Performance evaluation of hybrid thin layer solar tunnel-windmill dryer in the drying of brined and non-brined Tafi (Siganussutor) Fish

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Abstract: Studies were carried out to evaluate the performance of hybrid solar tunnel-windmill dryer in thin layer drying of brined and non-brined Tafi (Siganus spp.) fish. The fish were eviscerated, and split into pieces of approximately 6cm×4cm×5mm and was soaked in brine at 0% and 5% concentrations. The samples were dried in the dryer for 44 hours. The moisture content of the drying fish was evaluated by the AOAC oven drying procedure. In addition, analysis was carried out to establish the best thin layer drying model that describes the drying of fish in the hybrid wind-solar tunnel dryer. The moisture content of the drying fish was found to reduce linearly from 4.2 and 3.9kg/kg (db), respectively for brined and non-brined fish to 0.8kg/kg(db).A two-way Students t-test did not establish any significant difference in the drying of salted and unsalted fish (tstat=1.4032, tcrit, 5%=2.0687). Further, the page thin layer drying model was found to be the best model describing the thin layer drying of Tafi fish in the hybrid solar tunnel-windmill dryer (R2=0.9655 and 0.09434; RMSE=0.0539 and 0.0840 for unsalted;□ □ □ =0.0032 and 0.0077, for salted and unsalted fish, respectively). These results provided useful information in the modelling and design of solar drying systems for the drying of Tafi fish.

Keywords: Fish, hybrid wind-solar tunnel dryer, diffusivity, modelling, moisture content, drying rate constant

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1 Introduction

The principal economic activities along the Kenyan coastline, which supports about 2.7 million coastal communities, depend on exploitation of natural resources, which includes fishing. However, despite an annual production of over 350,000 metric tonnes of fish, earning about US$105million, the fish industry in Kenya constitutes about 5% of the national GDP, and supports about half a million people who rely on fish for proteins and employment (Abila, 2003). In addition, of the total fish catch in Kenya, 50% is wasted as a result of lack of proper storage and preservation technologies. Most of the existing preservation and storage technologies available are electricity driven and are not applicable to the artisanal fishermen, as most landing sites lack supply of electricity, which is a pre-requisite for such technologies. Further, the landing sites are far from consumption and commercial centres, and this leads tothe high percentage of spoilt fish. Thus, necessary measures must be taken to reduce the spoilage of fish in order to improve food security, artisanal fishermen earnings and the economy of the country.

Measures adopted at the artisanal fishermen level for preservation of fish include salting, pickling, deep frying and, smoking and drying. While salting and pickling introduce salt levels in fish that are unfit for human consumption, deep frying uses enormous quantities of vegetable oil, which, together with the huge quantities of

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firewood used in smoking lead to environmental degradation. In addition, smoking has the possibility of embedding carcinogenic substances in the smoked fish and this makes the fish unsuitable for human consumption (Sugimura, 2000; Delgado et al., 2005; Husam et al., 2011). Accordingly, safe affordable and environment friendly techniques must be adopted in the storage and preservation of fish.

Drying is a simple technology that has been used the world over for a long time in the postharvest management of biological materials. It refers to the deliberate reduction of moisture content of material to shelf stable levels. In order to dry fish, several technologies have been developed. However, most electricity-driven technologies are not applicable at the artisanal fishermen level due to inadequate supply and high cost of electricity. Use of biomass in drying has similar challenges as identified earlier in deep frying and smoking. It is necessary to introduce easily accessible safe and affordable methods for preservation of fish. Open sun drying is the most widespread method of drying fish at the artisanal fishermen level. However, this method contaminates fish by exposing it to dust, excreta from birds and animals, and subjects it to destruction by birds, blowflies' larvae and animals. The drying process is usually slow, and the fish dries to unstable moisture content that is conducive for micro-organisms proliferation, in which the fish becomes a source of food poisoning. Further, the direct exposure of fish to sunlight destroys light sensitive nutrients in the fish (Suzuki et al., 1988). Consequently, the alternative to the open sun drying of fish at the artisanal level is to enclose the fish in solar dryers whose temperature can be regulated.

Solar dryers have not been extensively used in Kenya, although a few designs have been tried, especially in mango drying. Other solar dryers used at experimental level include the cabinet dryers, the batch dryers and green house dryers. The disadvantages of these dryers include exposure of fish to direct sun-light, resulting in destruction of light-sensitive nutrients. These dryers also lack temperature regulation mechanisms leading to high dryer chamber temperatures. The high temperatures in the dryers lead to over-drying and subsequently to poor quality of the dried fish. As such, these dryers are unsuitable for the drying of fish. Hence, there is a need to seek alternative techniques in solar drying of fish. An alternative that has been tried in drying of vegetables is a solar tunnel dryer, which has a dark drying chamber, therefore eliminating the destruction of light sensitive nutrients in the other solar dryers, and a temperature-regulating fan.

Several authors have developed, and analysed models for thin layer drying of biological products, using conventional or solar tunnel dryers (Joshi et al., 2005; Mujaffar and Sankat, 2005), some of which subject fish to direct contact with sunlight. However, the solar tunnel dryer provides a hygienic and environmental friendly fish dryer design capable of enclosing fish away from contaminants and sunlight, with the possibility of temperature control within the dryer. Some of the challenges that influence the drying of fish in the solar tunnel dryers are environmental factors. Of particular interest in the coastal regions along which most of the fish is landed, Kenya included, are the ambient temperatures which range from 22°C to about 34°C. Such high ambient temperature could result in substantial increase in the temperatures of the harnessed solar tunnel dryer, which would result in increased drying rate. However, the high ambient relative humidity as experienced along coast which ranges from a low of 73% and peaks at around 90 can retard the rate of drying of fish, resulting in spoilage, with consequential food poisoning. It is therefore crucial to seek ways of reducing accumulation of moisture in the drying chamber to increase drying.

In an attempt to solve these problems, Kenya Marine Fisheries Institute, in collaboration with Jomo Kenyatta University of Agriculture and Technology developed an integrated hybridwind-solar tunnel dryer for the drying of fish, at Kipini, in the Ungwaya bay, Tana delta. However, the performance of this dryer in the drying of fish, under the high relative humidity environment of the coastal region has not been established. Based on these observations, studies were carried out with the aim of establishing the performance of the integrated hybrid thin-layer solar tunnel-wind dryer in the drying of Tafi (Siganusssp) fish, and determining the thin layer drying model that best describes the drying of the fish in the integrated hybrid thin-layer solar tunnel-wind dryer.

2 Materials and methods

2.1Description of the hybrid wind-solar tunnel dryer system

The hybrid solar-windmill tunnel dryer system used in this study (Figure 1) consisted of two chambers: the energy harnessing section, termed the tunnel section, and a drying section termed the drying chamber. The tunnel section is used for heating the drying air before it enters the drying chamber. Both chambers are completely sealed from light to preserve light sensitive nutrients in fish. The tunnel section of the dryer measures 7.32m long and is divided into six portions, each measuring 1.2m × 1.2m. The depth of the energy harnessing chamber is 0.4m.

Figure 1The hybrid solar-windmill solar tunnel dryer

The drying chamber is made of two rectangular sections, each measuring 1.2m ×1.2m× 0.8m, and thus has a total length of 2.4m, and is 0.8m deep. The drying chamber is constructed such that each rectangular section would carry twotrays in a vertical direction, one at the bottom of the section, and the second at a height of 0.4m from the bottom of the section.Thus, four trays are able to fit in the drying section. The rear walls and the bottom of the drying section are made of GI sheets, with the inner walls highly polished and painted with reflective aluminium paint, to reduce energy losses through them. The outer walls are painted black to increase temperature absorption, in order to reduce temperature differential between the inner and outer walls, which reduces heat transfer through the wall. Similar to the solar collector walls, the bottom and the rear walls are insulated with fibreglass, sandwiched between the inner and outer GI sheets to minimise energy losses. The front of each rectangular section of the drying chamber has two sets of overlapping doors through which fish trays are inserted and removed from the chamber. In addition, temperature and humidity sensing cables are inserted into the chamber through these doors.

In order to enhance the performance of the dryer, a direct current (*DC*) heating element (Figure 2a)is incorporated in the dryer at the point of exit of air from the solar tunnel section. The purpose of the coil is to supplement solar radiation in heating the drying air during bad weather and at night, to improve capacity of the dryer. In addition, to supplement the energy from the heating element and the solar energy, solar powered copper hot water jackets are incorporated for heating the air in the drying chamber. The water in the jackets is heated by solar panels (Figure 2b), and circulated to the dryer through the jackets, using a water pump. The hot water which is heated by the pannels and recirculated to a hot water resevoir tank (Figure 2b) through solar powered water pump.A windmill (Figure 2c) supplements solar energy in charging batteries which run fans at the inlet and exhaust fans, and in heating the *DC* heating element.

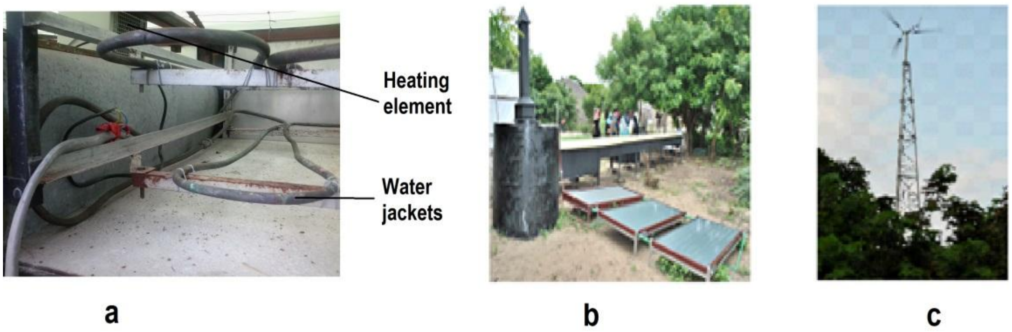

Figure 2 Alternative renewable energy harnessing and distribution system: (a) A DC heating element in the drying chamber, and water jackets (b) the dryer assembly showing water tank, the dryer, exhaust system and solar panels, and (c) wind mill

After air has been used for drying of fish in the dryer, it gets moist and is exhausted from the dryer through an exhaust system secured at the top end of the drying chamber (Figure 1;Figure 2b). Midway from the base of the exhaust pipe, a suction fan is fitted to induce forced convection in order to improve the performance of the system. In addition, the roof of the solar energy harnessing material is made like an arc. The arc roof design, with a height of 10cm has been adopted to enhance drainage in the rainy season. This roof is extended to cover both the tunnel section and the drying section. The cover material for the roof of the system is stabilized UV polythene (200 µm gauge, AMIRAN, Kenya).

2.2The preparation of the fish samples

Tafi fish was procured from the Shimoni fish landing of Mombasa, Kenya, which is 100km from KEMFRI offices. The fish were eviscerated, thoroughly washed and kept in ice boxes and transported to KEMFRI offices where they stayed overnight, before being further transported to Kipini drying site, 240km in the North Coast of Mombasa. At Kipini, the fish were filleted and washed thoroughly, before being cut into samples, approximately 5 mm thick. Three pieces of fish samples were selected for determination of initial moisture content of the fish. A minimum of 270 pieces were prepared and divided into two sets of samples, each containing at least 135 pieces. One sample was soaked in 5% brine with concentrations and the other in 0% concentration, for 12 hours. In addition, two fish samples were prepared by eviscerating and filleting of fish. One of the samples was brined while the other was soaked in water, for 12 hours. These two samples were used to monitor the change in weight of the fish during drying.

2.3The fish drying process

After brining and initial fish moisture content determination, the remaining samples were spread in the same tray such that no sample lied on top of another, which is typical of thin layer drying. The arrangement of the samples was such that air that has been used to dry a sample would not be used to dry the next sample (Figure 3a). The trays were then placed in the dryer (Figure 1) for the fish samples to dry. The dryer was exposed to the sun under the prevailing atmospheric conditions. The progress of drying of the samples was monitored by periodic weighing of the two samples used to monitor change in weight of the fish using a cell powered electronic balance(Decker, USA) at two hour intervals from the start of the experiment. This was continued until when there was no noticeable change in weight of these samples, when the experiment was stopped.

In order to analyse the drying process, samples were selected randomly from each treatment at the start of drying, and subsequently at two hour intervals. The samples were picked in triplicate at any sampling time. Since there wasno equipment for detailed analysis of the samples at the experimental site, the samples were weighed to determine their wet weight (w_w). They were then wrapped in properly labelled aluminium foil, and placed in airtight plastic bags, which weresubsequentlyplaced in ice boxes (Figure 3b), to reduce biological activity in the samples.The sampling was repeated at twohour intervals, till the end of the experiment.

(a)

(b)

Figure 3Fish samples (a) spread in a drying tray, and (b) in ice boxes

For further analysis, the samples were delivered to the Kenya Marine Fisheries (KEMFRI) laboratories in Mombasa, where they were placed in a constant-temperature oven set at a temperature of 105^{o}C for 24 hours. The samples were removed from the oven, and cooled in a desiccator, after which the dry weights, w_d corresponding to the recorded wet weights w_w, wererecorded. The dry basis moisture content M for each sample was determined using Equation 1. Based on the Handerson and Pabis thin layer drying model and observations by Kingsly et al.(2007) and Uluko et al. (2006) for material drying under varying relative humidity, which is typical of solar drying, the moisture ratio(MR) is determined using Equation 2. In this equation M_o, k and t are the initial moisture content (kg/kg, d.b), the drying rate constant (per sec) and the drying time (sec), respectively.Based on the analysis, moisture ratio drying curves were developed.

$$M = \frac{W_w - W_d}{W_d} \quad (1)$$

$$MR = \frac{M}{M_o} = Ae^{-kt} \quad (2)$$

The partial differential equation for moisture diffusion can be written as in Equation 3, in which D_{eff} is the effective diffusivity. In addition, the solution to Equation 3, for thin layer drying of fish in a tray is as given in Equation 4. In which d is half thickness of the drying fish (Vasićet al., 2012).

$$\frac{\partial M}{\partial t} = D_f \nabla M \quad (3)$$

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \left(\frac{1}{2n-1} \right)^2 \exp\left(-(2n-1)^2 \left(\frac{\pi}{d} \right)^2 D_f t \right) \quad (4)$$

For large values of t typical of drying processes (Sacilik and Unal, 2005), the first term of the series shown in Equation 4 obtained by considering only first term of the series n = 1 and neglecting the higher term is used to evaluate moisture ratio as in Equation 5 (Mudgal and Pande, 2007; Hassini, 2006). Based on Equations 2 and 5, the effective diffusivity of fish can be evaluated as in Equation 6.

$$MR = \frac{8}{\pi^2} \exp\left(-\left(\frac{\pi}{d} \right)^2 D_f t \right) \quad (5)$$

$$D_f = k \left(\frac{d}{\pi} \right)^2 \quad (6)$$

2.4 Modelling thin layer drying of fish

The actual moisture ratio data was fitted to thin layer drying models in order to get the best model fitting the experimental drying data. In total, 18 models (Table 1) were considered as cited by Barbosa et al. (2007), Gunhan et al. (2005) and Alibas (2012). In order to obtain the best model based on the two sets of data, the *solver* function in excel spreadsheet (MS Excel 2008™) was used to optimise the sum of the difference of the squares between the simulated and actual data, for a minimum value. The values obtained were taken through the various statistical measures of goodness of fit. In Table 1, the parameters a, a_o, b, c, g and h are coefficients, n is drying exponent, k, k_o, k_1, k_2 are drying rate coefficients specific to each equation, t is drying time and L is the thickness of the drying sample.

Table 1Thin layer drying models used to model the drying of fish in the dryer

S/No	Model Name	Equation
1	Lewis	$MR = \exp(-kt)$ $MR = \exp(-kt^n)$
2	Page	$MR = \exp(-kt)^n$
3	Modified page	
4	Handerson and Pabis	$MR = a\exp(-kt)$ $MR = a\exp(-kt) + c$
5	Yagcioglu et al (Logarithmic)	$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$
6	Two-term	$MR = a\exp(-kt) + (1-a)\exp(-kat)$
7	Two term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$
8	Diffusional approach	
9	Verma et al	$MR = a\exp(-kt) + (1-a)\exp(-gt)$
10	Modified Handerson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
11	Simplified Fick's diffusion Equation	$MR = a\exp\left\{-ct/L^2\right\}$
12	Modified page equation-II	$MR = a\exp\left\{-c(t/L)^2\right\}$
13	Midilli and Kucuk	$MR = a\exp(-kt^n) + bt$
14	Weibul Distribution	$MR = a - b\exp(-kt^n)$
15	Logistic	$MR = a_o/1 + (\exp(-kt))$
16	Jena and Das	$MR = a\exp\left(-kt + b\sqrt{t}\right) + c$
17	Demir et al.	$MR = a\exp(-kt)^n + c$
18	Alibas	$MR = a\exp(-kt^n + bt) + c$

Source: Barbosa et al. (2007), Gunhan et al. (2005); and Alibas (2012)

2.5Measures of performance of the models

If $y_i$is an observed value, and has an associated modelled value f_i then, the mean of the observed data, $\bar{y}$, for a total of N number of observations, is given by Equation 7.

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i \qquad (7)$$

In addition, the coefficient of determination, R^2, can be used to test the linear relation between measured and modelled values, as computed in Equation 8.

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - \bar{y})^2 - \sum_{i=1}^{N}(y_i - f_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \qquad (8)$$

The root mean square error, RMSE, which provides information on the short term performance may be computed from Equation 9. The value of RMSE is always positive, with an ideal value of zero being.

$$RMSE = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N}(f_i - y_i)^2\right)} \quad (9)$$

The reduced chi-square, χ^2,may be calculated as in equation 10, where n is the number of constants in the equation. The lower the values of the reduced χ^2 the better the better the correlation between actual and simulated data.

$$\chi^2 = \frac{\sum_{i=1}^{N}(y_i - f_i)^2}{N - n} \quad (10)$$

These parameters were used in the evaluation of the goodness of fit of the thin layer drying models to the drying data.

3 Results and discussions

3.1Performance of the dryer in the drying of fish

The relationship between the moisture content of salted and unsalted *Tafi* fish and drying time is presented in Figure 4. The figure also shows how the relative humidity and temperatures of the air in the drying chamber and in the ambience varied with drying time. The figure shows that the moisture content for the drying fish under the two treatments reduced as the drying time increased. The figure further shows that the reduction of moisture content of the drying fish as the drying time increased was exponential. The exponential reduction of moisture content as drying time increased is consistent with observations by Corzo et al.(2005) and Kituu et al. (2014) for sardines and Tilapia (*OreochromisNiloticus*), respectively. As illustrated inFigure 4, the reduction in moisture content for the fish under the two treatments shows similar trends. However, the figure shows that the moisture ratios for the unsalted fish reduced relatively faster compared to the salted fish, which agrees with the observations made by Graivier et al. (2006) and Jittinandana (2002) for pork- and trout fillets, respectively. The reduction in the rate of drying associated with the salting of fish could be attributed to the binding of moisture by salt in the fish flesh. On the other hand, a two way statistical *Student's t- test* did not show the existence of any significant difference between the moisture contents of the salted and unsalted fish during drying (t_{stat}=-1.4832, $t_{crit, 5\%}$=2.0686).

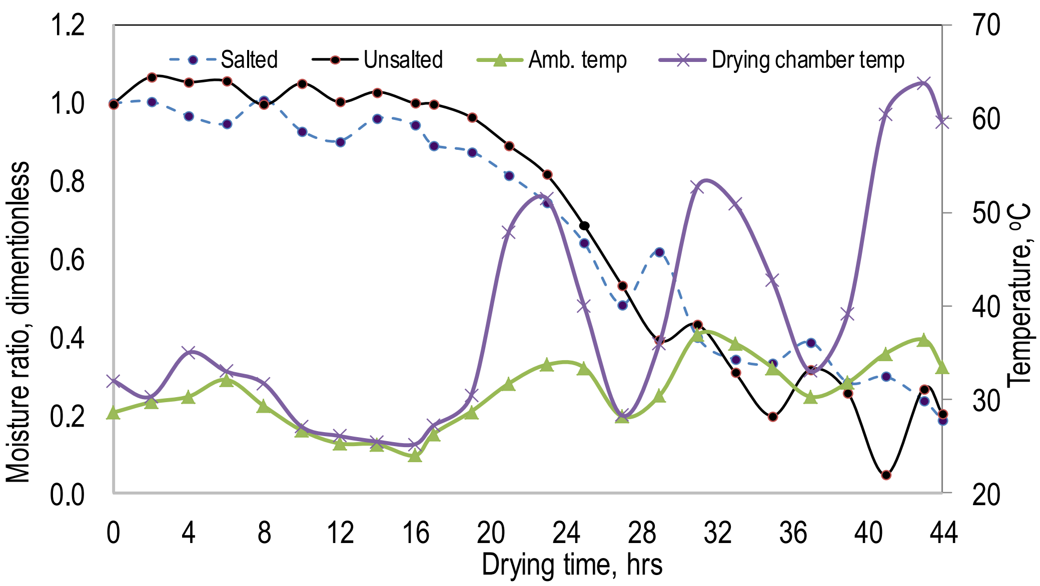

Figure 4Variation of moisture ratio, solar dryer and ambient temperatures and relative humidity during drying

As observed from Figure 4, the harnessing of energy by solar tunnel dryer can be demonstrated by the high temperatures observed in the drying chamber, compared to the ambient temperatures. The figure further shows that as the ambient temperatures increased, the drying chamber temperatures increased. However, despite the higher temperatures developed in the drying chamber, a two way statistical analysis did not show the existence of significant difference between the ambient and drying chamber temperatures over the entire drying period ($t_{stat}=9.6689\times10^{-16}$, $t_{crit, 5\%}=2.0687$). In addition, the mean temperatures in the drying chamber were not high enough to cause protein denaturing of the fish proteins.

Figure 5 presents the variation of ambient and plenum chamber relative humidity over the drying period. The Figure shows that the ambient relative humidity was generally high, above 25%, throughout the drying period. This is characteristic of relative humidity along the coast, due to the high water vapour in the atmosphere. The high levels of ambient relative humidity must have reduce the drying rate of fish and this can lead to prolonged drying periods, and consequently to spoilage of fish. In addition, for the first 18 drying hours, the ambient and drying chamber relative humidity values were almost indistinct.

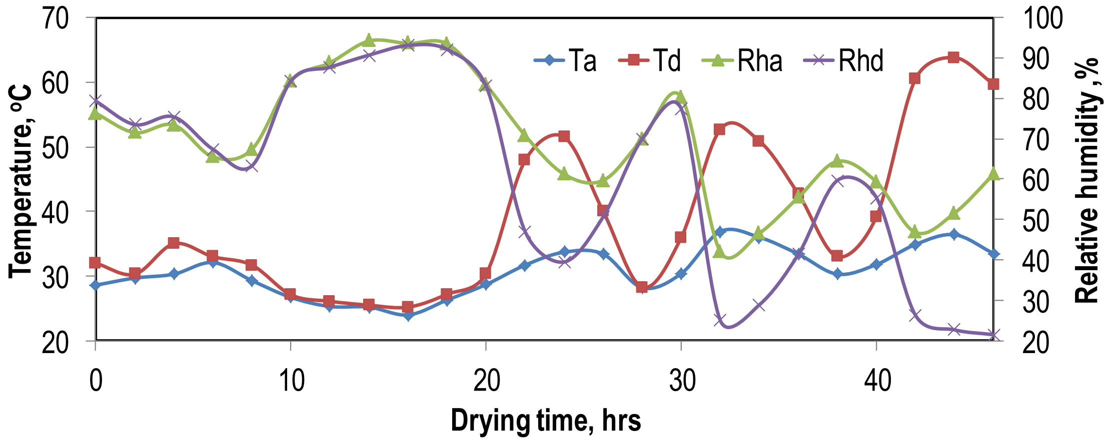

Figure 5Variation of ambient and drying chamber temperatures and relative humidity with drying time

Since humidity is related to air temperature, this behaviour can be attributed to the ambient and drying chamber temperatures. The temperatures were low, demonstrated similar trends, and were almost indistinct within the stated drying period. However beyond the 18th drying hour, the ambient temperatures increased, and subsequently, the drying chamber temperature increased. However, the increase in drying chamber temperature was much more than the increase in ambient temperature, which demonstrated energy harnessing by dryer. The increase in the temperatures must have resulted in reduction of the ambient and plenum chamber relative humidity values, and hence improving the ability of the system to dry fish the fish to a better quality. This is because lower air humidity result in increased moisture absorption potential (Mujaffar and Sankat, 2005). A two-way statistical Student's *t*-test showed the existence of significant difference between ambient and drying chamber relative humidity ($t_{stat}=7.2543$, $t_{crit, 5\%}$=2.0687). This further augments the view that the solar dryer was able to harness solar energy for drying. The high solar dryer temperatures must have resulted in significant reduction in the relative humidity in the solar dryer compared to the ambient humidity resulting in increased drying potential for the solar tunnel dryer. This is in agreement with the observation by Sahoo (2012) who noted that relative humidity reduces exponentially as air temperature increases. According to Brugay et al. (2003) the safe storage moisture content values of fish at zero and 15% brine concentrations are 0.15 and 0.35 kg/kg, d.b., respectively. This implies that the final moisture content of 0.8kg/kg, db was not shelf stable for dried fish. The drying of the fish to unstable values of moisture content could be associated with high ambient relative humidity in the area, which must have resulted in reduced drying potential of the drying fish.

Figure 4 illustrates the relationship between moisture ratio and drying time for the brined and non-brined fish. The best curves of fit for the four treatments are also presented the figure. The corresponding equations and their respective R^2 values are shown in equations 11-12. In these equations, MR_s and $MR_{us}$are the moisture content values for salted and unsalted fish samples, respectively. The results show that moisture ratio decreased exponentially with drying time. They also show that there exists a strong correlation between moisture ratio and drying time as the values of R^2 are high (0.7192-0.8733).The drying rate constant (k) values ranged from 0.037-0.05 per hour for salted and unsalted fish. However, the values decreased with the increase in brine concentration. This implies that an increase in salt concentration binds water to the fish flesh, and this makes it unavailable for drying.

$$MR_{us} = 1.676\exp(-0.05t), \quad R^2 = 0.7192 \quad (11)$$
$$MR_s = 1.3697\exp(-0.037t), \quad R^2 = 0.8733 \quad (12)$$

Based on the equation 6, the drying rate constants and the thickness of the materials, values of the effective diffusivity (D_f) were found to range between 6.53×10^{-12} and 6.63×10^{-12} m^2/s for the salted and unsalted fish, respectively. These value further augments the observation that the unsalted samples dried much faster than the salted samples. The low values of R^2 of 0.7192 and 0.8733 for unsalted and salted fish, respectively, indicated that the Lewis model might not be the best model that describes the drying of *Tafi* fish in the integrated hybrid wind-solar tunnel dryer. It was therefore necessary to evaluate the thin layer-drying model that best describes the drying of fish in this dryer.

3.2Modelling of the drying of fish in the dryer

The performance parameters of the various thin layer-drying models in Table 1 were as presented in Table 2. The table shows the various magnitudes of the performance parameters used to test the performance of the models. Based on R^2, *RMSE* and reduced χ^2, the table further shows that different models performed differently, in modelling the drying of fish in this dryer. Based on the performance criteria, where the best performing model would have the highest value of R^2, and least values of RMSE and reduced χ^2, for salted fish, models 2, 9, 12 and 16 had the highest R^2 values at 0.9665, 0.9432, 0.9665 and 0.9154, respectively. Similarly, the same models had the least values of RMSE(viz., 0.0539, 0.0691, 0.0539 and 0.0843, respectively) and χ^2(=-0.0032, 0.0055, 0.0033 and 0.0081, respectively). Thus, based on R^2 and RMSE, and χ^2, models 2 and 12 were the best performing models. Therefore, it is possible to conclude that model 2 is the best model describing the drying of the salted fish in the integrated solar tunnel dryer=, since it had the highest value of R^2, and the least values of RMSE and reduced χ^2. The observed trend was similar for unsalted fish, in which the models 2, 9, 12 and 16 had the highest values of R^2 (0.9434, 0.9228, 0.9434 and 0.8940, respectively), lowest values of RMSE (0.0840, 0.0980, 0.0840 and 0.1148, respectively) and χ^2 (0.0077, 0.0110, 0.0081 and 0.0151, respectively). Since model 2, the page model, had the highest value of R^2 and least values of RMSE and reduced χ^2 in the drying of unsalted fish in the integrated solar tunnel dryer, it was considered the model that describes the drying of unsalted *Tafi* fish in this dryer. Thus, it can be inferred that model 2, the page model, best describes the drying of salted (5%) and unsalted *Tafi* fish drying in the integrated wind-solar tunnel dryer. A two-way statistical analysis did not prove the existence of significant difference between modelled and actual moisture ratio for salted (t_{stat}=8.0267×10^{-2}, $t_{crit,\ 5\%}$=2.0687) and for unsalted (t_{stat}=2.8740×10^{-5}, $t_{crit,\ 5\%}$=2.0687) at 5% level of significance.

Table 2 Model performance parameters

S/No	Model parameter values		R^2		RMSE		χ^2	
	Salted	Unsalted	Salted	Unsalted	Salted	Unsalted	Salted	Unsalted
1	k=0.0213	k=0.0215	0.7616	0.6549	0.1417	0.2079	0.0210	0.0451
2	k=1.05725×10^{-4}, n=2.5664	k=4.7870×10^{-6}, n=3.4946	0.9655	0.9434	0.0539	0.0840	0.0032	0.0077
3	k=0.1459, n=0.1459	k=0.1466, n=0.1466	0.7616	0.6540	0.1417	0.2079	0.0219	0.0471
4	a=1.1819, k=0.0277, n=1	a=1.2882, k=0.0310, n=1	0.8327	0.7736	0.1186	0.1678	0.0153	0.0307
5	a=1.1819, k=0.0277, n=0	a=1.2882, k=0.0310, n=0	0.8327	0.7736	0.1186	0.1678	0.0161	0.0322
6	a=0.5910, k_1=0.0277, b=0.5910, k_2=0.0277	a=0.6441, k_1=0.0310, b=0.6441, k_2=0.0310	0.8327	0.8557	0.1186	0.1678	0.0169	0.0338
7	a=1, k=0.0213	a=1, k=0.0215	0.7616	0.6540	0.1417	0.2079	0.0219	0.0471
8	a=1, k=2.1277×10^{-2}, b=1.0037	a=1, k=2.1485×10^{-2}, b=1.0037	0.7616	0.6540	0.1417	0.2079	0.0201	0.0432
9	a=5.0488, k=0.0594, g=0.0816	a=8.0298, k=0.0714,g=0.0907	0.9432	0.9228	0.0691	0.0980	0.0055	0.0110
10	a=0.3940, k=0.0277, b=0.3940, g=0.0277, c=0.3940, h=0.0277	a=0.4294, k=0.0310,b=0.4294, g=0.0310, c=0.4294, h=0.0310	0.8327	0.7736	0.1186	0.1678	0.0188	0.0376
11	a=1.1820, c=0.1824, L=2.5668	a=1.2882, c=0.2054, L=2.5725	0.8327	0.7736	0.1186	0.1678	0.0161	0.0322
12	c=0.01734, L=2.7009, n=2.5664	c=0.0065, L=2.8063, n=3.4962	0.9655	0.9434	0.0539	0.0840	0.0033	0.0081
13	a=1.3840, k=0.1401, n=0.5372, b=0	a=1.4307, b=0.0617, n=0.8233, b=0	0.6389	0.7085	0.1748	0.1906	0.0367	0.0436
14	a=0.6754, b=0, k=1.0958, n=1.0791	a=0.6904, b=0, k=1.1109, n=1.0935	0.00	0.00	0.2899	0.3527	0.1009	0.1493
15	a=0.1289, k=0308	a=0.1802, k=0.0349	0.8034	0.7181	0.1286	0.1872	0.0180	0.0382
16	a=0.8604, k=0.0612, b=0.2368	a=0.8130, k=0.0841, b=0.3450	0.9154	0.8940	0.0843	0.1148	0.0081	0.0151
17	a=1.1819, k=0.1664, n=0.1664, c=0	a=1.2882, k=0.1762, n=1, c=0	0.8327	0.7736	0.1186	0.1678	0.0169	0.0338
18	a=0.3387, k=1.9999, b=0, c=0.6612, n=4.3963	a=0.3218, b=1.9999, c=0, n=4.4121	0.0545	0.0332	0.2819	0.3468	0.1004	0.1519

4 Conclusions

The results of this study show that an integrated solar tunnel dryer is capable of harnessing solar energy compared with open sun conditions, as the ambient temperatures were always lower than the plenum chamber temperatures, despite the temperatures not showing any statistical difference ($t_{stat}=9.6689\times10^{-16}$, $t_{crit, 5\%}=2.0687$). In addition, it showed that the moisture content of fish reduced with drying time, and the reduction was exponential, both under salted and unsalted conditions. Based on the Handerson and Pabis model, the drying rate constant for the salted and unsalted fish was 0.0371 and 0.0377hr^{-1}, respectively, while the values of the effective diffusivity (D_f) were found to be 6.53×10^{-12} and 6.63×10^{-12} m^2/s for the salted and unsalted fish, respectively. The final moisture content of 0.8kg/kg, db was much higher thanshelf stable moisture content of 0.15kg/kg, db for unsalted and 0.35kg/kg for salted fish, and therefore the final moisture attained after threedrying days was not safe for storage. The page model was established as the best model that describes thin layer drying of Tafi(*SiganusSutor*) fish in the integrated wind-solar tunnel dryer.

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