

CROAKER FISH DRYING USING ARTIFICIALLY ROUGHENED SURFACE COLLECTOR SOLAR SYSTEM

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Abstract

Issues like health hazards, curtailed product taste and durability, atmospheric pollution, pest attack, and truncated efficiency of drying a product with firewood fuel or open-sun can be overcome by the solar dryer, where electricity is unavailable for microwave-assisted drying. In this study, croaker *P. Elongatus* was solar-dried using a system with an artificially roughened collector. Drying chamber energy was conserved with deposited black gravels and aluminium foil wrapper while a feedback system was deployed for air recycling and exchange with the environment. Whereas chamber, plate, and collector hourly temperatures had respective average increments over the ambient in the ranges of 4-21°C, 1-45°C, and 1-10°C, the fish mass reduced from 1.445 kg to 0.264 kg. The optimal collector and drying efficiencies for the system were approximately 0.65 and 0.45, respectively, while the sample was dried for 13 days to withstand up to six months of storage. Though adverse weather can reserve moisture removal, atmospheric cloudiness affects solar radiation but not ambient temperature, whereas the rains affect both. Moisture content in wet-basis reduced from 82% to 15%, while the gravels sustained durable drying from 8:00 to 20:00. Although solar drying is a viable option, efforts should reduce its long drying period for better attractiveness.

Keywords: Solar dryer, Artificially roughened surface collector, Croaker fish, High moisture content reduction, Chamber energy conservation

Introduction

Despite the growing human population, even in slummy areas of the globe, and the relatively high level of our technological advancement, energy for preserving agricultural foods like fishes and vegetables is still insufficient, unclean or unavailable (El-sebaili and Shalaby, 2012). Fish has tremendous economic and health benefits: fishing is an agricultural occupation for several occupants of

riverine locations, particularly in the rural areas, and fish provides high-quality proteins for the human diet. There are numerous fish species, which can be classified depending on the water (whether freshwater or marine) they reside in, fin-type, size, trait, and others. Besides the proteins they give, fishes also have vitamins, their immune system genes are rarely found in higher vertebrates, and

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they provide several nutritional elements such as iron and magnesium. For instance, the croaker fish, which can be found in the Atlantic Ocean, contains chemokines used in producing drugs for curing inflammation or wound healing (McManamay *et al.*, 2015; Andreassen and Høyheim, 2017). The fish market is vast, and we can obtain many other products such as cod oil and fish-chips from fish. However, the fresh fish moisture content is approximately 80%, making it highly perishable when not residing in water. Consequently, efforts are being made to improve fish cultivation and preservation (Bal *et al.*, 2010; Vansconcellos *et al.*, 2015).

Drying reduces moisture from the surface of a product to a desirable fluid content by evaporation. Besides drying, other fish preservation methods include smoking, fermentation, salting, freezing, and braising (the target is to reverse fish's perishability by preventing bacterial and mould growths while also preserving its quality). Food consists of both chemically and physically held water, simultaneously removed during drying; hence dual heat and mass transfer operations occur in the drying process. While heat directly removes the physically held water, the chemically bound water is removed as some mass is transformed into water and transferred to near the sample's surface. Fish's moisture content should be reduced from the high 80% to 15% to avoid mould growth during storage, while drying temperature should be sufficiently held below cooking temperature. Although the temperature range for safe drying of agricultural food products is from 40-70°C, depending on thickness, fishes can withstand temperatures between 40°C and 55°C before cooking starts and proteins transform. Salting prevents bacterial growth and promotes water removal by osmosis. However, such preservation methods, including smoking and braising, may not sustain the fish for an extended period from perishing, and the taste could change (Bal *et al.*, 2010; Prakash and Kumar, 2013; Vijayan *et al.*, 2017).

While other preservation methods may be relatively costly to maintain, fish smoking increases greenhouse gas concentration in the atmosphere and subsequently leads to global warming. However, the solar dryer may not require electricity to operate, and it is also eco-friendly. Nonetheless, solar dryers are season-dependent in their operation: the drying rate is fast during the dry season but slow during the rainy season due to differences in the atmospheric conditions between the two seasons. Solar fish drying takes an average of three days to one week or more to accomplish while its colour changes from whitish to brownish or

yellowish. Although open-sun drying is a primitive preservation method still being used, and fish smoking is still predominant in some places, there are more efficient drying techniques like the microwave oven and solar drying. The open-sun drying is defective and hazardous due to birds and rodents damage and has a slow drying rate and low efficiency compared to the solar dryer. Moreover, a considerable disadvantage of the microwaving or freezing preservation method is its electricity requirement, which may be unavailable in rural areas and epileptic in some urban places (Bal *et al.*, 2010; Oparuku, 2010; Omodara and Olaniyan, 2012).

The efficiencies of solar energy technologies such as photovoltaics and thermal systems are relatively low, despite the abundant solar energy reaching the earth. Worse still, evolving solar technologies are also mostly untested in many locations worldwide, notwithstanding such technologies' climate-dependent disposition (Hubbert, 1971; Tian and Zhao, 2013). Solar thermal systems are those technologies that use shortwave solar radiation to heat fluids such as water and air. Subsequently, the heated fluid or absorbed heat energy is further used for desired purposes, including food drying, water purification, space heating or cooling, refrigeration, and electricity generation. Solar thermal systems are often combined with other units for some tasks like refrigeration and power production. Solar thermal systems or solar collectors can be classified based on the purposes they are being used, their mode of operations, heat collector types, designs, and whether they are single or hybrid systems or the temperature range they produce. Nonetheless, solar collectors can also be generally segmented into passive or active dryers. Passive solar thermal systems, which are regarded as natural circulation dryers, use the natural flow of heated air for drying. Solar dryers can be made from cheap and readily available local materials. While the active solar dryers use external air flowing units such as fans or pumps for hot air circulation, the mixed-mode dryers (or hybrids) combine both passive and active systems as a single unit. A subsection for classifying solar thermal systems is whether the rays transmitted through the glass fall on the sample (direct solar dryers) or if the product is placed in an opaque section in the dryer (indirect solar dryers) (Duffie and Beckman, 1991; Lingayat *et al.*, 2020).

Irrespective of the classification, an efficient solar dryer should regulate its temperature and humidity, be affordable, and prevent dust settling and pest attack on the fish (or any other agricultural food sample). A typical solar dryer is one with an artificially roughened absorber plate and a unit

(feedback system) for forcing convective airflow (Figure 1(a) and Figure 1(b)).

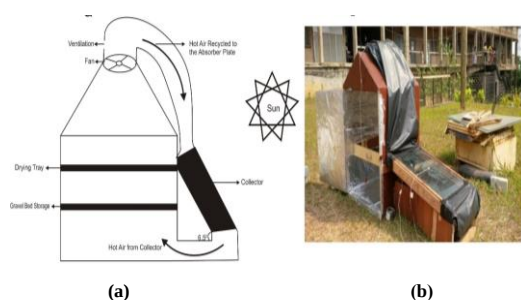


Figure 1. Solar dryer with artificially roughened collector, (a) Schematic diagram of an active house-like solar dryer, and (b) experimental setup of the solar dryer

An artificially roughened solar dryer is considered a unique dryer because of its peculiar collector. Turbulent air improves a typical solar fluid heater by increasing the usually low convective heat transfer coefficient between the absorber and air. Turbulence in the collector can be achieved operationally by casting several designs such as U, V, or W-shaped, rectangular, fixing wires, grooves, ridges, and other methods. Artificial roughness perturbs the vicious sub-layer of the flowing fluid, thereby inducing turbulence. Nonetheless, more pumping is usually required in the artificially roughened collector owing to pressure drop (Lingayat *et al.*, 2020; Yadav and Thapak, 2014). To the best of our knowledge, artificially roughened absorber has not been linked to the solar drying of croaker fish; hence, this study aims at developing relatively basic solar technology to dehydrate croaker *Pseudotolithus elongatus*. Remarkably, the *Pseudotolithus* species are prevalent in the Atlantic Ocean of West Africa (Etim *et al.*, 1994).

Material and Methods

Fish Solar Dryer

Cost-effective and readily available materials were used in the construction of the dryer of this study. The solar dryer comprised three basic units: the drying chamber, a collector unit, and a feedback system. Highly polished plywood with thermal conductivity of 0.15 W/mK was used to construct a box (house-like) drying chamber (0.61×0.58×0.91) m with openings at the bottom and top for air passageway. Heat loss was reduced by lining the drying chamber with aluminium foil paper. Simultaneously, black gravels of a total mass of 4.28 kg were deposited in the energy storage tray

near the basement (Figure 1(a) and Figure 1(b)). The drying tray with gauge wire base was placed in-between the energy tray and the top air passageway. Though the gravels somewhat also served as an energy supplying medium in the drying chamber, the foil wrapper served as a heatwave reflector. Additionally, the smooth surface plywood was deployed to minimise radiative heat loss from the system due to its low thermal conductivity.

The heat collector unit, which mainly comprised the absorber plate, glass cover, and artificial roughness, was linked to the drying chamber. A galvanised sheet metal with length and breadth of 0.762 m and 0.406 m, respectively, served as the absorber plate, while a transparent glass cover with similar dimensions of the sheet metal was placed 55 mm above the absorber. Artificial roughness in the solar collector was created by riveting binding wires (the type used in construction) permanently to the absorber plate's surface. While the binding wires were lined 15 mm apart (i.e., the roughness pitch), the height was 3 mm (i.e., the roughness height). Fibre wool was used as an insulator to line the rare before covering the sides and bottom with a 1.2 mm thick ply wool. In line with the standard technique, the inside of the collector was painted black to maximise solar radiation absorption through the glass cover. The collector-dryer assembly was ducted together through two black tarpaulins while the absorber plate was tilted at an angle of 6.5° (being the latitude of Lagos). Furthermore, silicone sealant was used to seal each end of the two tarpaulins to the system. A wooden stopper was nailed on the backside of the drying chamber to firmly hold the artificially roughened collector and maintain the appropriate tilt angle at all times.

As earlier mentioned, although artificial roughness improves the turbulence of the fluid, it is accompanied by pressure drop; hence, a feedback system that uses a 12-volt little fan for air pumping was part of the solar dryer. The feedback system also comprised a ventilator section for some moisturised hot fluid to escape. The pump was used to channel most of the hot air back to the collector for reheating and continuous dehydration. Relative humidity and temperature sensors were attached inside the chamber and around the collector, and the setup was arranged such that the collector faced southward (Figure 1b). Besides the hydraulic duck diameter of 96.0994 mm, the values for the artificial roughness parameters like relative roughness pitch and relative roughness height of the solar dryer are given in Table 1. A beam balance was used to measure the mass of the product, while a calibrated Middleton pyranometer measured the solar radiation.

Table 1. Relevant parameters of the solar dryer

Parameters	Value or definition
Material for collector	1.8 mm thick galvanised metal sheet
Material for roughness	Binding wire
Roughness pitch (p)	15 mm
Hydraulic diameter (h)	96.0994 mm
Roughness height (e)	3 mm
Relative roughness pitch (p/e)	5.00
Relative roughness height (e/D)	0.03122
Insulation thickness (fibre wool)	9 mm
Air pump	A fan powered by 12 Volts and 100 Amps vehicle battery
Cover	Transparent glass of 5 mm thickness

Heat Transfer

Besides the atmospheric impact on the system, the solar dryer's performance was also examined by evaluating parameters like the collector and drying efficiencies and sample's moisture ratio (Duffie and Beckman, 1991; Kalogiron, 2009; Vijayan *et al.*, 2017). The methodologies are described in the following subsections.

Suppose the mean forward blowing air temperature ($\bar{T}_f$), the mean glass cover temperature ($\bar{T}_g$), the mean ambient temperature ($\bar{T}_a$), and the mean absorber plate temperature ($\bar{T}_p$) are at a steady-state. The energy balance on the glass cover of a solar air heater is:

$$h_{cf-g}(\bar{T}_f - \bar{T}_g) + h_{rp-g}(\bar{T}_p - \bar{T}_g) = U_t(\bar{T}_g - \bar{T}_a) \quad (1)$$

h_{cf-g} is the convective heat transfer coefficient between the forward blowing air and the glass, h_{rp-g} is the radiative heat transfer coefficient between the absorber plate and the glass cover, and U_t is the heat loss coefficient of the glass cover.

Secondly, the energy balance on the plate, S can be given as:

$$S = U_b(\bar{T}_p - \bar{T}_a) + h_{cp-f}(\bar{T}_p - \bar{T}_f) + h_{rp-g}(\bar{T}_p - \bar{T}_g) \quad (2)$$

In this case, U_b is the bottom heat loss coefficient, while h_{cp-f} is the convective heat transfer coefficient between the plate and the forward blowing air.

Thirdly, the energy balance on the air stream can be obtained as:

$$\dot{m}C_p(\bar{T}_o - \bar{T}_i) = A_c[h_{cp-f}(\bar{T}_p - \bar{T}_f) - h_{cf-g}(\bar{T}_f - \bar{T}_g)] \quad (3)$$

$\dot{m}$ is the mass flow rate of the air flowing through the collector, C_p is the specific heat capacity of the air, $\bar{T}_o$ is the average outlet temperature at

the track, $\bar{T}_i$ is the average inlet temperature at the track, and A_c is the collector area.

The radiative heat transfer coefficient for the thermal radiation transmitted between the plate and the glass cover of the collector in Equation 1, can be calculated from:

$$h_{rp-g} = \frac{\sigma(\bar{T}_p^2 + \bar{T}_g^2)(\bar{T}_p + \bar{T}_g)}{\left| \frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1 \right|} \quad (4)$$

σ is the air absorptivity, ε_g is the glass cover emissivity, and ε_p is the absorber plate emissivity.

Based on the algebraic solution of the above expressions (Duffie and Beckman, 1991; Kalogirou, 2009), the analysis of the mathematical modelling of the heating system can be simplified as follows:

$$\dot{m}C_p(\bar{T}_o - \bar{T}_i) = h_{cp-f}A_c(\bar{T}_p - \bar{T}_f) \quad (5)$$

Furthermore, the energy output of the collector can be expressed as:

$$Q_u = A_c[I_T(\tau\alpha) - U_L\Delta T] \quad (6)$$

I_T is the global solar radiation incident on the tilted collector, τ is the transmittance between the collector and the sky, α is the absorptance between the collector and the sky, $(\tau\alpha)$ is regarded as the transmittance-absorptance product, U_L is the overall heat loss coefficient of the collector, and ΔT is the temperature difference between the absorber plate and ambient.

Instead of using averages and for simplicity, the change in temperature in the above expression can be given by:

$$\Delta T = T_i - T_a \quad (7)$$

T_i is the fluid inlet temperature, and T_a is the ambient temperature.

Hence, Equation 10 can be rewritten as:

$$Q_u = A_c[I_T(\tau\alpha) - U_L(T_i - T_a)] \quad (8)$$

Nevertheless, the overall heat loss coefficient of the solar heat collector, U_L can be calculated from:

$$U_L = U_t + U_b + U_e \quad (9)$$

Therefore, the overall heat loss coefficient is the sum of three others namely, the heat loss coefficient of the glass cover (U_t), the bottom heat loss coefficient (U_b), and the heat loss coefficient of the edge of the collector (U_e). It systematically accounts for losses at the top, bottom, and edge of the collector.

Firstly, the expression for the heat loss coefficient of the glass cover of the solar collector is:

$$U_t = \frac{\frac{1}{N_g}}{\frac{c(T_p - T_a)^{0.33}}{T_p(N_g + 3)} + \frac{1}{h_w}} + \frac{\sigma(T_p^2 + T_a^2)(T_p + T_a)}{\frac{1}{\varepsilon_p + 0.05N_g(1 - \varepsilon_p)} + \frac{2N_g + f - 1}{\varepsilon_p} - N_g} \quad (10)$$

Where

$$f = (1 - 0.04h_w + 0.005h_w^2)(1 + 0.091N_g) \quad (11)$$

$$C = 365.9(1 - 0.00883\beta + 0.000128\beta^2) \quad (12)$$

And

$$h_w = 5.7 + 3.8 V_w \quad (13)$$

N_g is the number of glass used as cover, T_p is the plate temperature, h_w is the wind heat transfer coefficient, V_w is the vapour of water, while f and C are constants as stipulated above.

Secondly, the bottom heat loss coefficient can be determined from:

$$U_b = \frac{K_b}{L_b} \quad (14)$$

K_b and L_b are the conductivity and thickness of the insulation material, respectively.

Thirdly, the heat loss coefficient arising from the energy lost at the edge of the collector, U_e is given as follows:

$$U_e = \frac{(UA)_{edge}}{A_c} \quad (15)$$

$(UA)_{edge}$ is the edge loss coefficient-area product.

Solar radiation provides energy to the absorber plate in the collector that powers the working fluid. The collector receives more energy if it is tilted;

however, the solar radiation falling on the tilted collector, I_T (W/m^2) can be expressed as:

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos\beta}{2} \right) + I \rho_g \left(\frac{1 - \cos\beta}{2} \right) \quad (16)$$

I_b is the beam radiation, R_b is the beam radiation tilt factor, I_d is the diffuse radiation, β is the tilt angle which can be the latitude of the location, I is the global solar radiation on the horizontal surface, and ρ_g is the absorptance of the glass.

If the collector is not tilted, then I is used instead of I_T . Any other method for converting solar radiation from the horizontal plane to the tilted plane apart from Equation 16 can be used.

However, the seasonal magnitude of solar radiation changes with the earth's revolution at varying inclined angles around the sun. The declination angle can be expressed as:

$$\delta = 22.45^\circ \sin \left[360 \left(\frac{284 + n}{365} \right) \right] \quad (17)$$

n is the day of the year starting from 1st January.

Furthermore, the clearness index, k_t can be obtained from:

$$k_t = \frac{I}{I_o} \quad (18)$$

I_o is the extraterrestrial radiation on the horizontal plane.

Additionally, I_o can be expressed as:

$$I_o = G_{sc} \left(\frac{12 \times 3600}{\pi} \right) \left(1 + 0.0033 \cos \left(\frac{360n}{365} \right) \right) \left(\cos \phi \cos \delta \sin \omega_s + \frac{\pi \times \omega_s}{180} (\sin \phi \sin \delta) \right) \quad (19)$$

G_{sc} is the solar constant and is equal to 1353 W/m^2 , ϕ is the latitude of the location, and ω_s is the sunset hour angle.

Besides, the sunset hour angle can be obtained from:

$$\omega_s = \cos^{-1}(-\tan\phi \tan\delta) \quad (20)$$

The capacity, by which the working fluid takes up heat-energy from the plate, has to be evaluated before determining the efficiency of the collector. The absorber plate's heat removal factor could be defined as the ratio of actual useful energy gained to the result if the entire collector surface were at the fluid inlet temperature. Furthermore, when expressed with the transmittance-absorptance product, it indicates the heat removal factor at an intercept point or an analytical correction where actual test results are not available. However, the heat removal factor of the plate, F_R can be expressed as:

$$F_R = \frac{\dot{m}C_p}{A_c U_L} \left[1 - \exp - \left(\frac{A_c U_L F'}{\dot{m}C_p} \right) \right] \quad (21)$$

F' is the collector efficiency factor, which can be expressed as:

$$F' = \frac{1}{\left(1 + \frac{U_L}{h_{cp-f}} \right)} \quad (22)$$

The collector flow factor, F'' , which links the efficiency factor with the heat removal factor, is given by:

$$F'' = \frac{F_R}{F'} = \frac{\dot{m}C_p}{A_c U_L F'} \quad (23)$$

Generally, the thermal efficiency of the absorber plate can be expressed as follows:

$$\eta = \frac{\text{useful energy}}{\text{available solar radiation}} \quad (24)$$

For solar air heaters operating without recycling of air, the thermal performance can be represented based on outlet air temperature as:

$$\eta_{th} = \frac{Q_u}{I_{ST} A_c} = F_R \left[(\tau\alpha) - \frac{U_L(T_i - T_a)}{I_T} \right] \quad (25)$$

The above expression is the well-known Hottel-Whiller-Bliss equation which is otherwise known as the thermal efficiency. Thus, a famous linear relationship between the collector performance and change in temperature per solar intensity can be given as:

$$\eta_{th} = a - m \frac{\Delta T}{I_{ST}} \quad (26)$$

where $a = F_R(\tau\alpha)$, and $m = F_R(U_L)$.

Additionally, the efficiency of the solar collector can otherwise be given by:

$$\eta_{th} = \frac{\dot{m}C_p(T_o - T_i)}{I_T A_c} = \frac{h_{cp-f}(T_p - T_f)}{I_T} \quad (27)$$

The energy output from the solar collector is channelled by the working fluid to the drying chamber to dry the sample; hence, another principal target is to evaluate the drying efficiency of the system. η_d is the drying efficiency defined as the ratio of the energy for water vaporisation from product to the total energy supplied from the collector to the chamber, and is given as:

$$\eta_d = \frac{W L_w}{I_T A_{com}} \quad (28)$$

W is the mass of water evaporated from the product, L_w is the latent heat of vaporisation of

water, and A_{com} is the combined area of the dryer and collector.

Nevertheless, the mass of evaporated water can be obtained as:

$$W = \frac{m_i(M_i - M_f)}{100 - M_f} \quad (29)$$

A significant aspect of the analysis of an agricultural dryer is the evaluation of the moisture removal from the product. Moisture content reduction can be evaluated by considering the masses of the product before and after dehydration; hence the moisture content in percentage (wet-basis) of the drying product at any instance, m_c is given as:

$$m_c = \left(\frac{m_i - m_f}{m_i} \right) \times 100 \quad (30)$$

m_i is the mass of the product before drying, and m_f is the mass of the product after drying. Besides, the dry-basis moisture content, M_c can be given as:

$$M_c = \left(\frac{m_i - m_f}{m_f} \right) \times 100 \quad (31)$$

The moisture ration, MR can be calculated as:

$$MR = \frac{M_f}{M_i} \quad (32)$$

M_f is the final moisture content while M_i is the initial moisture content.

The moisture ratio is unique because it does not distinguish between wet-basis or dry-basis though agricultural products' moisture content is mostly expressed in wet-basis.

Experimental Setup

In this study, croaker *Pseudotolithus elongatus* harvested from the slummy water of Makoko, Lagos, Nigeria (Figure 2), was solar-dried; however, the dryer operated in the open field of the Faculty of Science in our University campus (Figure 1(b)).

After evaluating the dryer's workability, the fish was cut into pieces and placed in the silvery-walled drying chamber. Thus, solar radiation was not directly incident on the product, but air heated by the artificially roughened collector was ducted to the drying chamber to dry the sample. The entire weight of the fish was approximately 14 N (i.e., 1.445 kg). Temperatures of the glass cover (T_g), ambient (T_a), artificially roughened surface collector or plate (T_p), the air entering the drying chamber (T_i), the air circulating the drying croaker

fish (T_c), and the air leaving the drying chamber (T_o) were all taken. Furthermore, the respective relative humidity inside the drying chamber (RH_c) and the atmosphere (RH_a) were also measured.



Figure 2. Fish smoking in the slummy area of Makoko, Lagos

Results and Discussion

Patterns of Atmospheric Parameters

The average temperature variation in the drying chamber for a selected clear day fluctuated between 33°C and 60°C, but the maximum temperature was 65°C. The corresponding range of ambient temperature was from 28-39°C, and all the measured temperatures followed a nearly similar pattern, except the chamber temperature. As a result of the foil paper and deposited gravels heat conservation impacts, the drying chamber maintained a steady temperature after sunset, even as the other temperatures decreased (Figure 3).

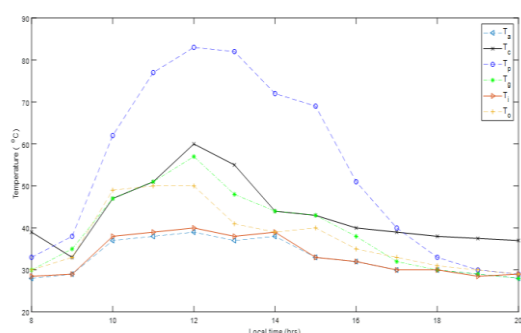


Figure 3. Hourly variations of the temperatures for the experiment

Between 8:00 and 20:00, the average increase of hourly chamber temperature over ambient ranged from 4-21°C, though the maximum difference

occurred at noon. Similarly, the hourly plate temperatures also increased between 1°C and 45°C over the ambient. However, the difference between outlet and inlet temperatures of the collector was 0-10°C on average. The sample's drying was extended to 20:00 but not aborted at either 17:00 or 18:00 because the chamber temperature remained relatively steady after sunset. At every instance, the other temperatures (e.g., plate, glass, inlet and outlet) surpassed the ambient temperature and were rarely equal.

Daily ambient temperature was not influenced by solar radiation intensity under overcast skies, except when the clearness index was relatively high. Figure 4(a) depicts the relationship between the average daily temperature and solar radiation.

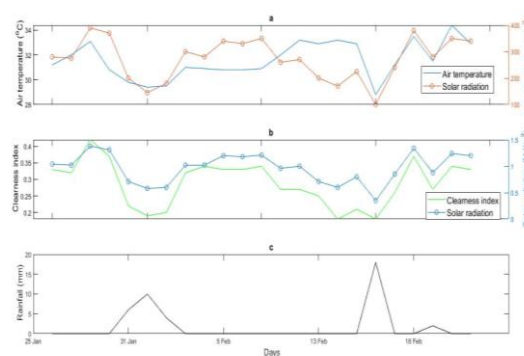


Figure 4. Atmospheric parameters at the site of the experiment, (a) daily variation of ambient temperature with solar radiation, (b) daily variation of clearness index with solar intensity, and (c) daily rainfall amount

While Figure 4(b) shows the standard curves of the average clearness index and solar radiation, Figure 4(c) illustrates the intensity of rainfall. A comparison between Figures 4(a) and 4(b) reveals some instances where the air temperature remains normal while the solar radiation dips in magnitude due to heavy cloudiness. Generally, global solar radiation intensity was directly proportional to the clearness index (Figure 4(b)).

Averagely, global solar radiation varied indirectly with both the dryer's relative humidity and atmospheric relative humidity (Figure 5). Furthermore, the representative atmospheric relative humidity was at a minimum value of 32% at 10:00, though the relative humidity inside the drying chamber was at a minimum amount of 42% at 13:00. Because the circulating hot air took up the moisture around the sample, the dryer's relative humidity was low compared to that of the atmosphere; hence, drying processed accordingly. Concerning the variation of the solar intensity and relative

humidity, both inside and outside the drying chamber: the highest solar insolation and the highest relative humidity inside the drying chamber coincided at 14:00.

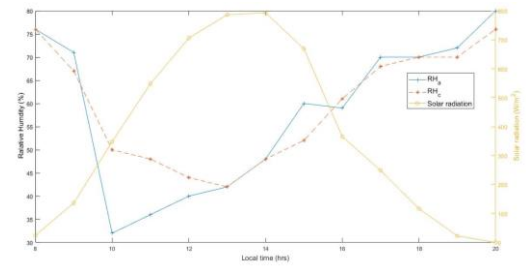


Figure 5. Hourly variations of relative humidity of the atmosphere (RHa) and relative humidity inside the chamber (RHc) with the global solar radiation

System Performance

Figure 6 shows the weight reduction of the croaker fish under forced convection at the corresponding drying period (12 hours each day) in the drying chamber—which has three distinctive drying phases. The first is the optimum drying segment (from day zero to day five): when moisture vaporisation from the product's surface was much, the rapid decline in the drying rate also occurred. A steadily slow decline happened during the second phase, which lasted from the sixth to the tenth day of the experiment. At this stage, there was no much water migration from small structural spaces of tissues inside the croaker fish to its surface. Drying was terminated when no further meaningful weight reduction occurred during the last three days, which was the final phase. Though the drying could have been aborted after the fifth day for consumption or local trading to increase the shelf life, the experiment was extended to the twelfth day.

The daily moisture transfer was directly proportional to the weight loss, while the average weight loss per day was 68.95% for the 1.445 kg croaker fish. The average drying efficiency during the experiment was 11.21%. The curves of the moisture transfer and the drying efficiency are similar (Figure 7(a)). In contrast, the cumulative weight loss and the drying efficiency vary inversely (Figure 7(b)). In the beginning, the moisture transfer corresponded with the highest drying efficiency of 45% since the moisture content of the croaker fish was very high at that stage before both decreased gradually (Figure 7(a)). However, the onset drying efficiency of 45% can be retained for the system

instead of using the average value because it was mainly dependent on available moisture content. Furthermore, the sample's cumulative weight loss increased with time while the moisture transfer (dependent on the daily initial moisture content) decreased.

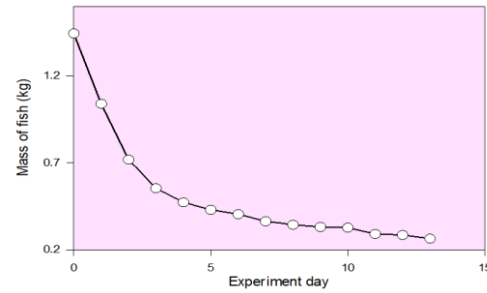


Figure 6. Daily mass reduction of the drying sample

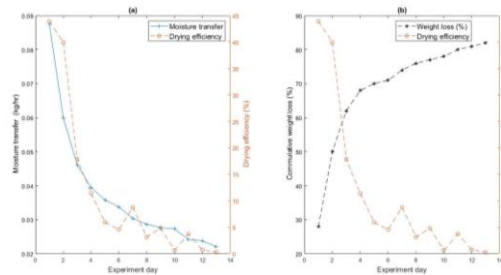


Figure 7. System efficiency variation with (a) the moisture transfer and (b) weight loss of the drying croaker fish

Because the drying efficiency of the first day was retained, only the corresponding thermal efficiency was considered. Moreover, collector efficiency was mostly the same except during bad weather when it would decrease in the region of about 25%. With a daily total solar radiation and average solar irradiance of 4913 and 428 (W/m^2) respectively at the tilted plane for 10 hours of sunlight, the collector thermal efficiency was approximately 65%. The dried croaker fish samples are shown in Figure 8, where the colour had changed from whitish (Figure 2) to yellowish. In this study, the sample's mass reduced from 1.445 kg to 0.264 kg, the percentage of the initial moisture content in wet-basis was 82% (Equation 30), while the wet-basis final moisture content was 15% (Vijayan *et al.*, 2017). Based on Equation 32, the moisture ratio at the end of the experiment was 0.18, whereas a remarkable 67% moisture content reduction in solar fish drying was attained in this study.



Figure 8. Handheld samples of the solar dried croaker fish, whose colour has turned yellowish

Atmospheric Factors Effect on Drying

Expectedly, the highest temperature range was that of the absorber plate, which was from 30-83°C, and at noon the absorber plate maximally amplified the ambient temperature by approximately 200%. The operation of the system was often dependent on the severity of the weather. For instance, instead of the drying efficiency decreasing continually as time increased, it increased at some periods. The fish was moisty when it rained on two separate days during the drying. Irrespective of the continuous decrease in the sample's overall weight, the moisture content change was unexpectedly much during the rainy periods. However, the expected decreasing pattern was usually attained the next day after the effect caused by unfavourable weather condition. Hence, the drying chamber's moistness arising from the rainy situation could not penetrate deep into the drying product and was quickly removed after that. The clearness index, air temperature and solar radiation are altogether small whenever it rains. Otherwise, while the clearness index and solar radiation would be little under heavy cloudiness, the ambient temperature would remain normal. Measurements of solar intensity and air temperature were already in progress during the trial phase, so Figure 4 includes the period before the main experiment. A comparison of Figures 4(a) and 4(c) shows that the periods when it rained can be detected, coinciding with the periods when there were upturns in the drying efficiency trend (Figure 7). It rained whenever both the air temperature and the global solar radiation were low. Furthermore, the tendency of the drying sample to absorb moisture depended on the stage of the drying. As seen from the second rain, the influence of the wet weather was minimal on the drying.

Figures 4(a) reveals that the air temperature in this vicinity does not always depend on global solar radiation but could rely on diffuse solar radiation or any other factor. As such, if the cloud is overcast to

the extent that little direct shortwave solar radiation reaches the solar dryer, factors like relative humidity, air temperature, and diffuse radiation can still enable the dryer to function correctly, apart from when it rains. Furthermore, energy-storing material was deployed in our solar dryer, so all together, the system was not meaningfully affected by slight changes in the meteorological factors of the location. Hence the gravels and the foil paper also served as temperature control for the dryer.

In most cases, solar dryers produce a temperature range of 40-50°C; however, 33-60°C was obtained in our dryer with an average of 43°C. Sometimes, high drying temperatures at the beginning can harden and turf the surface, thus preventing moisture within the body of the fish from migrating to the surface during drying. It is also crucial for cooking not to occur during drying. However, forced air convection in a hybrid solar dryer of this nature helps regulate the chamber temperature, prevents the surface of the fish from hardening, and reduces microbial growth on the product (leaving the product hygienic) while it dries. Since there is no universal benchmark for solar dryers' size and materials, a comparison between studies could be challenging. Besides, regional differences in topography and climate may compound the problem of comparing solar dryers. However, the temperature difference between the dryer and atmosphere, the drying rate, and sample weight loss are viable indices for comparing similar studies. Croaker fish is slightly bigger than other fishes such as Tilapia, jelly, silver jaw, catfish, and electric fish, so it takes much longer to dry croaker fish than the others (Oparaku, 2010; Omodara and Olaniyan, 2012).

Most importantly, the moisture ratio can be used to compare and determine the standard for solar drying. If this is the case, the percentage of fish's moisture content should be reduced from 75% to 15% when solar-dried (Prakash and Kumar, 2013), hence the moisture ratio (wet-basis) is 0.2. In this study, the wet-basis moisture ratio of 0.18 was obtained and compared to the reference value of 0.2; the standard for fish drying was met since 0.18 is approximately equal to 0.2.

Though fish smoking is achievable within a couple of hours, the moisture content could be as high as 60%, so the product has to be consumed within a few days else it would perish. The taste of fish after smoking also depends on the type of wood used as fuel. Though smoking sustains fish for less than a week, solar drying can support the product for up to six months. For optimum drying to occur, like the moisture content reduction from 82% to 15% achieved in this study, mainly if it is intended for foreign exchange, approximately one and a half

kilograms of croaker should be dried for 13 days, all things being equal. The consideration for temperature control, such as the deposition of black-painted gravel in the basement of the solar dryer adopted in this study, enabled more prolonged daily drying of the sample. Gravels tend to absorb energy and release it when the temperature of its surrounding drops; hence heat for about three hours of drying was gained after sunset in our experiment.

Conclusions

While the high moisture content in fresh fish should be reduced from about 80% to 15% for long-term storage, the taste should also be well-kept-up after drying. However, the usual drying method around slums is firewood fuel or open-sun, which is hardly suitable for the appropriate drying of fish. In this study, we used an active solar tent dryer with an artificially roughened collector to dry West African croaker *P. elongatus* harvested at a floating slum located in Lagos, Nigeria. Furthermore, adverse weather impact occurred during the process while the whitish fish turned yellowish after drying. Expectedly, the fabricated solar dryer performed well regarding the mitigation of health hazards, e.g., eye irritation and breathing problem, and other issues like atmospheric pollution, food contamination, and pest attack usually associated with the firewood fuel or open-sun drying of agricultural produce like fishes and vegetables. Adverse weather has a meagre 'dehydration-reversal-effect' on a drying fish, which quickly wears off. The artificially roughened collector and the drying maximum efficiencies were approximate 0.65 and 0.45 respectively, while the sample's moisture content reduced from 82% to 15% after 13 days of drying to endure up to six months of storage. The final mass of the sample was 0.264 kg, down from 1.445 kg.

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