_c = collector's\ absorber\ temperature\ (K)$
$T_a = Air's\ predominant\ temperature\ (K)$

Thus, the collector's obtained usable energy is stated as;

$$Q_U = (a_L)I_T - U_L(T_c - T_a) \tag{2.12}$$

$The\ energy\ per\ unit\ area\ ; Q_U$

$$= (Q_T)I_T - U_L(T_c - T_a) \tag{2.13}$$

2.5.8 Thermal efficiency of the collector (Kumar et al., 2024)

$$\eta_c = \frac{Q_U}{A_C I_T} \tag{2.14}$$

$where;$

$Q_u = useful\ energy\ acquired$
$A_c = area\ of\ the\ collector$
$I_T = total\ amount\ of\ incident\ \ solar\ radiation$

2.5.9 Efficiency of the dryer

$$\eta_d = \frac{M_L}{I_C\, A_C t_d} \tag{2.15}$$

$where\ M = Quantity\ of\ \ food\ (kg)$
$L\ = Latent\ heat\ of\ vapourisation\ \left(\frac{kJ}{kg} of\ H_2o\right)$
$t_d = drying\ period\ (s)$

The expression for Latent heat of vaporization is given by;

$$L = 4.186 \times 10^3\ \{597 - 0.56(T_P)\} \tag{2.16}$$

$where\ ; T_P = product\ temperature$

3. RESULTS AND DISCUSSION

3.1 Temperature Variation

The temperature changes offered are essential metrics for assessing the effectiveness of the solar dryer intended for *Omena* drying as well as its potential to improve food security by means of sustainable preservation (Table 3).

The temperature of the area around the solar dryer was represented by the ambient temperature. Due to its effect on the amount of solar energy available to heat the drying chamber, this temperature has an overall effect on the efficiency of the solar dryer. The amount of energy available for the drying process usually increases with ambient temperature; conversely, a lower temperature may cause the drying process to proceed more slowly. From Table 3, it is clear that the average recorded ambient temperature was 25.97°C, the temperature was enough to facilitate start of the drying process. Also, the temperature of the air entering the solar dryer referred to as the inlet temperature. It is essential in establishing the starting parameters for the drying process. The fact that the mean entrance temperature (26.7°C) in this instance was marginally higher than the outside air temperature (25.97°C) raises the possibility that the air was warmed before entering the drying chamber, which could have improved drying efficiency.

The drying chamber temperature represents the internal temperature of the solar dryer where the *Omena* is being dried. This temperature indicates the heat level within the drying chamber necessary for the effective removal of moisture from the *Omena*. An average temperature of 30.93°C suggests that the drying chamber is adequately heated, creating optimal conditions for the drying process to occur efficiently.

The chimney temperature (outlet) which refers to the temperature of the exhaust air leaving the solar dryer through the chimney. The outlet chimney temperature(28.3°C), being lower than the drying chamber temperature(30.93°C) indicates that heat energy has been utilized to extract moisture content from the samples, hence resulting in a decrease in temperature as the air exits the chamber.

Figs. 5 and 6 illustrate the hourly temperature variations in the solar collector and the drying chamber relative to the ambient temperature. Temperature recordings were obtained from 8 am to 5 pm. The results show that the solar energy dryer's performance is dependent on the intensity of solar radiation incident on the collector and ambient temperature. Data collection and analysis were facilitated using the ThingSpeak (Matlab) extension as shown in Fig. 7.

During the morning hours, minimum temperatures as low as 18°C were recorded, while maximum temperatures of approximately 37°C were observed during mid-day when solar insolation was higher. These findings align with previous research conducted by (Ssemwanga et al., 2020) and (Blanco-Cano et al., 2016), which indicated that solar dryer efficiency is significantly influenced by solar radiation levels.

3.2 Relative Humidity Variation

The relative humidity of the surrounding air, which is 49.49%, indicates how much moisture is present in the area where the solar dryer is operating. The proportion of water vapor in relation to the maximum amount that the air can retain at that temperature is shown by this measurement (Table 4). Higher relative humidity in the surrounding air may make it more difficult for drying processes to move moisture from the *Omena* to the air because of reduced moisture gradients. The air entering the drying chamber appears to have a similar moisture content to the surrounding air, based on the mean inlet relative humidity reading of 49.72%. Consequently, air with a relatively high moisture content enters the drying chamber.

Table 3. Temperature variations for the solar dryer

Mean Ambient Temperature ℃	**Mean Inlet Temperature ℃**	**Mean Chamber Entrance Temperature ℃**	**Mean Chimney Temperature ℃**
26.64	27.19	28.5	29.17
25.87	26.7	30.93	28.31
S.D	4.2	4.43	6.66
AVERAGE	25.97	26.7	30.93

S.D = Standard deviation

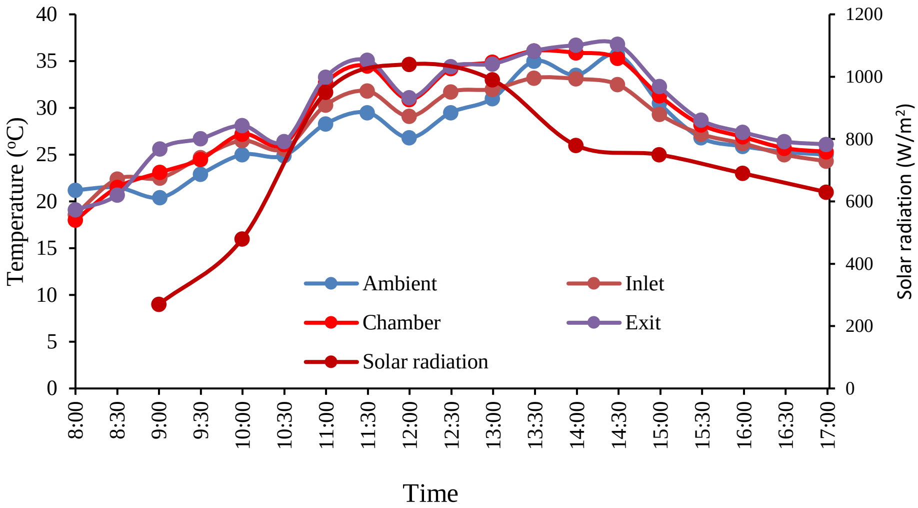

Fig. 5. Variation of temperature and solar radiation against time (Day 1)

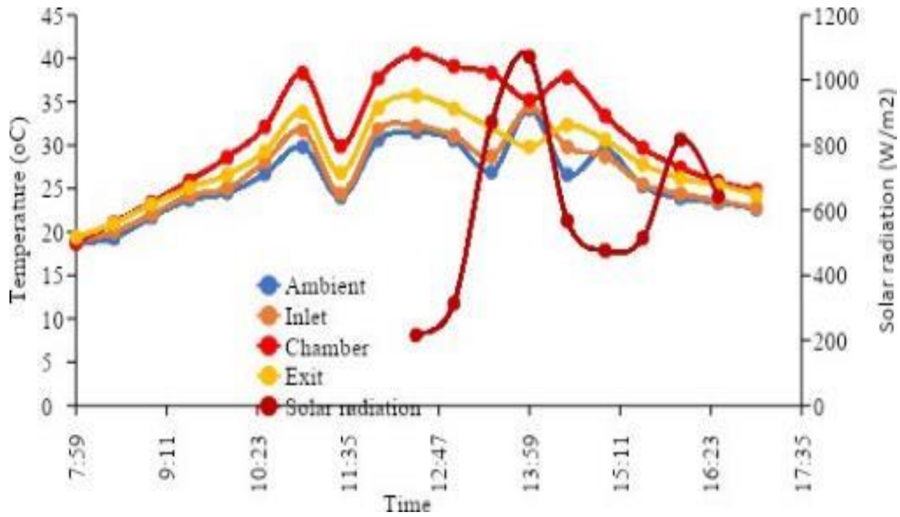

Fig. 6. Variation of temperature and solar radiation with time (Day 2)

Fig. 7. Data recording and tracking using thing speak matlab extension

Table 4. Relative humidity variations for the solar dryer

Mean Ambient Humidity	Mean Inlet Humidity	Mean Chamber Entrance Humidity	Mean Chimney Humidity
49.26	50.28	45.47	45.52
49.72	50.44	39.77	42.15
S.D	12.91	11.94	14.68
AVERAGE	49.72	50.44	39.76

With an average mean humidity of 50.44%, the drying chamber's moisture content is marginally greater than that of the inflow and ambient air. This implies that the *Omena* will have a favorable atmosphere for the removal of moisture throughout the drying process. However, the average chimney relative humidity (output) is 39.76%, indicating that moisture was successfully extracted from the *Omena* throughout the drying process. Effective moisture removal from the *Omena* is shown by the reduced relative humidity at the chimney output as compared to the inlet. All things considered, these relative humidity data imply that the solar dryer efficiently lowers humidity levels inside the drying chamber, aiding in the *Omena*'s moisture removal. Fish must have their moisture removed and released into the surrounding air in order to be dried. High relative humidity indicates that the air is already saturated with moisture, which reduces its ability to absorb more moisture from the fish (Doe & Olley, 2020).

3.3 Hourly Fluctuations in Solar Radiation Versus the Dynamics of Moisture Content

The impact of hourly fluctuations in solar radiation on the dynamics of moisture content reduction is notable in the observed patterns (See Fig. 8). The drying curve show that primary desorption of the massive occurred within first three hours and that the moisture was reduced from 66.6% to 44.19% due to surface drying resulting from solar heating. This is succeeded by a relatively slow drying, the deeper damp being more difficult to remove and at 8.70% after six hours. But, the moisture content from 420 to 480 minutes was almost constant at 5.62% which probably suggested that the sample was in the plateau phase of drying. The findings (See Table 5) align with prior research by (Kituu et al., 2010). This indicates that the remnant water is trapped within the fish tissue matrix in a manner which is difficult for its removal through any evaporation processes without the application of more energy. This is also probably best explained by the inherent limitations of drying processes such that stabilization occurs between fish moisture content and various environmental characteristics including temperature and humidity in the plateau. In essence, the solar dryer established effectiveness in removal of moisture, in that, it only took a day when the environmental factors were favorable. It is noteworthy that the use of a microwave could have expedited the drying process, potentially enhancing the achieved results. These findings align with prior research conducted (Arslan & Özcan, 2010, Al-Hilphy et al., 2024), further corroborating the observed dynamics of weight loss.

3.4 Dryer Calculations

3.4.1 The inclination angle of the solar collector

The latitude of Egerton was found to be -0.369734;

From eqn (2.1);

$$\beta = 9.630^{\circ} \tag{3.1}$$

3.4.2 Moisture content

Substituting the data into eqn (2.2), the percentage moisture content was obtained;

$$MC = 66.67\% \tag{3.2}$$

3.4.3 Average drying rate

Referring to eqn (2.3);

$$d_A = 0.372\frac{kg}{hr}\ \ in\ each\ of\ the\ three\ \ decks \tag{3.3}$$

3.4.4 Mass of air needed for drying

Referring to eqn (2.4);

$$M_a = 1.484kg/hr \tag{3.4}$$

3.4.5 Equilibrium relative humidity

Substituting data in eqn 2.5,2.6 and 2.7 yielded;

$$a_w = 0.03377 \tag{3.5}$$

$$ERH = 3.377 \quad (3.6)$$

3.4.6 Required pressure

The density difference between the hot air within the dryer and the surrounding air caused the necessary pressure differential over the food bed.

Referring to eqn (2.8),

$$P = 0.3446\ Pa \quad (3.7)$$

3.4.7 Efficiency of the dryer

Given that;

$$t_d = 9\ hrs \qquad I_c = 610 \qquad T_p = 15^{\circ}$$

From eqn 2.15,

$$\eta_d = 51.94\% \quad (3.8)$$

The findings demonstrated a significant reduction in moisture content by 66.67%, indicating effective moisture removal during the drying process (Nguyen & Eikevik, 2014). The average drying rate was 0.372 kg/hr, reflecting the speed at which water was evaporated from the fish. A mass flow rate of 1.484 kg/hr was observed, highlighting the volume of air moving through the system to facilitate drying. The drying efficiency was measured at 51.94%, indicating that just over half of the energy utilized was effectively used for drying, suggesting room for optimization to improve energy usage and overall system performance (Deef et al., 2023).

3.5 Effect of Solar Incident Variability on Temperature Dynamics on Solar Collectors

Solar plate temperature depends on the amount of solar radiation incident into it. After receiving solar energy, the solar collector converts the solar energy into heat energy which is needed for drying (Fernandes & Tavares, 2024). The temperature of the drying chamber does not solemnly depend on the solar radiation incident on it but may also be attributed to the losses of heat from the drying chambers through the walls of the dryer, this lowers the overall performance and efficiency of the dryer. From Fig. 9, it was recorded that at the start of the experiment, the solar radiation was measured to be 216 W/m2 at about 9 am while at noon the solar radiation reached a maximum value of 1072 W/m2.This peak performance demonstrates the collector's efficiency under favorable solar conditions. When the sun radiations tilted towards the west in the afternoon, the temperature of the solar collector reduces due to decreased solar radiation.

The rise and fall of temperature profiles is depicted due to non-regularity of the solar incident on the solar collector. These findings align with research conducted by (N'Tsoukpoe, 2022) depicting the significant impact of solar incident variability on temperature dynamics on solar collectors.

3.6 Effect of Sensory Attributes and the Overall Acceptability Index on the Drying Methods

The impact of sensory attributes and overall acceptability on drying methods is significant in assessing dried fish quality. Among other distinctive features, colour stands out as the most critical parameter influencing the overall acceptability index of 4.125 out of the maximum value of 5- (Five-point hedonic scale of sensory evaluation. During the evaluation process, the experts drawn from the Department of Dairy, Food Science and Technology of Egerton University scrutinized colour for discrepancy and uniformity (Fig. 10). Optimal and consistent coloration is an indicator of freshness and proper drying techniques, resonating positively with consumer choices and preferences. Traditionally, open sun-dried samples were least preferred for their color and texture, but solar-dried fish were preferred for their color and texture. According to (Rasul et al., 2019), solar dried fish contains comparatively higher amount of protein than the traditional sun dried samples. Further, the results revealed that colour, flavor, test, and smell of the dried *Omena* attained good acceptable standards. More clients preferred to consume the *Omena* dried by the use of the solar dryer than the normal sun drying. The findings align with some researchers (Oparaku et al., 2010) who demonstrated that fish products dried in solar dryers exhibit superior organoleptic characteristics, particularly in odor and moisture reduction, compared to those dried by sun drying. The overall market and demand for dried *Omena* are greatly affected by the aspect of sensory evaluation, hence the need to observe a high level of acceptable food handling procedures to enhance the acceptability index.

Table 5. Weight loss of *Omena* over time

Time	9:00 HRS	9:30 HRS	10:00 HRS	10:30 HRS	11:00 HRS	11:30 HRS	12:00 HRS	12:30 HRS	13:00 HRS	13:30 HRS	14:00 HRS	14:30 HRS	15:00 HRS	15:30 HRS	16:00 HRS	16:30 HRS	17:00 HRS
Weight (Kg)	5.03	4.86	4.27	3.87	3.59	3.33	3.01	2.68	2.43	2.2	2.14	1.94	1.84	1.78	1.68	1.68	1.68

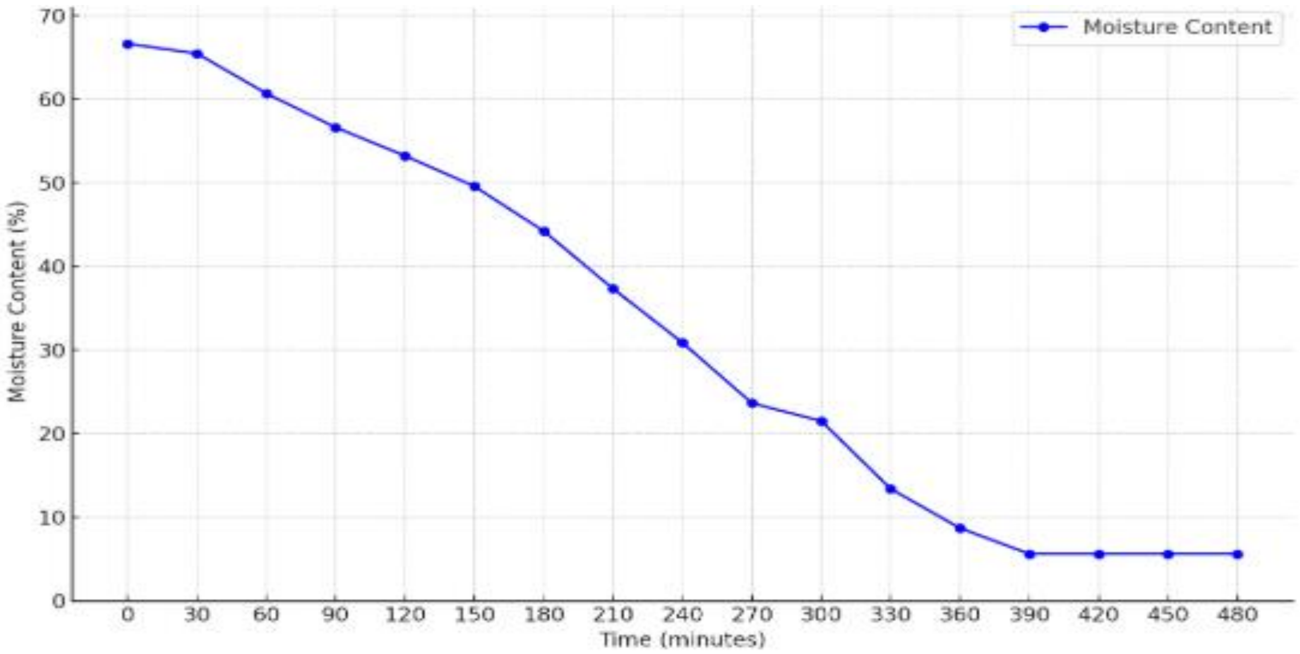

Fig. 8. Drying curve for *Omena*

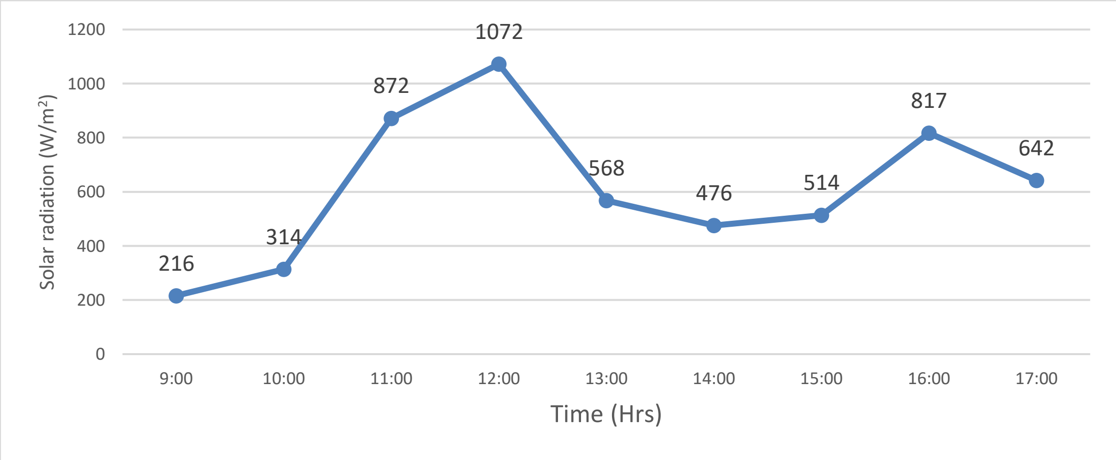

Fig. 9. Variation of solar radiation with time

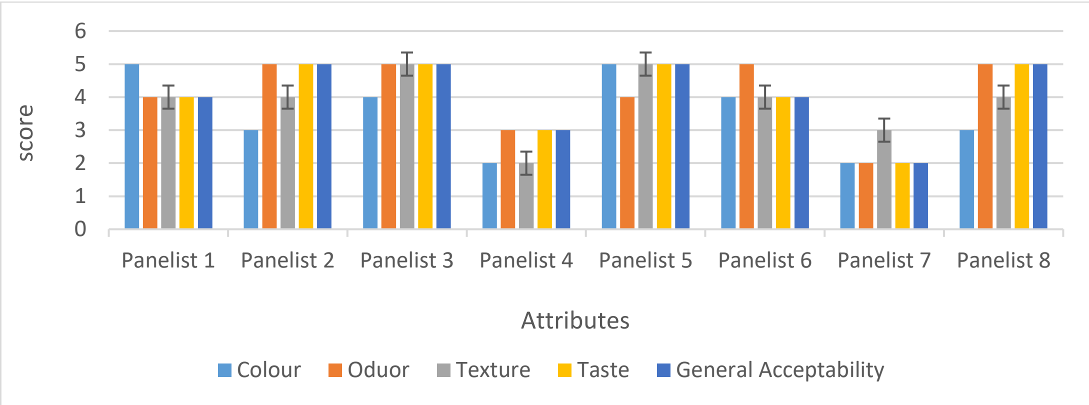

Fig. 10. Variation in sensory evaluation scores

4. CONCLUSION AND RECOMMENDATIONS

This research aimed to evaluate the performance of a solar dryer for silver cyprinid in order to enhance food security by improving drying efficiency, product quality, and sustainability in fish preservation. The results demonstrated that solar drying significantly improved the sensory qualities of fish, such as color, flavor, and texture, compared to traditional sun drying. The controlled drying process effectively reduced moisture content from 66.6% to 8.70% and finally attained a stable moisture content of 5.62%, enhancing both texture and shelf life. Additionally, the higher temperatures achieved in solar dryers preserved the natural color and flavor while preventing off-odors, making the fish more appealing, safer, and more marketable, thus boosting consumer satisfaction and value. The findings also highlighted the impact of ambient temperature and solar radiation on the efficiency of solar drying for silver cyprinid, stressing the need for further research into energy storage solutions during sunny periods. Solar drying not only reduces moisture content and enhances product quality but also minimizes microbial growth and aflatoxin contamination. With an overall acceptability score of 4.125 out of 5 in sensory evaluation, it is clear that solar drying is an ideal preservation method for *Omena*. These positive sensory scores underscore the importance of adhering to strict food handling standards to achieve commercial success.

To fully leverage the benefits of solar drying and improve its drying efficiency, future research should prioritize enhancing solar collector designs, optimizing drying conditions, and investigating the actual cost of solar dryers for better commercialization. Additionally, more studies are required to assess the impact of drying on nutritional value. Understanding the price dynamics will enable wider adoption of solar dryers, making the technology more accessible to small-scale fishers and promoting sustainable fish preservation methods. Moreover, implementing educational programs for fishermen that emphasize hygienic fish handling, effective storage practices, and advanced drying techniques is essential. These initiatives will not only contribute to food security through sustainable preservation practices but also improve the livelihoods of individuals in the fish industry. Government should promote policies that encourage the use of solar fish drying technology due to its supports towards enhancing livelihood and sustainability.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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