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The design and testing of an indirect cabinet solar dryer, for thin layer drying of *Rastrineobola argentea* fish, under the climatic conditions of Maseno, Kenya

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In spite of the high global demand for fish which is a major source of animal protein, nearly 10% (13 million tons) of the world's total fish production is lost through spoilage due to inadequate cold storage and poor marketing/distribution channels. Fish is a highly perishable product that is processed by freezing, canning, salting and drying. About 40% of fish landings in developing countries are preserved through traditional processing methods (smoking, drying and salting) organized at artisanal level. As a result of increased trade and co-operation among neighboring African countries over the past years, processed products from the artisanal sector now form a significant part of the small pelagic fish products traded intra-regionally. Lake Victoria provides about 95% of the total fish landings in Kenya, with *Rasrineobola argentea* (one of the pelagic species) being the second commercially important fish. It is harvested in very large quantities and is readily available at affordable price and widely used for both domestic and industrial purposes. Open-sun drying is the main preservation method employed by the fish farmers and involves spreading the fish on open ground where it is exposed to contamination, infestation and adverse weather conditions. It is estimated that post harvest losses of between 20 and 50% occur especially during rainy seasons. Although, the landings of *R. argentea* are higher as compared to other fish species, the value of the catch is often very low due to these huge losses. In an effort to curb these losses, a model of an indirect forced convection solar dryer was developed and tested for thin layer drying of *R. argentea* fish. The fish, in 10 kg batches were loaded onto the dryer and the moisture content reduced from an initial value of 73% (w. b.) to between 16 and 20% (w. b.) after 11 h of drying at average air flow rate of 0.017 kg/s, where open sun drying took 18 h. The mean efficiencies of collector and drying systems were 9.36 ± 3.95% and 11%, respectively. The drying rate constants of the fish in dryer were found to be: 0.146, 0.206 and 0.148 for the fish in the top, middle and bottom trays, respectively.

Key words: Twin collector, indirect, forced convection, cabinet solar dryer, *Rastrineobola argentea* fish.

INTRODUCTION

The food shortage in developing countries is partly due to inadequate preservation of food products so as to cater for long term needs (Madhlopa et al., 2002). When properly dried, food products have longer shelf life, better marketability and maintain a steady price. Open sun drying is the simplest and cheapest preservation option, for small scale farmers in developing countries who cannot afford artificial dryers. It involves laying the products bare on the ground where it is exposed to contamination and attack by bacteria, infestation by insects, birds, animals and rodents (Madhlopa et al., 2002). It is also laborious as the food layers have to be turned over and over again periodically to ensure uniform drying. The food may even lose some of the more fragile vitamins because of being exposed directly to sunlight. Furthermore, there are no mechanisms for controlling the drying process which is heavily dependent on weather conditions (Alamu et al., 2010). Thus, the use of open sun drying method in the preservation of agricultural and marine food products is partly responsible for the huge post harvest losses of 30 to 40%, encountered by farmers in developing countries (Azhrarul and Hawlader, 2010).

Given the tropics and subtropics have a abundant solar energy resource potential, as confirmed by the numerous studies that have been conducted in these regions, the use of solar technologies (solar dryers) in the drying of fruits, vegetables, cereals legumes, spices, fish and meat has been shown to be promising (EPZ, 2005). They are a better option since the drying of the food product takes place in an enclosed and protected unit, under controlled conditions of temperature and air flow, where the quality of the final dried product and rate of drying can be controlled (Gunasekarau et al., 2012). Solar dryers produce a better quality in the final dried product than open sun drying (Eventurk and Eventurk, 2007) and are classified as either active or passive depending on the mode of application of the solar energy. Active dryers have forced air circulation while passive models make use of air buoyancy caused by temperature and pressure gradients. Although passive dryers are cheap to implement and have no electrical or mechanical components, the air flows generated are not sufficient to penetrate bulk products (Buchinger and Weiss, 2002).

In general, active dryers (forced convection) have higher reliability and efficiency since they maintain continuous flow although their use is limited by the requirement of electricity needed to operate the electrical and mechanical components. They are more suitable for drying high moisture content products such as fruits, vegetables bananas and marine products (Jayaraman et al., 2000). Natural convection dryers typically exhibit lower overall drying efficiencies, (10 – 15%) than forced convection models (20 - 30%) (Buchinger and Weiss, 2002).

Solar dryers are further grouped as direct or indirect depending on whether or not the product is exposed to direct solar radiation. For direct solar dryers, the product is held in an insulated unit with a transparent plastic or glass cover which allows air flow through small holes at the top and bottom. Heat generated by the solar radiation Is absorbed by both the surfaces of the product and dryer is transferred to the air inside the collector which then flows over the product laid on perforated trays and causes drying (Buchinger and Weiss, 2002). The main disadvantage of these dryers is the direct exposure of the product to sunlight which affects essential components often resulting in discoloration, vitamin loss and overheating in the thin top layer of the product (Sreekumar et al., 2008).

In contrast, indirect dryers consist of two separate units; solar collection and drying chamber such that the product is not exposed to direct solar radiation. The interior surfaces of the solar collector absorb radiation and the heat generated increases the temperature of the surrounding air. The heated air is either forced or flows by natural convection through the drying trays. As the moist air exits through vents located at the top of the dryer, a reduction in the internal pressure is created within the cabinet and ensures the continual drawing of ambient air into the dryer.

In the design process of a solar dryer, the physical and thermal properties of the product; moisture diffusion, heat and mass transfer, specific energy consumption, activation energy, their dependence on the input air velocity and temperature have to be taken into account. The efficiency of a solar dryer depends on the ambient air temperature, air flow speed, relative humidity, quantity, thickness and moisture content of the product to be dried and the intensity of the incident solar radiation. Thin layer drying models are used to predict drying times and generalize kinetics of the drying processes of food/agricultural products. Since the kinetics of drying depends on ambient temperature, air velocity and material characteristics (Doymaz and Pala, 2002) the prediction of drying time is crucial to increasing dryer capacity and the reduction of energy consumption (Ismail and Wootton, 1992).

Fish is a major source of animal protein and an important food item in many countries. It is highly perishable and can be preserved by proper refrigeration or drying although dried fisheries are more popular because their special taste and flavor. The frequency of intake of small fish is between 50 and 80%, of all the fisheries eaten in many developing countries (Bala and Mondol, 2001). In Kenyan context, the fishing industry has in the last two decades evolved from a domestic consumption oriented to an export industry with value addition processing being applied (Nyeko, 2008). The sector provides live-hood, income and employment to more than 2 million people, with Lake Victoria providing 95% of the total fish landed (Odongokara, 2008). It has thus been identified in the country’s vision 2030, as one of the sectors that if improved could effectively contribute

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to the improvement of food security (Nyeko, 2008). The fishing is mostly carried out by artisan fishermen operating small boats in inland lakes and marine waters. Some of the harvested fish is sold fresh while a significant portion is processed for later consumption. The main fish landed in Lake Victoria include: *Rastrineobola argentea*/Dagaa (62.9%) Nile perch/*Lates niloticus* (29.9%), Tilapia/*Oreochromis niloticus* (5.3%) *Halplochromines*/Fulu (1%) and others (0.8%) (Ofulla et al., 2007). The poor infrastructure systems coupled with the lack of adequate cold storage and distribution facilities, has made the artisan fish farmers to resort to indigenous fish preservation methods such as smoking, salting and open sun drying. But open sun drying is the most prevalent method and involves the laying of fish bare on the ground or on raised racks. This method exposes the fish to infestation by insects, bacterial attack and contamination; moreover the drying process is very slow (lasts about one week) and depends on the climatic conditions and spoilage often occurs. On the whole, the physical and organoleptic qualities of most traditional sun dried fish products available in the market are not satisfactory for human consumption, and as such a large proportion of these fisheries are being utilized for production of animal feed and fishmeal (EPZ, 2005). Although the landings of *Rastrineobola.* argentea are higher compared to other fish species, the value of the catch is often very low due to losses (Owaga et al., 2011) and the use of these methods is one of the major causes of the huge economic and quality post harvest losses estimated at between 20 and 50% during rainy seasons, currently incurred by the fish farmers (Owaga et al., 2011).

As a result of the perceived role of the fisheries sector in the improvement of the country's food security, more hygienic processing practices need to be established that can enhance the economic and nutritional value of the fisheries and extend their shelf life. Already there is a threat of export ban on fish products from developing countries by the EU market and hence the urgent need to assess the technical feasibilities of improved drying methods such as drying racks and solar dryers (Mohamed et al., 2005). Very few studies have been reported on the use of solar dryers for the fish in Lake Victoria, in particular only one study has been reported on the investigation of the drying characteristics and quality attributes of *Rastrineobola. argentea* and *Stolephorus delicatulus* fish species, under the climatic conditions of coastal Kenya (Oduor-Odote et al., 2010), although a relevant study its findings are not directly useful to the development of a large-scale solar dryer for the prevailing climatic conditions around Lake Victoria due to the variations in the metrological factors in the two sites. The present work thus provides useful information on the drying characteristics of *Rastrineobola argentea* fish under the prevailing climate conditions of the relevant region and therefore forms part of the required data useful for the development of appropriate solar drying technologies for this particular fish product. Moreover, the results which have been obtained in this study are similar to what other studies have obtained (Oduor-Odote et al., 2010).

Description of the solar dryer

The indirect cabinet solar dryer was designed for the climatic conditions of Maseno, the materials used in the construction were: well-seasoned cedar timber, G.I sheets, transparent glass (5 mm thickness), white polythene sheets, PVC waste pipes (diameter 8.5 cm), electric fan and a 50-W solar PV module. The drying system consists of two solar air heaters with a total glazing area of 5.0 m^2 made from wooden frames and transparent glass (5mm thickness), the collectors were connected to the drying chamber using plastic waste pipes. The drying chamber consists of 20 trays made of wooden frames and aluminum gauzing, spaced 0.20 m apart each with area 1 m^2, a 30 cm tall chimney, an electric car fan and a 50-W solar PV module (Figure 1).

Design parameters of the solar dryer

The design parameters of the solar dryer, some of which are specified in Table 1, were calculated from the mathematical relations defined below, (Onyinge et al., 2014)

1. The collector tilt γ for maximum incident solar radiation is usually taken as the latitude of the location, and is given by:

$$\gamma = 10^o + lat\varphi \quad (1)$$

where $lat\phi$ is the latitude of the site location (since $\phi = 0^o$, for Maseno, Kenya), in this case to allow rain off a value of $\gamma = 10^o$ was used.

2. The ratio of length to width of the air heater was taken as 1.5 and the length of the drying chamber L_s therefore given by:

$$L_s = \frac{A_{dc}}{w} \quad (2)$$

where A_{dc} and w are the area and width of the collector, respectively.

3. The aggregate thin drying layer thickness $h_L \leq 200mm$ was used.

4. The quantity of moisture to be removed m_w was obtained according to the relation:

Figure 1. Photographic view of the prototype indirect cabinet solar dryer designed and fabricated at Maseno University, Kenya.

$$m_w = w_w \frac{m_i - m_f}{1 - m_f} \quad (3)$$

Where, m_i initial moisture content, m_f is final moisture content, w_w is initial product mass.

5. The total volume of air needed to remove the moisture was obtained using the relation:

$$V_A = \frac{m_w L_t R_a T_a}{C_{pa} P_a (T_o - T_f)} \quad (4)$$

Where, R_a is specific gas constant, P_a the partial pressure of dry air in the atmosphere, C_{pa} the specific heat capacity of air at constant pressure, T_f the temperature of air leaving the drying chamber, T_a the ambient temperature, L_t the latent heat of vaporization of water.

6. The volume air flow rate was then obtained from the relation:

$$\dot{v} = \frac{V_A}{t} \quad (5)$$

Where, t is total time needed to dry a given sample of the product.

7. The chimney length was taken to be $1/15$ of the collector length

8. Thermal efficiency of the solar collectors was obtained according to the equation:

$$\eta_c = \frac{mC(T_o - T_i)}{A_c I} \times 100 \quad (6)$$

Where, m is air mass flow rate, C specific heat capacity of air, T_i collector inlet air temperature, T_o outlet air temperature, I incident solar radiation and A_c the collector area. A plot was then made of the thermal efficiency of collector against time.

9. The system drying efficiency for the solar dryer was calculated according to the equation:

Table 1. The theoretical parameters of the solar dryer.

Quantity	Description	Theoretical values
w_w	Mass of product to be dried	10.0 kg
m_i	Initial moisture content of product	73% (Oduor Odote et al., 2010)
m_f	Final moisture content of product	15%
t	Total time of drying	15 h
m_w	Mass of water evaporated	6.8 kg
V_a	Volume of air needed to evaporate moisture	1092.4 m^3
v	Volume air flow rate	0.0202 m^3/s
η_c	Collector system efficiency	43.5%
η_d	Drying efficiency	11.4%
R_a	Specific gas constant	287.1 J/kg K
P_a	Partial pressure of air in atmosphere	101 KPa
C_{pa}	Specific heat capacity of air	1007 J/kg K
L_t	Latent heat of vaporization of water	2260 KJ/ K
T_f	Temperature of air leaving dryer	301.5 K
T_o	Temperature of leaving collector	343 K
T_a	Ambient air temperature	298 K
I	Mean solar radiation incident on collectors	496 W/m^2
A_c	Total surface area of collectors	5.0 m^2
l_s	Length of chamber	2.1 m
w	Width of collector	1.2 m
l	Characteristic length	2.0 cm
P_f	Power used to operate fan	14.6 W

$$\eta_p = \frac{m_w L_t}{I A_c + P_f} \quad (7)$$

m_w is weight of water evaporated from the product, L_t is the latent heat of vaporization of water , P_f power used to drive the fan.

10. The effective moisture diffusivity was obtained from the drying rate constant according to the relation:

$$k = \frac{\pi^2 D_{ef}}{4l} \quad (8)$$

where l is the characteristic length of the product.

EXPERIMENTAL PROCEDURES

Measurement of moisture ratio/drying rates

The drying tests on *Rastrineobola argentea* fish were conducted using the indirect forced convection solar dryer under full load conditions, with the first batch being dried on 10th and 11th June 2014 while the second was dried on 24th and 25th June 2014, between 9:00 and 16:00 h. The performance of the dryer was evaluated for drying of 10 kg batches of *Rastrineobola argentea* fish with an initial moisture content of 73% (w. b.) (Oduor-Odote et al., 2010), loaded in thin layers on each of the trays. All the weight measurements were conducted using a digital balance model XL-6100, with measurement range: 0.0 to 6100 g and accuracy ± 0.1 g. The initial weights of the control fish samples in the top, middle and bottom trays were first recorded and thereafter the same samples were removed from the dryer and weighed at two-hourly intervals throughout the entire drying period. The drying was only stopped at the stage when there were no significant differences between three

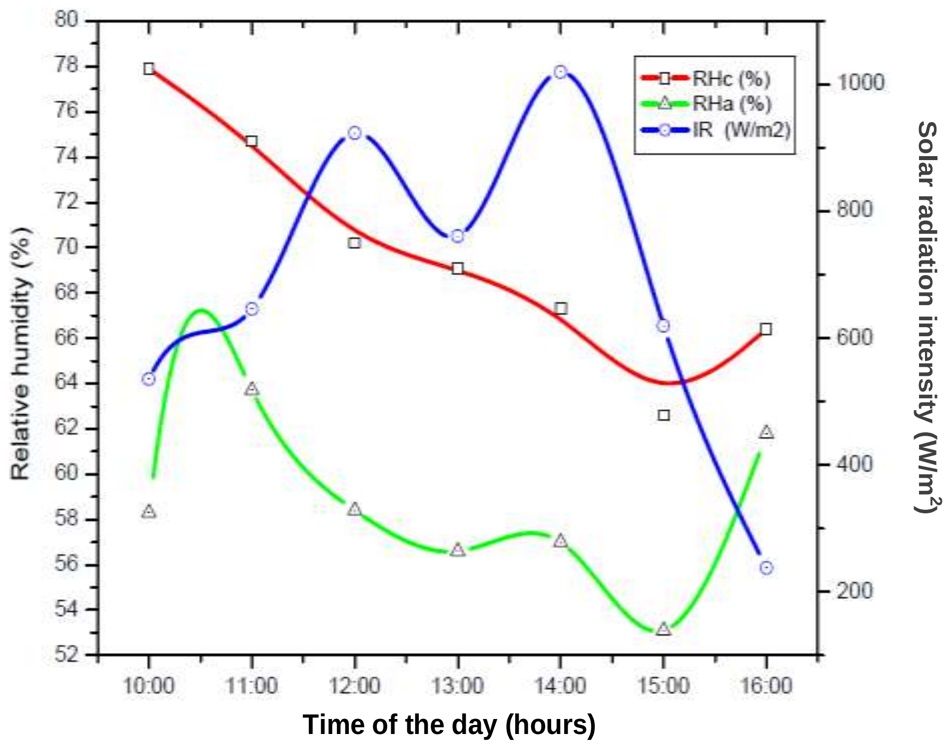

Figure 2. The variation of relative humidity of air inside and outside the chamber with the incident solar radiation on the first day of drying. R Hc: relative humidity of chamber air; R Ha: relative humidity of ambient air; IR: mean solar radiation intensity.

consecutive weights of the same sample. Simultaneous weight measurements were also recorded from open sun dried control samples during the same period to enable comparison of the drying rates.

Measurement of temperature

Temperatures readings were taken at intervals of 10 min for the ambient air and at various locations in the collectors and drying chamber using thermocouples connected to a data logging system, model 2286A, Company: Fluke, Country of manufacture: Everett WA, USA, consisting of type J (Iron - Constantan), K (Chromel - Alumel) and E (Chromel - Constantan) thermocouples with measurement ranges - 200 to 760°C, - 225 to 1350°C and - 250 to 1000°C, respectively.

Measurement of the incident solar radiation

The instantaneous incident solar radiation was measured at intervals of 1 min using a solariometer model SL 200, (Company: E-instruments, Country of manufacture: France), with measurement range of 1 to 1300 W/ m^2, accuracy ± 5 %, measurement frequency: 2 measurements per second.

Measurement of relative humidity

The relative humidity of air inside and outside the chamber was measured at hourly intervals using two digital Pyschrometer model 5105, (company: JENWAY, country of manufacture: UK). One placed inside the drying chamber and the other outside.

Measurement of air flow rates

The air speed and volume flow rates were measured at the collector outlets and chimney at hourly intervals using an anemometer; (VELOCICAL model 8357, Company: TSI, Country of manufacture: USA), with measuring ranges: 0.0424 to $1.170 \times 10^8 m^3/s$ for volume flow rates and accuracy ranges: ± 0.05 for 2.5 to 10 m/s, ± 0.025 m/s for 10 - 30 m/s and ± 0.5 for 30 to 50 m/s air velocities.

RESULTS AND DISCUSSION

Relative humidity of the air

The variation in the relative humidity of ambient and chamber air with time during the drying is presented in Figures 2 and 3. The mean relative humidity in the drying chamber on the first and second days of drying were 69.7 ± 4.78 and 52.7 ± 7.30%, respectively against corresponding ambient values of 58.5 ± 3.23 and 57.9 ± 3.52%, on the first and second days, respectively. There is a general decreasing trend in relative humidity of air with increasing solar radiation intensity, but the relative humidity in chamber is higher than for ambient air on the first day of drying while for second day, it is lower than that of ambient air. This observation is accounted for by the fact that on the first day, the fish is more moisture

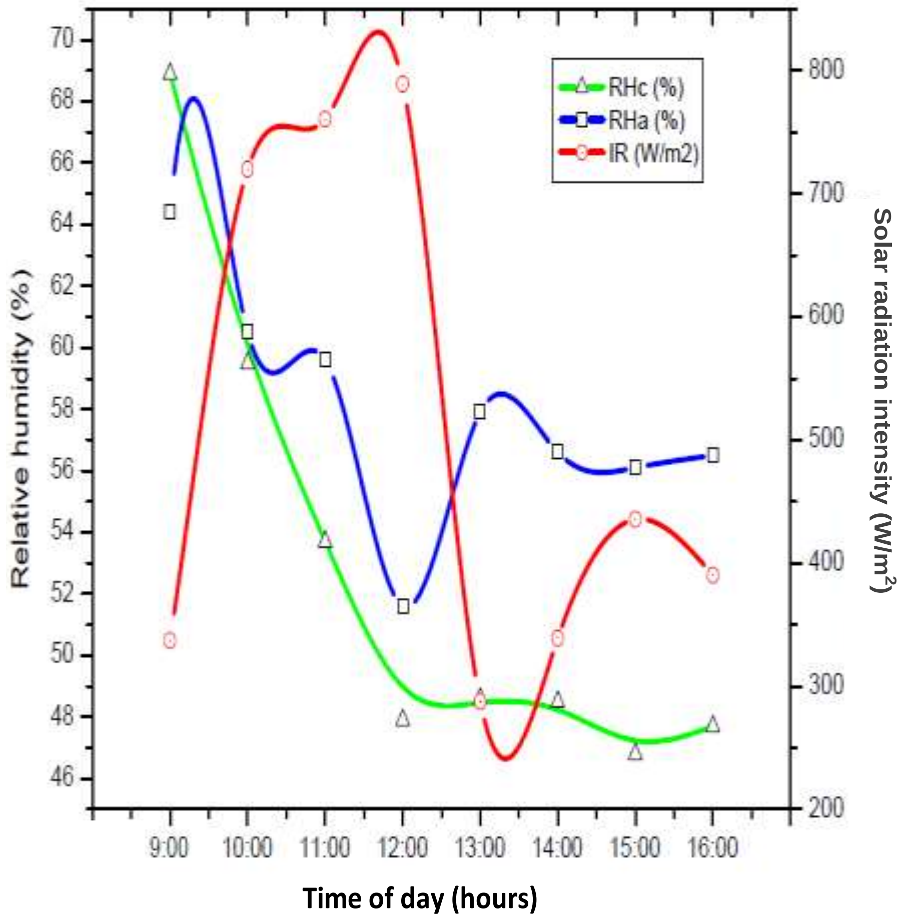

Figure 3. The variation of relative humidity of air inside and outside the chamber against the incident solar radiation on the first day of drying. R Hc: relative humidity of chamber air; R Ha: relative humidity of ambient air; IR: mean solar radiation intensity.

laden and so the humidity in the chamber is increased while on the second day, the fish is relatively drier and chamber humidity is lower.

Temperature

The temperature profiles for various locations in the drying system as well as the incident solar radiation at different times are presented in Figures 4 and 5. The mean solar radiation intensities were found to be 635.2 ± 250 W/ m^2 and 507.3 ± 197.9 W/ m^2 during the first and second day of drying respectively. It was found that the mean collector outlet temperatures were 43.6 ± 8.49 and 50.1 ± °C on the first and second day, respectively. The mean temperatures at the bottom, middle and top trays were found to be 25.9 ± 3.45, 25.1 ± 2.55 and 26.2 ± 3.54°C respectively on the first day and 28.2 ± 2.63, 27.2 ± 2.81 and 27.8 ± 3.12°C respectively on the second day. The mean temperatures at the bottom of the chamber and ambient air were found to be 31.2 ± 5.98 and 15.6 ± 2.99°C on the first day respectively and 32.8 ± 3.52°C and 27.2 + 1.84°C on the second day respectively. The temperature of the drying chamber is nearly constant and has a mean value of 31.2 ± 5.98°C and 32.8 ± 3.52°C on the first and second days of drying respectively while the mean ambient temperature was found to be 15.6 ± 2.99 and 27.2 ± 1.84°C on the first and second days of drying respectively.

There is a direct variation of temperature with solar radiation intensity for all the components of the drying system. The higher temperatures are observed at the collector system outlet as compared to other components. On all the drying days, the temperature of the bottom chamber is higher than that of the ambient air. It is also observed that the mean temperature of the bottom and top trays are higher than that of the middle trays. The fact that the mean temperature of the top trays is higher than the middle trays is accounted for by the absence of insulation on the dome of the dryer (made of un-insulated G. I. sheets), a unique design feature of this dryer, the dome therefore absorbs solar radiation and raises the temperature of the surrounding region. The

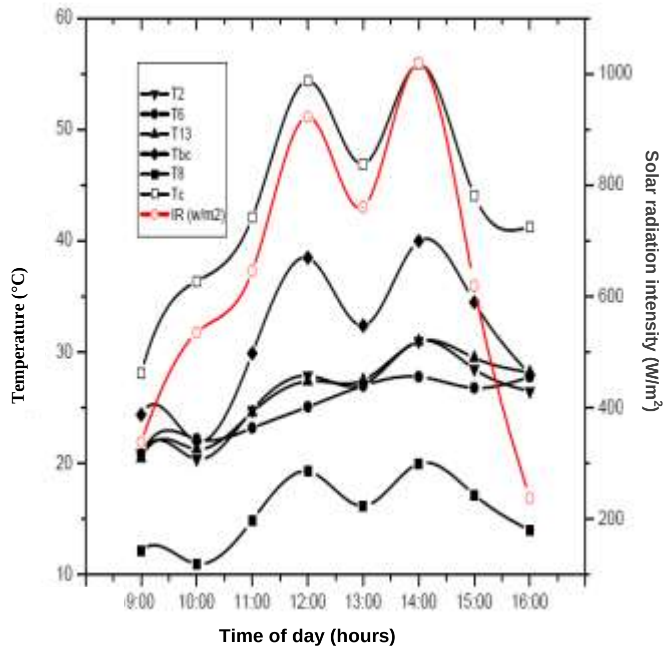

Figure 4. Variation of mean ambient, collector outlet and chamber temperatures with time for the first day of drying. IR: solar radiation intensity; T2: bottom tray temperature; T13: middle tray temperature; T6: top tray temperature; T bc: chamber bottom temperature; TC: collector outlet temperature; T8: ambient temperature.

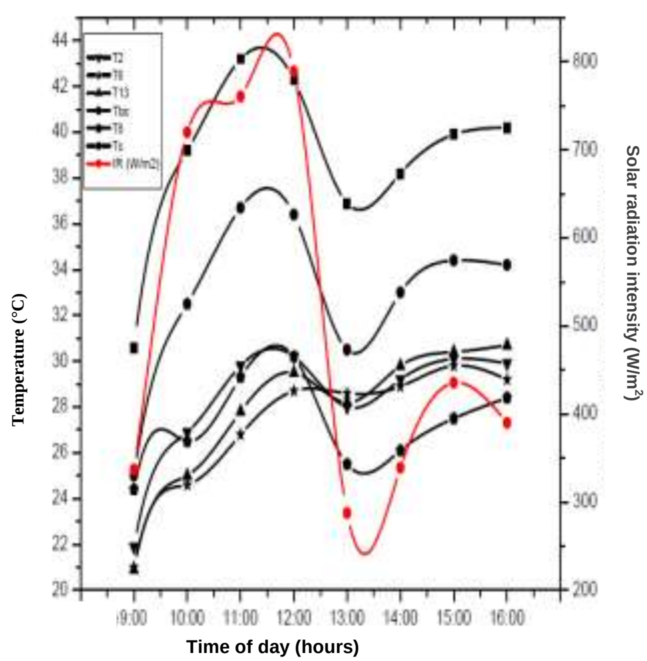

Figure 5. Variation of temperature of bottom, middle and top trays with time during the second day of drying. IR: solar radiation intensity; T2: bottom tray temperature; T13: middle tray temperature; T6: top tray temperature; T bc: chamber bottom temperature; TC: collector outlet temperature; T8: ambient temperature.

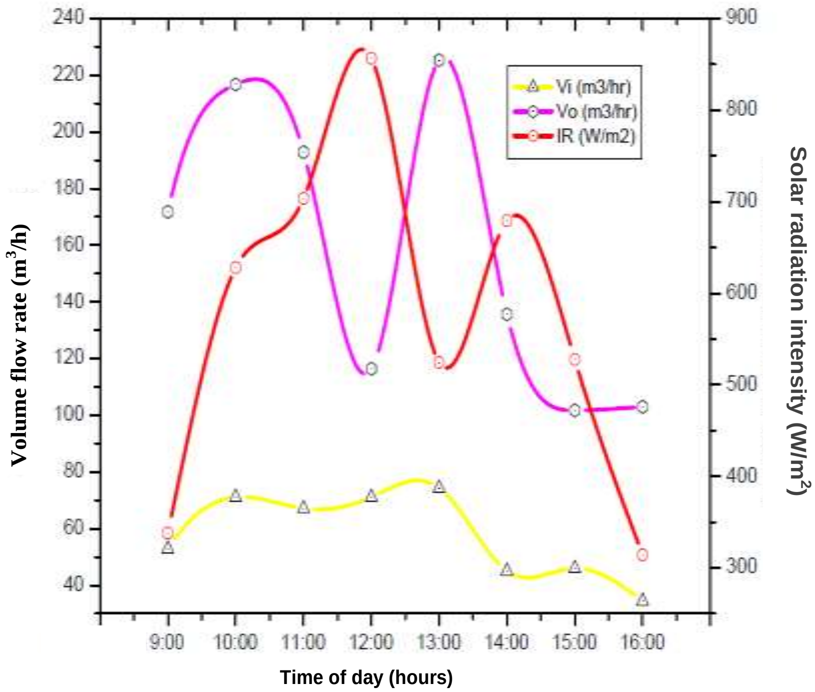

Figure 6. The variation of the mean in and outflow air volume flow rates with time during drying Vi: rate of air volume flow into dryer; Vo: rate of air volume flow out of dryer.

fact that the temperature of the bottom chamber is lower than that of the collector outlet suggests the existence of thermal losses along the air ducts.

Air flow rates

The variation of air volume flow rates with time in the solar dryer during the days of drying have been presented in Figure 6 below, from which it is observed that the total air volume flow rate from the collectors is nearly constant but there is a larger variation in the air volume flow rate out of the chimney. The average total air volume flow rate from the combination of collectors into the drying chamber was observed to be 0.0190 ± 0.0048 kg/s while the air flow rate out of the chimney was found to be 0.051 ± 0.0153 kg/s during the days of drying. The observed constant air volume flow rate from the collectors into the drying chamber is maintained by the exhaust fan incorporated within the dome of the dryer.

Moisture content

The moisture curves for *Rastrineobola argentea* fish presented in Figures 6 and 7, consists of falling and constant sections. The first (Figures 6) occurs at the initial stage of drying where the fish loses moisture more rapidly at almost constant rate while the next (Figure 7) occurs at later stages of drying where the rate of moisture loss decreases to almost zero. From Figure 6, it is observed that the moisture content of the fish in the solar dryer is reduced from 73 to 40, 29, 23, 42 and 31% (w. b.) for the middle trays, top right, top left bottom left, and bottom right trays respectively after the first 6 h on the first day and then to final values of: 8% (w. b.) for the middle right tray and bottom right trays, the bottom left and top right and middle right trays and 9% (w. b.) for the top left tray and 10% for the middle left tray after another 5 h on the second day (Figure 7). There is a greater loss in moisture for fish in the top trays as compared to other trays at the end of the first day, even though at the end of the second day of drying, there is no significant difference in the moisture ratio of fish with most of the fish in the various trays attaining moisture contents of less than 10%. The rapid loss in moisture of the fish at the beginning of drying is attributed to the increasing solar radiation intensity received at the collectors which raises the temperature of the inlet ambient air thus lower its relative humidity and increases its ability to absorb moisture from the fish in the solar dryer.

Drying rates

The variation of the drying rates with time for the two

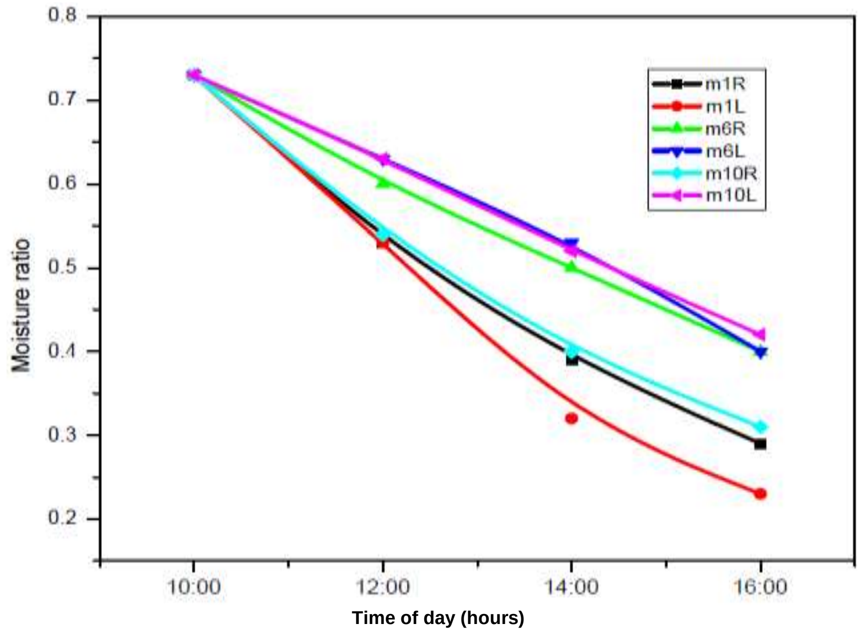

Figure 6. The variation of the mean moisture ratio of fish in the dryer with time on the first day of drying. m1R: mean moisture ratio of fish in the top right tray; m1L: mean moisture ratio of fish in the top left tray; m6R: mean moisture ratio of fish in the middle right tray; m6L: mean moisture ratio of fish in the middle left tray; m10R: mean moisture ratio of fish in the top right tray; m10L: mean moisture ratio of fish in the top left tray.

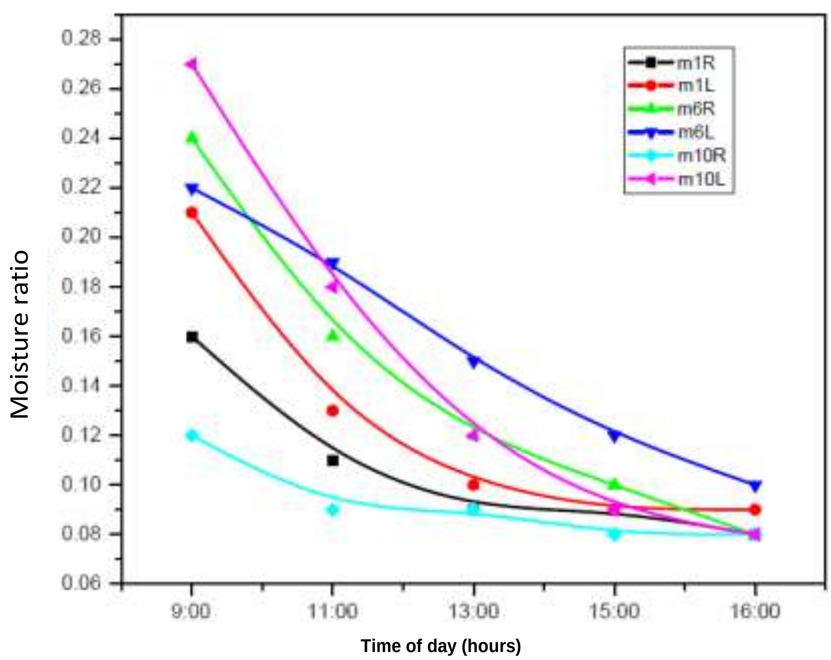

Figure 7. The variation of the mean moisture ratio of fish in the dryer with time on the second day of drying. m1R: mean moisture ratio of fish in the top right tray; m1L: mean moisture ratio of fish in the top left tray; m6R: mean moisture ratio of fish in the middle right tray; m6L: mean moisture ratio of fish in the middle left tray; m10R: mean moisture ratio of fish in the top right tray; m10L: mean moisture ratio of fish in the top left tray.

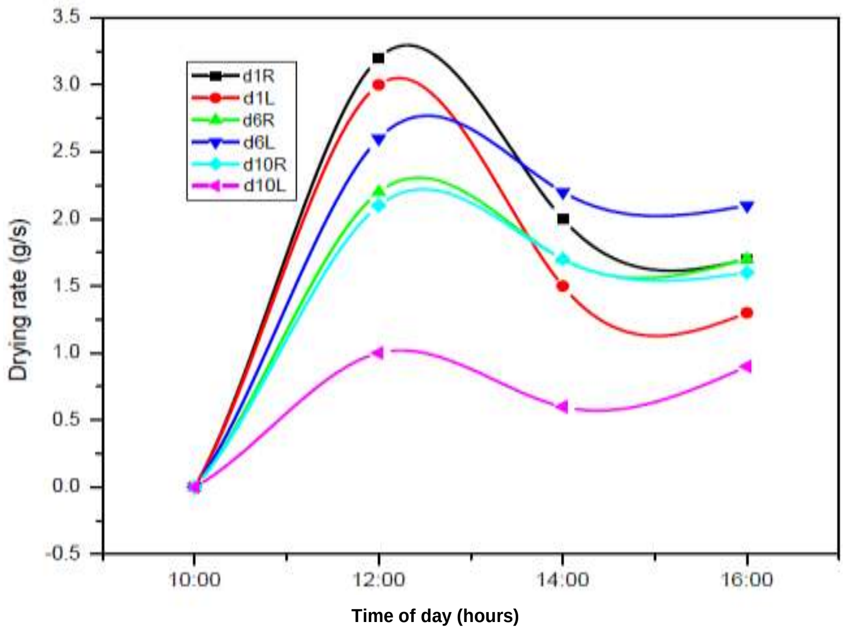

Figure 8. Variation of drying rates with time on the first day of drying. d1R: drying rate of top right tray; d1L: drying rate of top left tray; d6R: drying rate of middle right tray; d6L: drying rate of middle left tray; d10R: drying rate of bottom left tray; d10L: drying rate of bottom right tray.

days of drying are presented in Figures 8 and 9, from which it is observed that there is first an increase in the drying rates in the first two hours of drying, a slight drop in the next two hours and then finally almost constant rate at the end of the first drying day. On the second day, there is first a decreasing then an almost constant rate at the end of the second day when equilibrium moisture content of the fish is attained. The highest drying rates are observed in the top trays as compared to the other trays in the first four hours of drying. The drying rates of the fish are higher on the first day of drying because the (moisture content of the fish is higher) surface is saturated with moisture and the rate of evaporation of moisture from the fish surface rate which is controlled largely by external ambient parameters of temperature and air flow rate. The drying rate at later stages (second day) depends on the rate of the diffusion of moisture from the interior of the product to the surface rather than the external parameters as all the surface moisture has been removed. The moisture has to be diffused from the interior of the product to the surface first before being evaporated to the surrounding. The rate of diffusion decreases at lower concentration of moisture in the fish and hence the observed decrease in the drying rates on the second day.

Drying rate constant (*k*) **and effective moisture diffusivity (**D_{ef}**)**

The linear graphical plots obtained for the -In M. R. against time for the top, middle and bottom trays are presented in Figures 11 - 16. The drying constants were computed from the gradients of the graphs and obtained as follows: 0.146 ± 0.0146 hr^{-1} and 0.150 ± 0.0224 hr^{-1} for the bottom left and right trays, 0.135 ± 0.0077 hr^{-1} and 0.141 ± 0.0142 hr^{-1} for the middle left and right trays, and 0.141 + 0.0142 hr^{-1} and 0.151 + 0.0132 hr^{-1} for the top left and right trays. The effective moisture diffusivity values derived from the slope of In M. R. versus time plots according to Equation 8, were obtained as follows: $1.183 \times 10^{-3} m^2/s$, $1.119 \times 10^{-3} m^2/s$ and $1.183 \times 10^{-3} m^2/s$ for the top, middle and bottom trays, respectively. It is observed that the middle trays have a slightly lower value of moisture diffusivity as compared to the bottom and top trays. This observation can be explained by the fact that at the top and bottom trays the temperatures are higher than in the middle trays hence both the rate of moisture evaporation and diffusivity are higher which increases the rate of drying.

Thermal and drying efficiencies

The thermal efficiencies of the collectors were computed using Equation 5, and the variation of efficiency of the collector system and the instantaneous solar radiation intensities with time are presented in Figure 10. The efficiency of the collector system increases with the incident solar radiation and both peak at almost the same time of the day, between 11:30 and 13:30 h. The

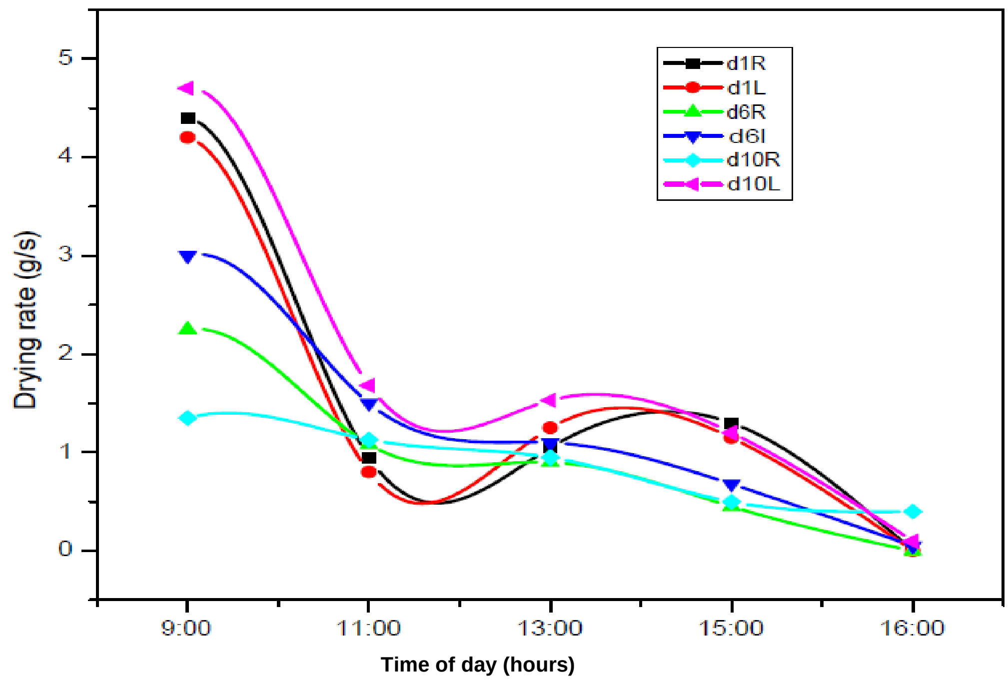

Figure 9. Variation of drying rates with time on the second day of drying. d1R: drying rate of top right tray; d1L: drying rate of top left tray; d6R: drying rate of middle right tray; d6L: drying rate of middle left tray; d10R: drying rate of bottom left tray; d10L: drying rate of bottom right tray.

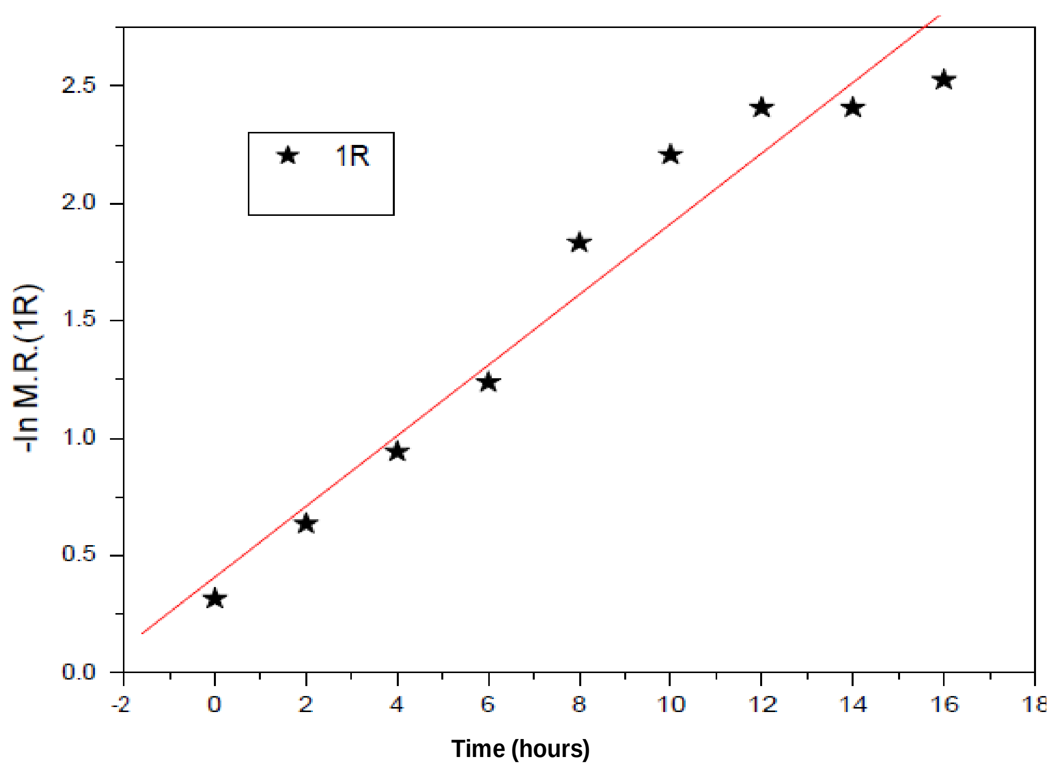

Figure 10. Variation of efficiencies of the collector system incident radiation with time. C. Eff. (D1): collector system efficiency on the first day of drying; C. Eff. (D2): collector system efficiency on the second day of drying. (1R): plot for top tray right; (1L): plot for top left tray; (6R): plot for middle left tray; (6L): plot for middle right tray; (10R): plot for bottom right tray; (10L): plot for bottom left tray.

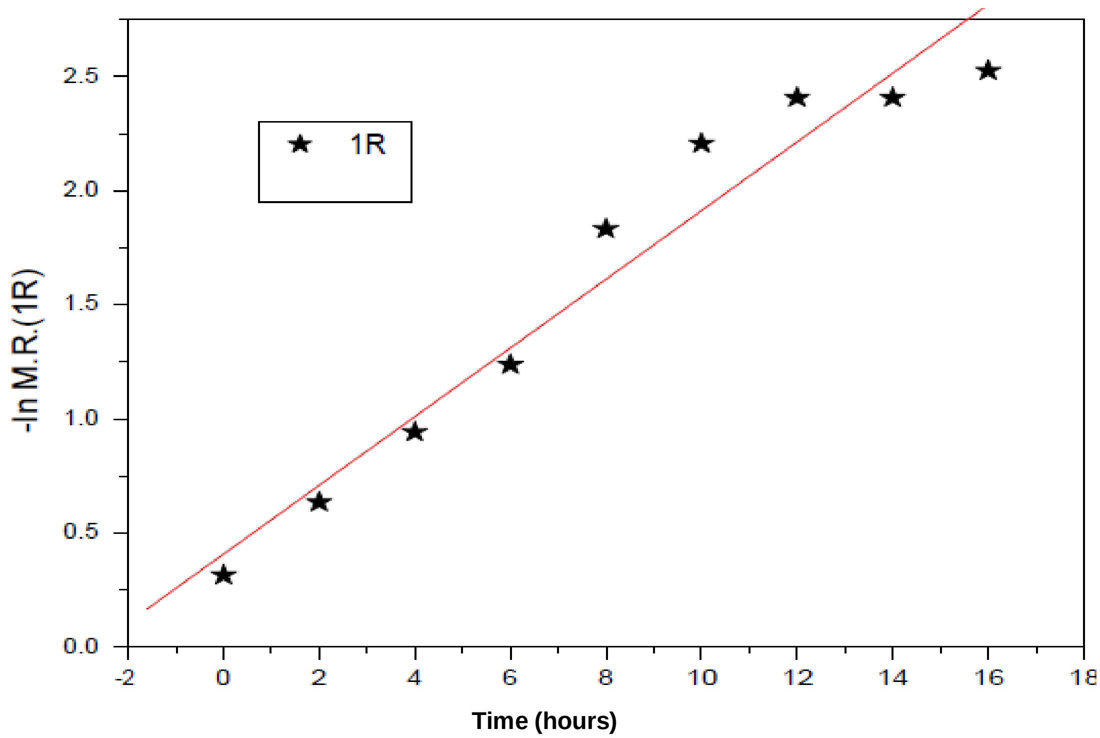

Figure 11. The plot of –In M.R. versus time for top right tray. (1R): plot for top tray right; (1L): plot for top left tray; (6R): plot for middle left tray; (6L): plot for middle right tray; (10R): plot for bottom right tray; (10L): plot for bottom left tray.

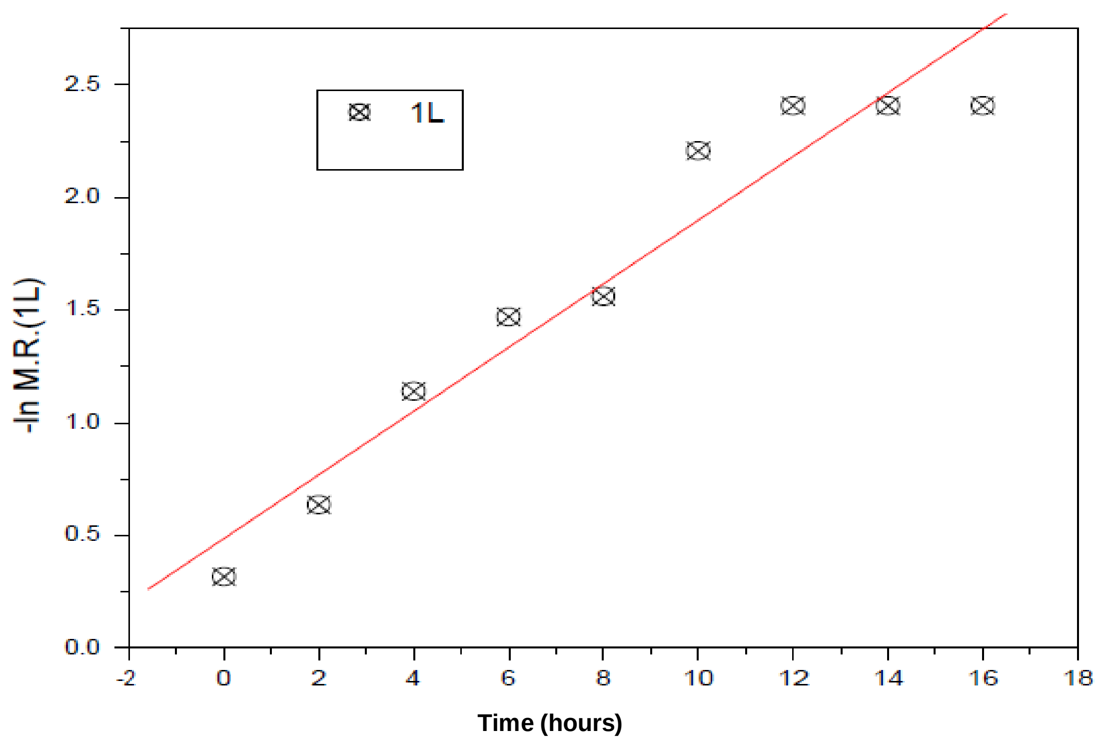

Figure 12. The plot of –In M.R. versus time for the top left tray. (1R): plot for top tray right; (1L): plot for top left tray; (6R): plot for middle left tray; (6L): plot for middle right tray; (10R): plot for bottom right tray; (10L): plot for bottom left tray.

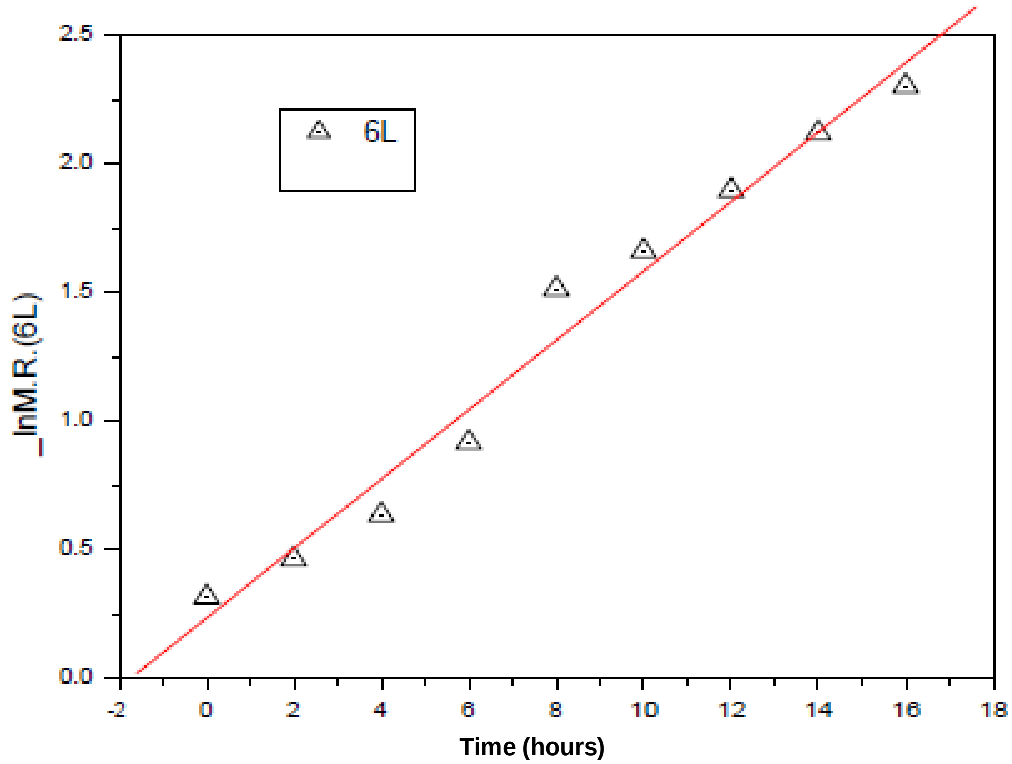

Figure 13. The plot of –In M.R. versus time for the middle left tray. (1R): plot for top tray right; (1L): plot for top left tray; (6R): plot for middle left tray; (6L): plot for middle right tray; (10R): plot for bottom right tray; (10L): plot for bottom left tray.

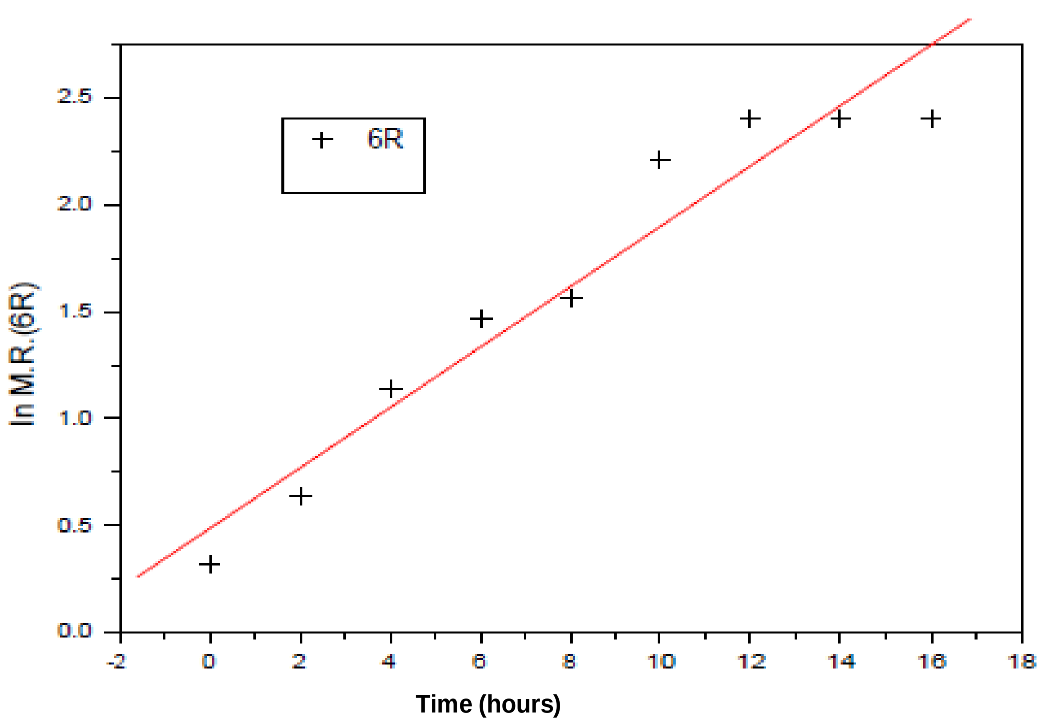

Figure 14. the plot of –In M.R. versus time for the middle right tray. (1R): plot for top tray right; (1L): plot for top left tray; (6R): plot for middle left tray; (6L): plot for middle right tray; (10R): plot for bottom right tray; (10L): plot for bottom left tray.

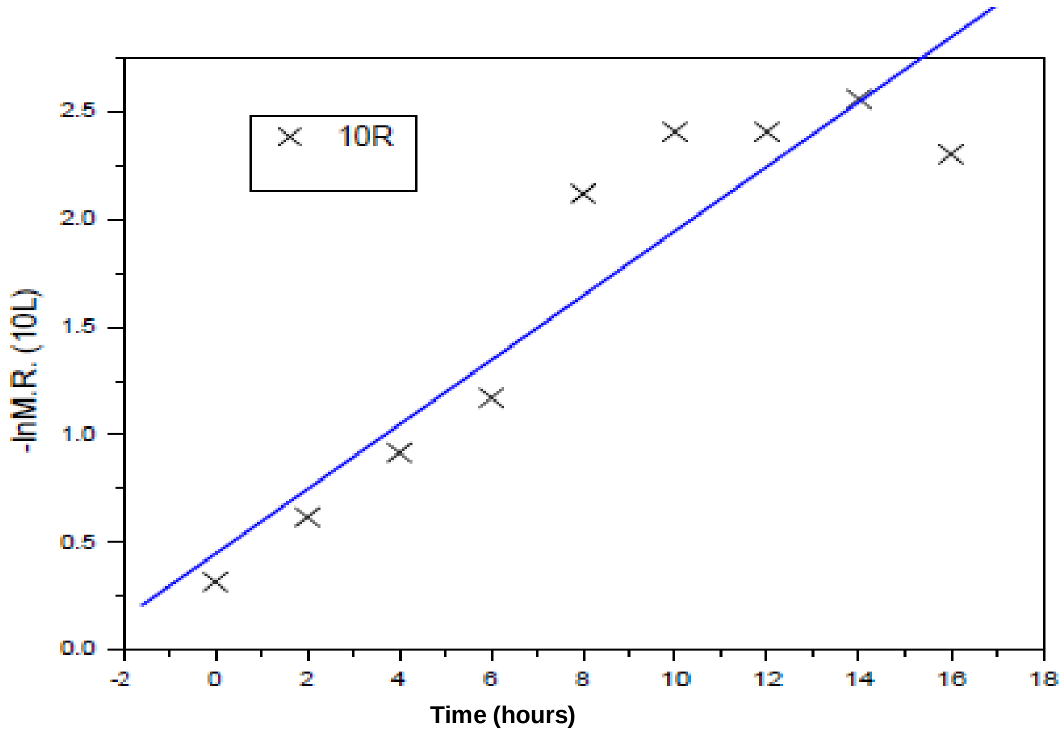

Figure 15. The plot of –ln M.R. versus time for the bottom right tray. (1R): plot for top tray right; (1L): plot for top left tray; (6R): plot for middle left tray; (6L): plot for middle right tray; (10R): plot for bottom right tray; (10L): plot for bottom left tray.

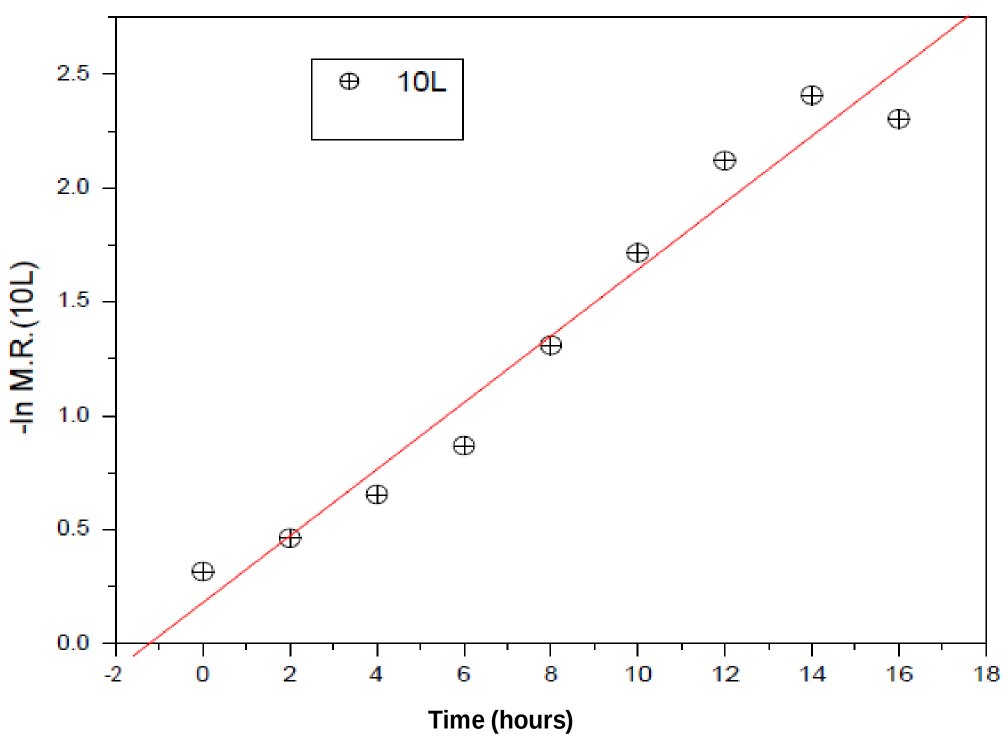

Figure 16. The plot of –ln M.R. versus time for the bottom left tray. (1R): plot for top tray right; (1L): plot for top left tray; (6R): plot for middle left tray; (6L): plot for middle right tray; (10R): plot for bottom right tray; (10L): plot for bottom left tray.

thermal efficiency of the collector system has maximum and minimum values of 19.96% at about 11:30 h and 5.30% at 16:00 h respectively on the first day and 19.3% at 12:30 h and 4.33% at 11:15 h for maximum and minimum values, respectively, on the second day. The mean collector efficiencies calculated according to equation 6 were found to be: 10.5 ± 2.95 % and 9.36 ± 3.95% on the first and second days respectively, while the mean drying system efficiency was computed according to Equation 7 and found to be: 9.93 + 3.53 %.

Conclusions

The twin collector (5.0 m^2 glazing area) indirect forced convection solar dryer was designed and the performance tested for the drying of *Rastrineobola argentea* fish. The drying tests were conducted with 10 kg batches of the fish, between 09:00 and 16:00 h on each day at mean ambient and drying chamber temperatures of 26.5 and 39°C, respectively. The temperature of the drying chamber in the indirect forced convection solar dryer was increased by an average of 12.5°C above the mean ambient value, while the relative humidity of air in the chamber was reduced by an average value of 23.4% at an average air mass flow rate of 0.0163 kg/s and 496 W/m^2 mean incident solar radiation, under full load conditions. The mean thermal efficiencies of the collector and drying system were found to be between 12.63 and 9.93%. Drying of the fish occurred in the falling and constant rate periods, with the moisture content being reduced from 73% w. b. to between 8% w. b. and 10% according to the location in the drying chamber in approximately 11 hours in the solar dryer while open sun drying took 2 days to reach the same moisture content. The average drying rate constant for *Rastrineobola argentea* fish was found to be 0.167 h^{-1}, while the effective moisture diffusivity was found to be 1.36 $\times 10^{-3}$ m^2/s at an average air mass flow rate of 0.0163 kg/s. The overall quality and appearance of the solar dried fish was found to be better than sun dried samples.

Conflict of interests

The authors did not declare any conflict of interest.

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