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Original research

Design and Evaluation of a New Solar Dryer Equipped with Three Sides Flat Plate Collectors for Drying Tilapia Fish Fillets

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Abstract:

In the present work, a solar dryer was designed to useful maximize solar energy. The developed solar dryer was used for drying slated tilapia fish fillets. Three fish fillets with thicknesses of 4, 8, and 12 mm were dried using the developed solar dryer at an air speed of 0.5 m/s, and the obtained data were compared with the other samples dried in open air. The results showed that to achieve a final moisture content of approximately 18.08%, the drying times were 16, 18, and 21 hours for the solar dryer, and 30, 33, and 36 hours for sun drying, for fillet thicknesses of 4, 8, and 12 mm respectively. Additionally, the average drying rates were 8.038, 7.05, and 6.06 g_w/g_{dm}.h for the solar dryer compared to 4.33, 4.09, and 3.87 g_w/g_{dm}.h for sun drying of 4, 8, and 12 mm fillets respectively. The rehydration ratios were 62.47%, 67.13%, and 73.27% for solar drying versus 0.96%, 35.85%, and 42.8% for sun drying. The solar dryer efficiency increased from 42.35% in June (700 W/m^2 average radiation) to 44.1% in July (720 W/m^2) and 46.14% in August (750 W/m^2). Also, the obtained results indicate that the solar dryer method is more effective in reducing the number of bacteria, yeast, and mold when compared to the sun drying method. In addition, tilapia fish fillets dried using a solar dryer received an excellent general acceptance rating with regards to color and odor compared to the other samples dried in open air.

Key words: tilapia fish, drying, solar energy, microbial analysis, sensory evaluation

1- Introduction

Fish is a highly nutritious food source, renowned for its superior quality protein compared to meat and eggs (Ojutiku et al., 2009). Tilapia, a globally distributed fish species, ranks second among food fish and possesses remarkable traits that make it ideal for aquaculture.

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Its rapid growth rate, easy reproductive capabilities, adaptability to diverse environmental conditions, and acceptance of artificial feeds render tilapia a desirable aquaculture option (Duan et al., 2005; Watanabe et al., 2002). This fish plays a crucial role in securing food supplies, improving public health, and providing livelihoods for many artisanal fishers in developing nations. Fresh fish remains surplus and is wasted if not consumed or processed into finished goods Up to 50% of the fish caught in developing countries is lost, despite its importance to their economies, health, food security, and the livelihoods of artisanal fishermen (Danquah et al., 2021; Jain, 2006; Jain and Pathare, 2007).

The maintenance of fish nutritional value, preservation of its rich composition, and prevention of fish-borne diseases are of paramount importance. Several techniques have been developed to preserve fish quality and prolong its shelf life. The underlying principle of these techniques is to control specific parameters of the fish, thus minimizing metabolic changes that lead to fish spoilage. It is imperative to adopt these technologies to ensure that fish retain their nutritional value while avoiding the costly and debilitating impacts of fish-borne diseases (Bala and Janjai, 2005; Duan et al., 2005; El Magd and Elwakeel, 2021; Elwakeel et al., 2022; Radwan et al., 2021; Rizal and Muhammad, 2018; Watanabe et al., 2002). Access to refrigeration or ice is limited in many parts of the world, which can cause stress on the physical, chemical, and biological processes, leading to the spoilage and deterioration of fresh fish. To provide a consistent source of protein to communities with limited access to fresh fish, reducing moisture content through drying or smoking is an ideal option. Traditional methods of smoking and drying fish include direct sun drying and placing the fish either on the ground, on mats, or on racks, while modern quality control procedures, such as Hazard Analysis and Critical Control Point (HACCP) programs, are increasingly being used in the smoked, processed, and dried fish industries (Amaral et al., 2021; Duarte et al., 2020; Hammond et al., 2015; Sulieman and Sidahmed, 2012; Tavares et al., 2021; Tsironi et al., 2020).

In India, around 14% of the fresh fish produced is used for drying. Dried fish are popular with Indian consumers. Consequently, fish drying has become a significant commercial activity in coastal areas (Chavda and Kumar, 2009). The drying of fish is a vital process that contributes to its preservation by deactivating enzymes and removing moisture, which is conducive to bacterial and mold growth. The acceptable moisture content for fishmeal storage, in order to maintain its safety, is below 12% db. The digestibility of fishmeal depends on the maintenance of appropriate moisture levels surrounding the protein. Therefore, it is necessary to ensure that the maximum temperature inside the dryers does not exceed 100 °C to maintain the optimal moisture content. Overheating the protein can alter its amino acid structure, making it unidentifiable and difficult to absorb by the intestines of animals, thereby rendering the fishmeal less digestible practically (Bala and Mondol, 2001; Bellagha et al., 2002; Metwally et al., 2024). Traditionally, fish is dried in the open sun. While solar drying is the simplest and most cost-effective method, it has the downside of potential contamination from dust, insects, and animal droppings (Chavda and Kumar, 2009).

Numerous research studies have been conducted globally, exploring the subject of fish drying. Researchers have employed various systems to conduct their investigations. They aimed to better understand the process of fish drying and its associated techniques. In order to dry fish in coastal areas, Mehta et al., (2018) designed and evaluated the efficacy of a mixed-mode tent-type solar drier. whereas in 18 hours of sunshine, the moisture content of the fish held in the solar dryer dropped from roughly 89% to 10%. Alvinika et al., (2021) presented fuzzy logic-based Internet of Things (IoT) monitoring and fish drying equipment design. According to their assessment, the system is functioning as intended based on the results of experiments conducted to test it using a thermometer. The relative error rate for the temperature system is 1.62%, and for humidity, it is 1.96%. Also, to increase fish drying rates, Richa et al., (2022) conceived and built a resistance heating device combined with a solar drying system. Under ideal circumstances, the developed ohmic heater decreased the moisture content of fish muscles from 348.5% (db) to 260.91% during the initial drying stage. In addition, in order to dry anchovy fish, Ragasudha et al., (2023)built and evaluated the efficacy of a PV-powered solar-infrared hybrid dryer (SIHD). The data obtained demonstrated that the anchovy's moisture content is decreased by the SIHD from 83.7 (w.b.) to 15.2% (w.b.) in 6.25 hours, but it requires 10.30 hours in a solar dryer and 16.20 hours in an open sun drying environment to reach the respective moisture content of 15.3% (w.b.) and 15.5% (w.b.). Additionally, the maximum drying efficiency of solar and solar-infrared hybrid drying was found to be 30.43% and 41.11%, respectively.

The present study endeavors to design and analyze the performance of a solar dryer equipped with three sides flat plate solar collectors to optimize the utilization of solar energy for drying tilapia fish fillets of varying slice thickness. Additionally, the study seeks to compare the data obtained from this process with that of open-air drying using various criteria. The experimental process will involve drying tilapia fish fillets at varying slice thicknesses to determine the optimal slice thickness for drying efficiency. The data collected from the solar dryer will be compared with data obtained from open-air drying using different criteria. The results of this study are expected to provide a better understanding of the utilization of solar energy in the drying process of tilapia fish fillets and contribute to the development of sustainable and cost-effective drying techniques.

2. Materials and Methods

2. 1. Material

All laboratory experiments and drying procedures were conducted at the Agricultural Research Center located in Giza, Egypt, in 2023. Tilapia fish (*Oreochromis niloticus*) were obtained fresh from Lake Nasser in Aswan, Egypt. After procurement, the tilapia fish were transported in an insulated icebox, with layers of ice placed between the fresh fish to maintain low temperatures and preserve quality. Before the experiments, the fish underwent cleaning by removing the skin, internal organs, head, and tail. The cleaned fish were then washed under running water and sliced into fillets of 4, 8, and 12 mm thicknesses. These prepared fish fillets were used for the drying experiments. The tilapia fish fillets were immersed in a 5% saline (NaCl) solution at room temperature for 15 minutes. The salted tilapia fish fillets were dried using the developed solar dryer at a constant air velocity of 0.5 m/s. For comparison, another set of fillets were dried by direct exposure to open sun (open-air drying). The drying process continued until constant weight was achieved, indicating the fillets had reached their equilibrium moisture content. Drying experiments were carried out from 8 a.m. to 5 p.m., then tilapia fish slices were put in plastic aluminum pages and well-sealed and stored in the refrigerator at 5 ^{o}C till the second drying day to prevent fish slices from contamination and rehydrate during the night.

(a) **(b)** **(c)**

Figure 1. Preparation and slicing of tilapia fish at different slice thicknesses for the drying process. (a) fresh tilapia fish, (b) slicing of tilapia fish, and (c) final shape of fresh tilapia fish after slicing (flesh).

2.2. Methods:

2.2.1. Description of the developed solar dryer

The solar dryer described in the current study was manufactured, and its performance was tested and evaluated in the New and Renewable Energy Unit, Food Technology Research Institute, Agricultural Research Center, Giza, Egypt. Figure 2 shows the developed solar dryer. While the main components and dimensions of the developed solar dryer are shown in Figures 2 and 3.

Figure 2. The developed solar dryer with three sides flat plate solar collector.

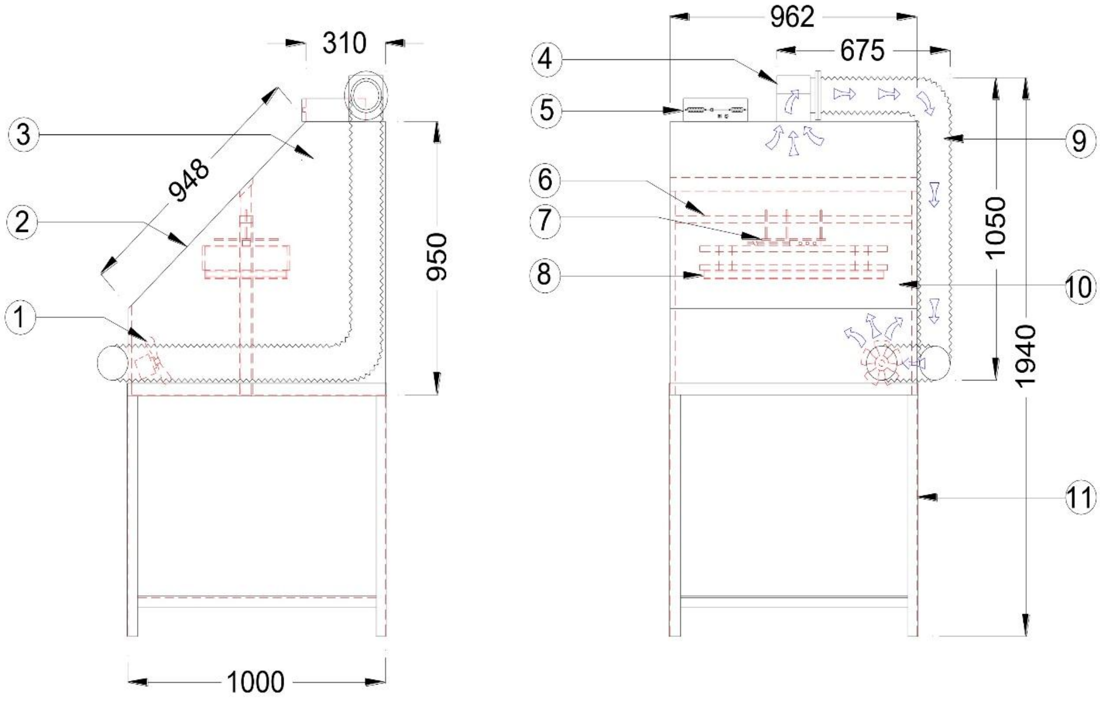

Figure 3. Main components and dimensions of the developed solar dryer, (a) side view and (b) front view. Where 1- a fan to circulate the hot air, 2- the inclined solar collector, 3- the vertical collector, 4- a fan to extract moisture-laden air, 5- a data logger, 6- weighing scale holder, 7- weighing scale, 8- tray, 9- filter, 10- air chimney, 11- dryer holder.

The developed solar dryer boasts dimensions of 1 meter in length, 0.96 meters in width, and 0.95 meters in height. The drying room features a triangular prism shape and is equipped with three flat plate solar collectors on its upper, east, and west sides. This design proves effective in increasing the amount of solar radiation absorbed. The solar collectors are double-walled, with a transparent glass cover on top to allow short-wave solar radiation to penetrate the black-painted absorber plate. This conversion process results in long-wave thermal energy.

The first collector is inclined at an angle of 30 degrees in the south horizontal direction. The second collector is on the vertical side of the dryer, facing east, and acts as an assistant to the inclined collector. It absorbs solar rays and converts them into thermal energy in the morning. The third collector is on the vertical side of the dryer, facing west. It serves to complement the inclined collector, absorbing solar radiation and converting it into thermal energy in the evening.

The drying room's back side is a double-wall insulated door, while its four drying trays are made of stainless steel, specifically assigned to carry salted tilapia fish slices for drying purposes. The hot air inside the drying cabin is distributed using an electric fan with a power rating of 0.1 kW and a constant air speed of 0.5 m/s. A suction fan with an average energy rating of 0.15 kW is used to carry moist air to a chimney containing a silica gel filter, which absorbs moisture effectively.

2.2.2. Description of direct sun drying in open air

The experiment involves exposing fillet slices of tilapia fish, each varying in thickness, to sunlight. The tilapia is placed on a perforated tray, which sits atop an iron stand. The salted fish slices are then covered with black gauze to prevent any dust or insects from compromising the experiment.

2.2.3. Design equations of the SD

2.2.3.1. Amount of moisture to be removed (M_w)

Tilapia fish slices contain a high moisture content that must be decreased at a safe level. The amount of moisture was estimated using Equation 1, as stated by Eissa et al., (2024), and Etim et al., (2019), (2020).

$$M_w = \frac{W_w \times [M_i - M_f]}{[1 - M_f]} \times 100 \qquad ..(1)$$

where: W_w is the total weight of dried sample in g, and M_i *and* M_f are the initial and final MC in %

2.2.3.2. Quantity of heat required for drying

Using Equation 2, the amount of heat needed to increase the temperature of tilapia fish slices within the drying room (Q_1, J) to the hot air temperature was calculated, as mentioned by Dissa et al., (2011).

$$Q_1 = W_w \times C_p \times \Delta T \qquad ...(2)$$

where: C_p is the specific heat of STFF (3.5174 ± 68.5 kJ/kg.K), and ΔT is the temperature difference between the STFF in K and the drying room temperature in K.

The heat quantity required for evaporating moisture content from the tilapia fish slices (Q_2, J) was calculated using Equation 3, as stated by Etim et al., (2019), where L_v is 2257 (J/kg) of water.

$$Q_2 = M_w \times L_v \qquad ..(3)$$

The total heat quantity required for removing moisture content from tilapia fish slices (Q_T, J) was calculated using Equation 4, as mentioned by Eke and Simonyan, (2014),

$$Q_T = Q_1 + Q_2 \qquad ..(4)$$

2.2.3.3. The surface area of the flat plate solar collector (A_c)

The surface area of the flat plate solar collector (A_c) required to receive solar radiation can be calculated by Equation 5, as reported by Babar et al., (2020),

$$A_c = \frac{Q_T}{\eta \times I_t \times t_d} \qquad ..(5)$$

where: η is the efficiency of the solar collector in %, I_t is the solar intensity in W/m^2, t_d is the drying time in h.

2.2.3.4. Determination of tilt angle

Eke, (2011) reported that the tilt angle (β) of the flat plate solar collector was found within Latitude (∅) 25.6890° N using Equation 6,

$$\beta = 2.66\,° + Lat\ \emptyset \qquad .. \qquad (6)$$

The design calculation and solar collector size were performed using the assumptions and parameters listed in Table 1.

Table 1. The assumptions and parameters for design calculation of the solar dryer.

Items	Conditions and assumptions
Orientation	Southwards direction
Tilt angle	30 °
Product	Tilapia fish
Loading capacity	6 kg
Initial moisture content, (w.b.)	74.83 %
Total drying time	10 hours
Total solar collector surface area	2.434 m^2
Drying room volume	877.34 Litter

2.2.4. Measuring devices and uncertainty

2.2.4.1.Air temperature and relative humidity Measurement

The study employed a specialized Internet of Things (IoT) data logger device to measure air temperature and relative humidity. As shown in Figure 4, this device comprised several electronic components detailed in Figure 5 (Mahmoud et al., 2021; Nasrat et al., 2024; Yang et al., 2024). The measuring unit recorded hourly air temperature and relative humidity data inside the drying room and ambient conditions. These data were stored on a micro-SD card and transferred to a laptop for analysis after each drying process.

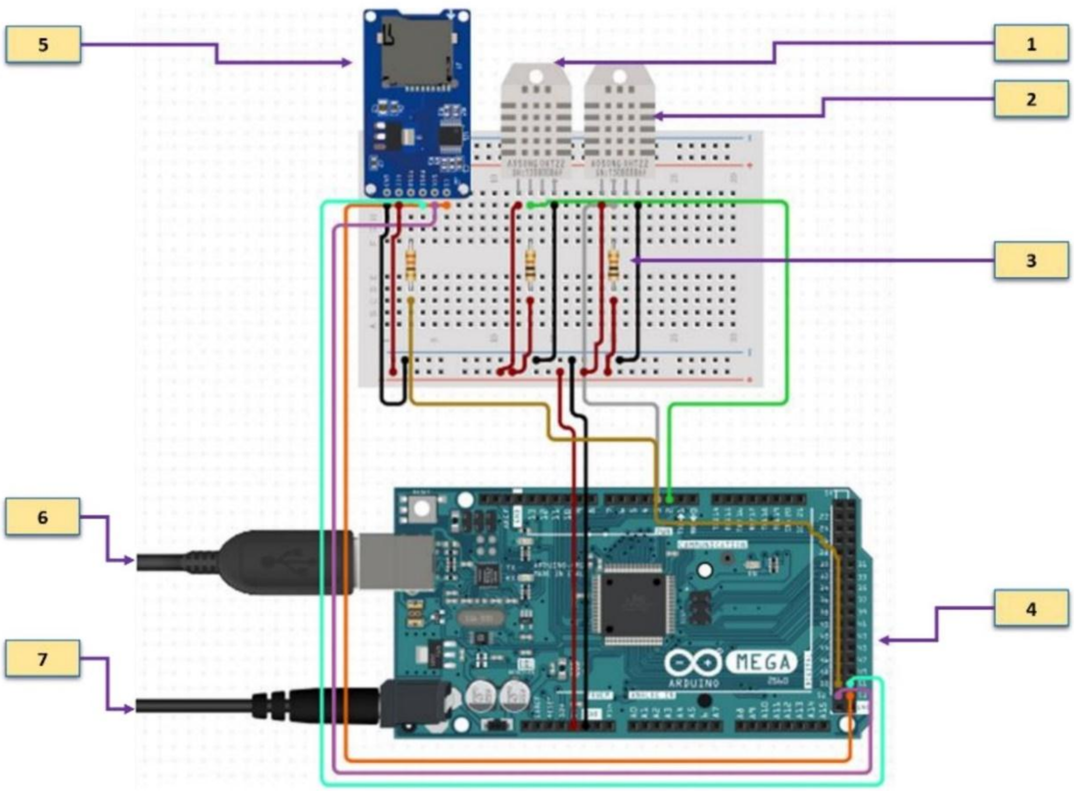

Figure 4. Measuring circuit for both air temperature and relative humidity. 1-DHT22 sensor inside drying room, 2- DHT22 sensor outside drying room, 3-linear resistance, 4-Arduino mega board, 5- micro-SD card, 6-USB cable connected with laptop, 7-power cable connected with adaptor.

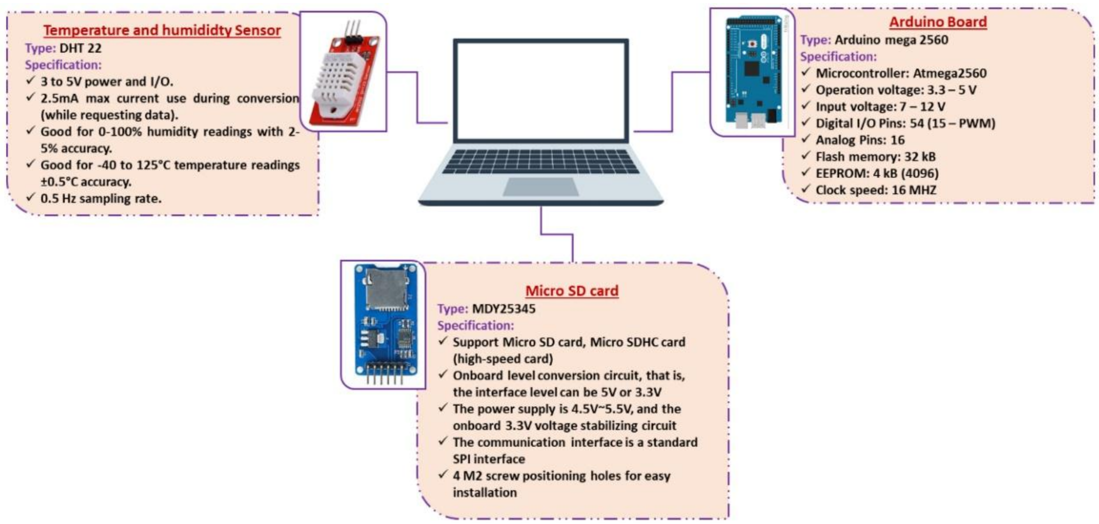

Figure 5. Specifications of the different electronic parts used in air temperature and relative humidity measuring device.

2.2.4.2.Sample weight measurement

An electronic scale with a range of 0.001 to 40 kg and an accuracy of 0.001 g was used to measure the weight of tilapia fish samples at different time intervals to determine moisture content. The scale, integrated with a GCB3 single-point anodized aluminum load cell, could operate from -20°C to 120°C and was humidity-resistant.

2.2.4.3.The air velocity measurement

A Sato Sk-73D hot-wire anemometer measured the air velocity inside the drying room. This anemometer had a measurement range of 0.0 to 30 m/s, with an accuracy of ± (3% of full scale + 1 digit) m/s and a resolution of 0.1 m/s.

2.2.4.4.Average fish fillets thickness measurement

The average thickness of fish fillets was measured using a Mitutoyo MDC-25M micrometer (MFG, Japan) with an accuracy of 0.0001 mm. Ten random measurements were taken at different locations on each fillet, and the average was calculated.

2.2.5. Drying procedure

Fresh slices of salted fish with an average thickness of 4, 8, and 12 mm and an initial weight of 100 gm for each slice were used for the drying process. The samples had an average initial moisture content of 74.83% (w.b.). The drying trays were placed inside a drying room with an air speed of 0.5 m/s. Hourly records were taken of the moisture content of the samples during the drying process until the final moisture content was reached. The drying process was carried out from June to August 2023.

2.5.1. Moisture content

The determination of moisture content in fish slices was conducted by heating the slices at 105°C for a duration of 3 hours in an electrical oven as stated by AOAC (2005) using Equation 7, as reported by Eke and Simonyan, (2014),

$$\mu_w = \left[\frac{W_w - W_d}{W_w}\right] \times 100 \qquad ..(7)$$

where: μ_w is the MC on a wet basis, %; W_w is the wet weight of the fish slices, gm; W_d is dry weight of the fish slices, gm.

While, the moisture content of different samples of fish slices during drying process was calculated every 60 minutes (one hour) during the experiments. Then it was estimated based on Equation 8 as reported by Tayel et al., (2012),

$$M_t = \left[\frac{b}{a} \times (1 + M_i)\right] - 1 \qquad ...(8)$$

where: a is the mass of fresh sample in gm, b is the mass of sample at any time, in gm and M_i is the initial moisture content is the sample, w.b. %.

2.5.2. Drying rate

The drying rate in (g_{water}/h) of different samples of fish slices after drying process was calculated once every 60 minutes (one hour) during the experiments according to Etim et al., (2019), using Equation 9.

$$DR = \frac{M_{(t+dt)} - M_t}{d_t} \qquad ..(9)$$

where: M_t is the moisture content at time 't', while $M_{(t+dt)}$ denotes moisture content at $(t + dt)$, and d_t is the time.

2.6. Solar collector efficiency

The solar collector efficiency ($\eta_{coll}\ in\ J$) is the ratio of the input power and output power using Equation 10. The input power ($E_{input}\ in\ J$) from solar radiation was estimated according to Equation 11, while the output power ($E_{output}\ in\ J$) of the solar collector that is used to increase the air temperature inside the drying room and evaporate the moisture content from fish samples was calculated by Equations 12 and 13 according to Bala and Janjai, (2005), and Usub et al. (2008).

$$\eta_{coll} = \frac{E_{output}}{E_{input}} \times 100 \qquad ...(10)$$

$$E_{input} = A_{coll} \int_0^t Ins_{coll}(t)dt \dots\dots\dots\dots (11)$$

Energy output from the SC ($E_{input.\ coll}$, J) is given as:

$$E_{output} = \left[\int_0^t m_a\ (t) \times C_{p,a} \times \left(T_{a,in} - T_{a,out}\right) dt\right] + [m_r \times L_h] \qquad ... (12)$$

$$m_a = \rho_a \times V_a = \rho_a \times u_a \times A_{coll} \qquad ... (13)$$

where: Ins_{coll} is the solar intensity in W/m^2, A_{coll} is the solar collector surface area in m^2, m_a is the air mass flow rate in kg/s, $C_{p,a}$ is the specific heat of fish (3.6 kJ/kg.k), $T_{a,in} and\ T_{a,out}$ are the air temperatures inside and outside the drying room, in k, m_r is the mass of moisture removal for the fish sample after drying in kg, L_h is the latent heat of water (2257 kJ/kg), ρ_a is the air density, kg/m^3, V_a is the air speed inside the drying material, and u_a is the air speed in m/s.

2.7. Quality evaluation of dried fish samples

2.7.1. Rehydration ratio

Ten grams of dehydrated fish samples were immersed in boiling distilled water to ascertain the rehydration ratio of the dried slices. After then, the fish samples were taken out at regular intervals of every two minutes and weighed until the variation between the subsequent weightings was negligible. The formula created by sSacilik et al., (2006), and Sacilik and Unal, (2005) was used to compute the rehydration ratio.

$$RR = \frac{W_f - W_i}{W_i} \qquad ...(5)$$

where: W_f is the final weight of the fish samples after drained, and W_i is the initial weight of the dried fish samples before soaking.

2.7.2. Sensory evaluation

A 10-point hedonic scale, with 1–3 denoting poor, 4-6 denoting average, and 7–10 denoting good, was used to assess the sensory qualities of dried fish samples (Majumdar et al., 2017). After ninety days, sensory analyses were performed on dried fish fillets to assess quality in terms of color, odor, and overall acceptability. The sensory evaluation was carried out in December 2023 in Egypt by the Food and Agricultural Technology Center (FAITC) of the Ministry of Trade and Industry.

2.7.3. Determination of microbial load

A spread plate count method aerobic plate count was used to ascertain the microbiological load of the sun-dried fish samples and the sun-dried samples following a 90-day storage period. The counts of microorganisms, mold, and yeast were ascertained in compliance with Downes and Ito, (2001).

3. Results and discussion

3.1. Moisture content

The moisture content of the various fish samples was determined following the guidelines outlined in the Materials and Methods section. The moisture content was then plotted as a function of time, with the results presented in Figure 6. It was observed that the drying time for fish samples subjected to the developed solar dryer increased by approximately 46.67%, 45.45%, and 41.67% for samples with fillet thicknesses of 4, 8, and 12 mm, respectively, compared to open-air drying. The drying times for 4, 8, and 12 mm thick fish fillets in the developed solar dryer were 16, 18, and 21 h, respectively. In contrast, open-air dried fish samples took 30, 33, and 36 h minutes, respectively, to reach the same dryness level. The faster drying of fish fillets inside the solar dryer can be attributed to the higher drying air temperatures, ranging from 38-65°C, compared to 28.44-39.64°C for sun drying. These results indicate that solar dryers significantly reduce the drying time of agricultural products when compared to open sun drying, as reported by Elwakeel et al., (2023) and (2024). Additionally, the moisture content of the dried fish samples from the developed solar dryer was lower than that of the open-air dried fish samples.

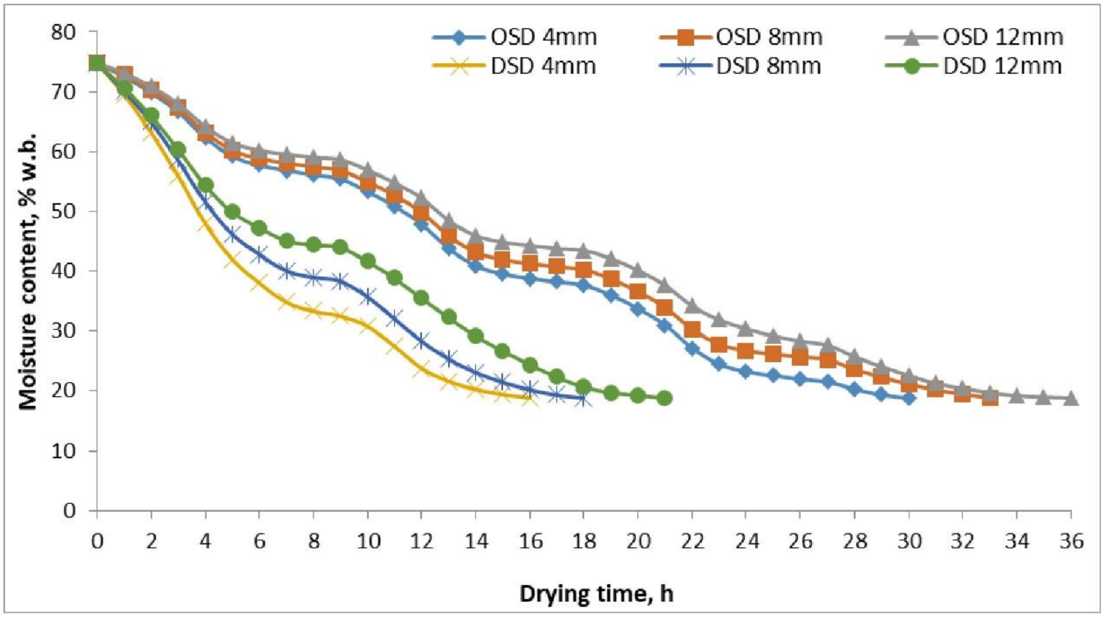

Figure 6. Effect of elapsed drying time on moisture content of salted tilapia fish fillets for solar and sun drying.

3.2. Drying rate

Figure 7 illustrates that the developed solar dryer exhibits higher drying rates for fish compared to open-air drying. The drying rates recorded for 4, 8, and 12 mm thick fish fillets were 8.038, 7.44, and 6.06 g water/g dry matter.h, respectively, when using the solar dryer. In contrast, the lowest drying rates of 4.33, 4.09, and 3.87 g water/g dry matter.h were observed for open-air drying of 4, 8, and 12 mm thick fish fillets, respectively. The higher drying rates achieved with the solar dryer are attributed to the increased energy gain, resulting in elevated temperatures inside the dryer and increased hourly evaporation rates of moisture content compared to open-air or sun drying. The differences in drying rates between all fish samples dried in the developed solar dryer and those dried using open-air sun drying were statistically significant ($P<0.05$), corroborating the findings of Sengar et al., (2009). Fluctuations in drying rates may be attributed to the cooling of fish slices during nighttime when they are stored in the refrigerator before resuming drying the next day. It takes some time for the slices to be reheated, after which the drying mechanism proceeds efficiently.

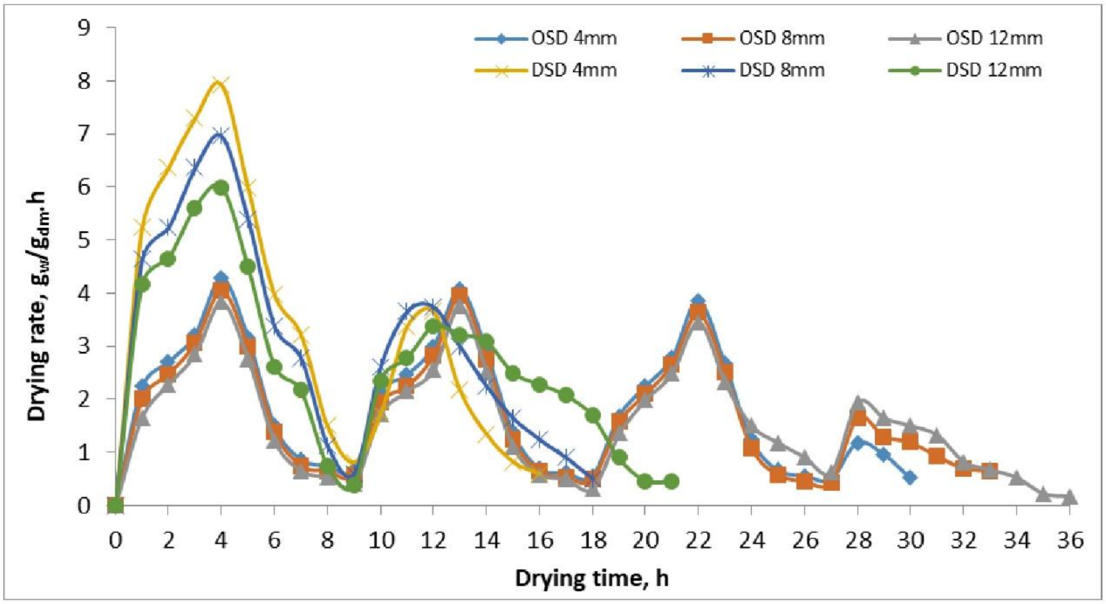

Figure 7. The effect of elapsed drying time on drying rate of salted tilapia fish fillets for solar and sun drying.

3.3.Rehydration ratio of dried fish samples

The effect of fish fillet thickness on the rehydration ratio (R.R.%) was studied within the range of 4, 8, and 12 mm fillet thicknesses for samples dried using the developed solar dryer and open sun drying (open air). Figure 8 shows the effect of fish fillet thickness on the rehydration ratio for the different drying systems. It is clear that the rehydration ratios increase linearly as the fillet thickness increases for both solar drying and sun drying systems. Higher rehydration ratios were recorded for solar drying compared to sun drying. The following linear relationships were satisfied for solar and sun drying within the studied fillet thickness range of 4 to 12 mm, as shown in Figure 8:

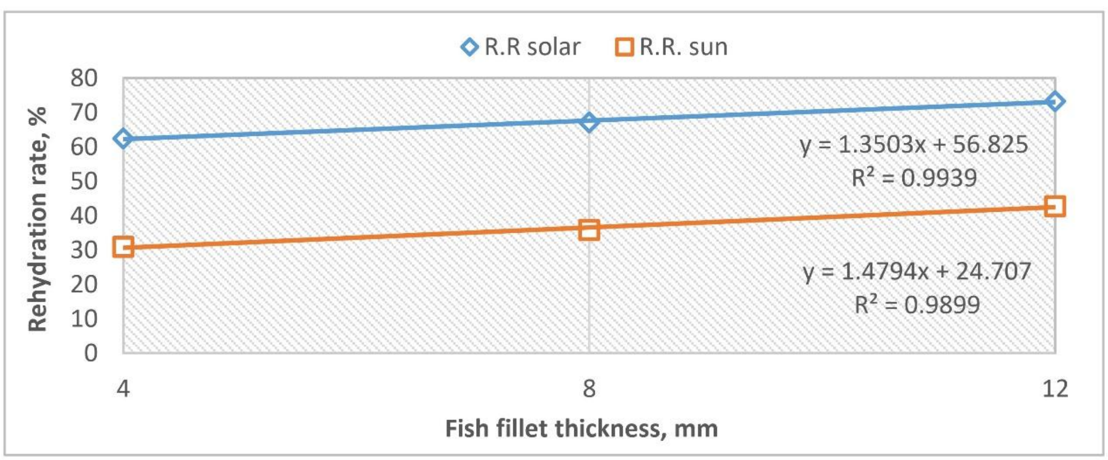

Figure 8. Effect of fish fillet thickness on rehydration ratio at different drying systems.

It is clear that the rehydration ratios are increasing linearly as fillet thickness increases for both solar drying and sun drying systems. Higher rehydration ratios were recorded for solar drying than for sun drying. The following relationships were satisfied for solar and sun drying within the range of studied fillet thickness of 4 to 12 mm, as shown in Figure 8.

$$y = 1.3503\ x + 56.824 \text{ and } R^2 = 0.9939$$

$$y = 1.4794\ x + 24.707 \text{ and } R^2 = 0.9899$$

Fish fillets with a 12 mm thickness achieved the highest rehydration ratio of 73.27% in the solar dryer versus 62.47% for open-air drying. In contrast, lower rehydration ratios of 62.47% and 35.85% were recorded for 4 mm thick fillets dried in the solar dryer and open air, respectively. The differences in rehydration ratio between all fish samples dried in the solar dryer and those sun-dried were statistically significant ($P < 0.05$). This may be due to the higher temperatures in the solar dryer and higher thermal energy, leading to larger voids between cells in the dried fish fillets. This increased the moisture evaporation rates for the same fillet thickness compared to sun-dried fish fillets. Consequently, the solar drying method has a greater ability to remove moisture during the drying process compared to sun drying. These results are consistent with the findings of Younis et al., (2018).

3.4.Efficiency of solar dryer

The conversion of solar energy into thermal energy is a crucial aspect when considering its potential as a viable energy source. In order to evaluate the efficiency of a solar dryer, three experiments were conducted in the months of June, July, and August. Each experiment made use of 6 kg of tilapia fish fillets, 4 mm thick, and an air speed of 0.5 m/s. The aim was to determine the efficiency of the solar dryer, with an average monthly solar insolation of 700, 720, and 750 W/m² recorded for June, July, and August, respectively. Findings showed that the average efficiency of the solar dryer was 42.35%, 44.1%, and 46.14%, respectively, in line with the study conducted by Ali and El-Sharabasy, (2012). These results demonstrate the potential for solar dryers as a viable and efficient method for the conversion of solar energy.

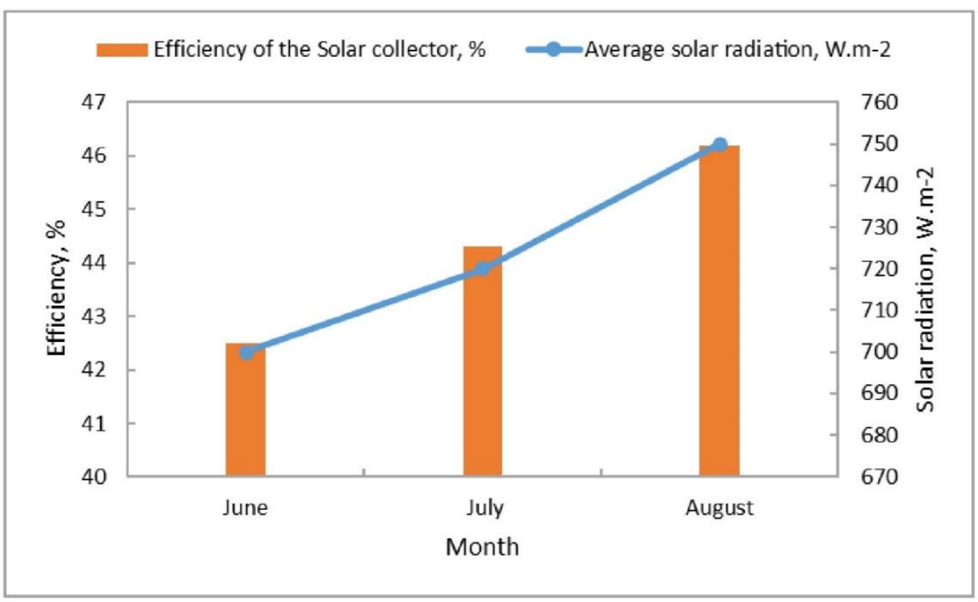

Figure 9. The effect of solar radiation intensity on the efficiency of the developed solar dryer.

3.5.Microbial load of dried fish fillets

Microbial analysis was performed on packed salted dried fish fillets stored for a period of 90 days. The fillets were of varying thicknesses, namely 4mm, 8mm, and 12mm, and were packed in metallic bags. The obtained results, illustrated in Figure 10, indicate that the solar dryer method is more effective in reducing the number of bacteria, yeast, and mold when compared to the sun drying method. The numbers of bacteria, and (yeast, and mold) in fish dried in the solar dryer were 4.34 (CfU×10^{-2}/g), and 4.75 (CfU×10^{-2}/g), respectively, in dried fish fillets with thicknesses of 4, 8, and 12 mm. In contrast, the sun-dried fish fillets had higher numbers of bacteria, yeast, and mold, albeit within safe limits. Specifically, the numbers of bacteria, yeast, and mold were 5.6, 6.12, and 6.84 (CfU×10^{-2}/g) in fish fillets of 4mm, 8mm, and 12mm thickness, respectively. The observed increase in the number of organisms might be attributed to lower temperatures during the sun drying process and increased drying elapsed time. Nevertheless, the number of microbes in the final products was within the permissible limits. Importantly, the final products were free of E. coli and Salmonella under all drying conditions.

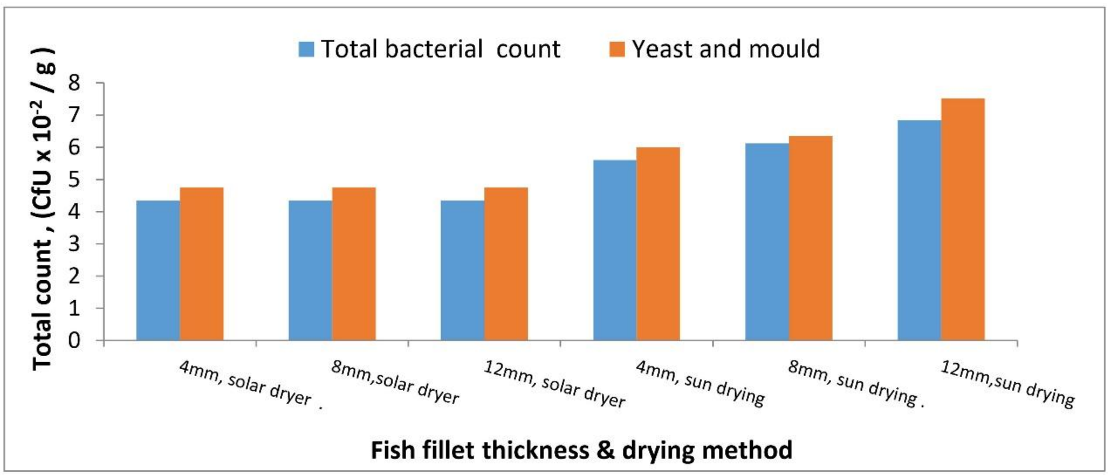

Figure 10. The effect of drying method on the total number of bacteria, yeast and mold in dried tilapia fillets.

3.6.Sensory evaluation

The sensory properties of a product are susceptible to alterations caused by the drying method and storage time (Rojas-Graü et al., 2009). Sensory evaluations of the dried fish fillets were performed after 90 days to assess the color, odor, and general acceptability of the products. The obtained results are tabulated in Table 3. The results revealed that the tilapia fish fillets with a thickness of 4 mm and 8 mm, which were dried using a solar dryer, received an excellent general acceptance rating with regards to color and odor, scoring a 10. The samples with a 12 mm thickness received a fairly low color level rating of 8 degrees, and the odor level decreased significantly to 7 degrees. The fish fillets with a thickness of 4 mm dried by sun drying received an average general acceptance rating, with the color and smell score reaching 6. Conversely, the acceptance score for fish fillets with a thickness of 8 mm and 12 mm was very poor, as the general acceptance decreased significantly at $P< 0.05$, in terms of color and smell. Moreover, during the storage period, the general acceptance of the samples within limits decreased to 3 due to the extended drying duration and exposure to dust and bacterial contamination. The results from this study suggest that the solar drying method is more effective in preserving the quality of dried tilapia fish fillets in terms of color, odor, and general acceptability, especially for samples with a thicknesses of 4 mm and 8 mm.

Table 3. Sensory evaluation for different samples of dried tilapia fish fillet slices.

Drying method	Fish fillet thickness	Sensory evaluation		
		Color	Aroma	Overall acceptability
Solar dryer	4 mm	10.00	10.00	10.00
	8 mm	10.00	10.00	10.00
	12 mm	8.00	7.00	7.00
Sun drying	4 mm	6.00	6.00	5.00
	8 mm	3.00	3.00	3.00
	12 mm	3.00	3.00	3.00

4. Conclusion

This study aimed to utilize tilapia fish from Lake Nasser, where fishing activities have declined due to the lake's distance from fish markets in other governorates of Egypt. Additionally, it sought to harness solar energy as an abundant and clean energy source. A solar dryer equipped with three-sided flat plate collectors was designed to maximize the utilization of solar energy for drying tilapia fish fillets. Fresh salted tilapia fillets of 4, 8, and 12 mm thicknesses were prepared and dried using the solar dryer at an air speed of 0.5 m/s. The performance was compared to direct sun drying. The obtained data showed that:

- The drying time required to achieve a final moisture content of approximately 18.08% was 16, 18, and 21 hours for the solar dryer, compared to 30, 33, and 36 hours for sun drying of 4, 8, and 12 mm thick fillets, respectively.
- The average drying rates were 8.038, 7.05, and 6.06 g water/g dry matter.h for the solar dryer, compared to 4.33, 4.09, and 3.87 g water/g dry matter.h for sun drying of 4, 8, and 12 mm thick fillets, respectively.
- The rehydration ratios were 62.47%, 67.13%, and 73.27% for solar drying, compared to 0.96%, 35.85%, and 42.8% for sun drying of 4, 8, and 12 mm thick fillets, respectively. A linear relationship was observed between fillet thickness and rehydration ratio for both drying methods within the studied thickness range, where the rehydration ratio increased with increasing fillet thickness.
- The solar dryer efficiency increased from 42.35% in June (700 W/m^2 average radiation) to 44.1% in July (720 W/m^2) and 46.14% in August (750 W/m^2), corresponding to the increase in average solar radiation intensity.

Based on the results, fish fillets of 4 mm thickness were recommended as the optimal treatment due to their high quality, minimum drying time, and total microbial count being below the permissible level compared to the other fillet thicknesses studied.

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