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Full Length Research Paper

Drying fish (*Rastrineobola argentea*) on the bank of Lake Victoria in a prototype solar-heated enclosure: Using renewable energy to reduce drying-time and improve product quality and value

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Silver cyprinids (*Rastrineobola argentea*) are small pelagic fish endemic to Lake Victoria. High-quality dried fish are an important protein-rich human food. This study was carried out to determine if it would be practical to use renewable energy to dry silver cyprinid. Drying is presently achieved by laying fish out in the sun on the ground or on racks. In the wet seasons, however, drying is compromised and much of the catch becomes fit only for animal consumption, or spoils. Lake Victoria's surface waters are c. 25°C year-round. Its enormous volume of tropical water offers a source of thermal energy that could be used to dry fish. As a proof of concept, we used solar-generated electricity to drive a heat pump to harvest heat energy from water in a 10,000-L rainwater tank beside Lake Victoria, used the energy to heat air, and blew the air over fish in a tent-like enclosure. Fish in the enclosure dried in about 4 h versus about 7 h outside, were free from insects, and not at risk of theft by or defecation upon by birds. The drying processes inside and outside the enclosure were modelled. The model correctly reproduced observed drying times, and enabled exploration of options to improve drying performance. Up-scaling the prototype could provide year-round sustainable fish-drying capability, reduce waste, boost food security, and add value to the catch.

Key words: *Rastrineobola argentea*, dagaa, mukene, omena, drying, renewable energy, food security.

INTRODUCTION

Fish is an important source of protein, omega-3 poly-unsaturated fatty acids and micronutrients for humans (Golden et al., 2021) and is also valuable as an animal feed. Lake Victoria, East Africa, yields c. 1 million tonnes

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of fish per annum (LVFO, 2016a). Nile perch, an introduced species achieves a high price (up to UGX23,000 per kg wet mass in 2022), and most of the annual catch of c. 250 thousand metric tonnes (approximate median annual value for the period 1994 to 2014 (LVFO, 2015)) is exported in frozen fillets as a luxury food for the developed world, generating foreign income ($260 Million in 2012, which was c. 2% of the riparian states' trade balance (LVFO, 2105)). The small (maximum length c. 9 cm) and endemic Silver cyprinid (*Rastrineobola argentea* - known locally as dagaa, mukene or omena) is less expensive (maximum price around UGX1,300 per kg wet mass in 2022), and is sold locally for human consumption or animal feed. Approximately 650 thousand tonnes of Silver cyprinid are landed each year (LVFO, 2016a). These fish are caught at night from open canoes using purse-seine-like nets after being attracted towards the surface by lamp light: catches are higher on dark nights around the new moon when lamp light stands out strongly against the background dark sky.

Fish are landed at dawn and spread on the ground or on elevated racks to dry in the sun in the open air. This open-air drying can be effective in the dry seasons (June to September, and January to February) and is sometimes achieved in a single day (it can take two days or more though). The target water content for safe, long-term preservation is around 15% by mass (Abdulmajid, 2015), but 'dryness' is judged by fish-dryers on appearance and feel rather than by formal measurement. In any case, since dried fish are sold by weight, and because reducing water content reduces weight, dryers can find it preferable to sell fish as soon as possible. Fish laid out to dry in the open are exposed to birds (that eat them and defecate on them) and insects, and the fish can become contaminated with foreign material. Sun drying also results in vitamin loss, discoloration, and if fish are not well spread, uneven residual moisture distribution can occur and leads to spoil (Sreekumar et al., 2008). In the wet seasons (March to May and October to December) when rainfall is high, open-air drying can be impossible and the low water content required for safe long-term storage is often unachievable (Oduor-Odote et al., 2010). Product-quality in the wet season is generally low, and much of it is fit only for animal feed: fish that fail to dry are dumped and losses can exceed 50% (Owaga et al., 2011). High post-harvest loss, including rotting or spoilage due to insufficient sun-heat to dry the catch, particularly during the wet seasons, has been identified as a key feature of Silver cyprinid trade in the Lake Victoria region (LVFO, 2016b). Paradoxically, the wet season is the time of year when catches are highest (fish migrate inshore to spawn and become more accessible to fishers), but because of product-quality issues, catch can fetch as little as UGX200 per kg wet mass. In 2014, Silver cyprinid contributed 55.4% to the total annual catch from Lake Victoria but contributed only 16.1% to the total catch value: development of a reliable and sustainable method to dry these fish in the wet season would bring substantial benefit in terms of food-availability, nutrition and value-chain improvement (LVFO, 2016b).

Several methods have been explored to improve fish drying. Wood-fired kilns are used to dry larger, more valuable species such as *Tilapia* and catfish, but kiln-drying is not viable for the large volumes of smaller and lower-value Silver cyprinid. In any case there are environmental concerns around unsustainable harvest of firewood, and wood smoke is damaging to human health. Passive indirect solar dryers have been able to dry fish to acceptable levels, and have sometimes achieved drying times quicker than in the open air (Abdulmajid, 2015). These passive dryers rely on absorption of solar radiation by black materials that then heat air indirectly, but the process is inefficient, especially during times of cloud cover. Active dryers have not been adopted because of the cost of energy, and the fact that some landing sites (fish are often dried close to where they are landed) are not on the electricity grid. A reliable low-cost and sustainable heat source is required.

Lake Victoria straddles the equator. It is the world's largest tropical lake (c. 60,000 km^2 area, and 2,400 km^3 volume). The lake has an annual average surface temperature of around 25°C and acts as a storage reservoir of radiational heat (Yin and Nicholson, 1998). In this study, we investigated whether this heat-energy could be harvested using a heat pump powered by solar-generated electricity and used to dry Silver cyprinid. Heat pumps transfer energy in the form of heat from one location to another. Domestic refrigerators, for example, cool down inside when a pump moves heat from inside to the cooling vanes outside (which get hot), from where the heat dissipates as 'waste' to the air. We report here some preliminary experiments to use heat-energy extracted with a heat pump from a 10,000-L rainwater tank adjacent to Lake Victoria using renewable off-grid electricity (solar power) to dry Silver cyprinids in a tent-like enclosure that served also to shield fish from birds and insects. In addition, we develop a numerical model of the drying process under ambient conditions and within the enclosure, and use the model to identify the key optimisation parameters for the system under constrained energy budgets. The data reported may be useful in up-scaling fish-drying capacity in the wet season (the tent enclosure provides shelter from rain), and for extending drying beyond periods of daylight since solar-generated electricity can be stored in batteries.

MATERIALS AND METHODS

Location of the study and physical setup

A 3 m long × 2 m wide × 2 m tall plastic tent-like enclosure (Figure

Figure 1. The drying enclosure with the heat pump in position in the eastern end (gaps yet to be closed), the 10,000-L rainwater tank, and the pipe along which water was pumped from the tank to the heat pump.
Source: Authors

1) was set up to dry Silver cyprinid at the National Fisheries Resources Research Institute (NaFiRRI) in Jinja, Uganda (0.416°N, 33.206°E) in February 2022. The enclosure was erected in the NaFiRRI grounds less than 1 km from Lake Victoria and only 10 m or so above lake level. The location chosen was flat, unshaded and adjacent to a 10,000-L rainwater tank that was used as a 'mini Lake Victoria' heat source. Water in the tank was c. 26°C. A nylon net rack (190 cm × 45 cm; mesh size = 1 mm) was suspended at waist height inside the enclosure to spread fish out onto dry (Figure 2A). The rack enabled air to circulate beneath the fish as well as over the top, facilitating evaporation from most of the fish surface.

Heat source

A Proteam Europe Model P8 swimming-pool heat pump (230 Volt AC, 1100 Watt) was positioned in the eastern end of the plastic enclosure and fed with water pumped along a 25 mm internal-diameter flexible pipe from the rainwater tank using a 24 Volt DC in-water pump (Figure 1). Water was returned to the tank after passing through the heat pump. The water pump and the heat pump were driven by electricity generated from four 845 × 670 × 30 mm/100 Watt solar panels. Electricity from the panels (42 Volt DC) was directed to the heat pump via an inverter (230 Volt; Iconica 3,000 Watt, 24 V hybrid pure sine wave inverter with 40 Amp MPPT Solar controller). This inverter also charged two 75-Amp Hour lead acid car batteries wired in series. The battery pack was included to bridge periods of cloud cover and to provide efficient power to the 24 Volt DC water pump. It also provided electricity for lighting that could enable start up before sunrise. The heat pump had the capacity to cool water to a minimum of 8°C, and it was set at that to give the maximum output of heated air. The heat pump specifications indicate that this configuration would produce a Coefficient of Performance (COP) of ca. 5.4 and therefore a heat output of ca. 6 kW. The heat-pump fan had an air displacement of 2,200 $m^3 h^{-1}$. For the tent cross section of 4 m^2, this corresponds to a minimum air velocity of 0.15 $m\ s^{-1}$. As air left the pump in a directed flow though, and because the fan outlet was quite close to the fish (c. 3 m range), we estimate that the air velocity over the fish was approximately an order of magnitude larger, at about 1 $m\ s^{-1}$.

Fish

Fish were obtained fresh from the landing site at Kikondo each morning. The site, on the opposite side of Napoleon Gulf to NaFiRRI, was about 2 km away by boat. The boat journey took around 10 minutes, and fish were at our experimental site within an hour of being landed. Two experiments were carried out to compare the fish-drying trajectory inside the enclosure with outside. The first, on February 24, 2022 involved the solar-powered heat pump described earlier blowing heated air into the enclosure. In the second, on February 25, the heat pump was replaced with a simple electric fan (Figure 3) that blew ambient air into the enclosure at the same rate as blown by the heat pump. Evaporation is a function of air speed, temperature and relative humidity (Hisatake et al., 1995), and we were interested to determine if gains in drying time in the enclosure compared with those in the open could be achieved with blown air alone since a simple fan has a lower energy requirement (80 Watts) and purchase cost (£30) than a heat pump (1100 Watts and £1000). As a control for both experiments, we suspended a rack of the same nylon mesh as used in the enclosure at waist height outside the enclosure to spread fish out on to dry (Figure 2B).

Figure 2. (A) Drying racks inside the enclosure and (B) outside, showing four 100-g samples of fish spread out to dry. The white cubes on the drying racks are SensorBlue temperature/humidity loggers.
Source: Authors

Experimental approach

For both experiments (heat-pump versus ambient, and fan versus ambient), we weighed 8 samples of 100.00 g of freshly caught fish and spread 4 samples on the rack in the enclosure and 4 samples on the control rack outside. Every hour for the next 7 h (experiment

Figure 3. The drying enclosure as used in Experiment 2 on February 25, with a simple fan in place of the heat pump used the day before in Experiment 1. The fan delivered air at the same rate that the heat pump had, but the fan diameter was smaller so fan speed was higher.
Source: Authors

1) or 6 h (experiment 2), we gathered each of the 8 samples, weighed them to the nearest 0.01 g on a portable electronic balance, and returned them to their respective racks. Temperature and relative humidity were recorded inside the enclosure and outside throughout each experiment using SensorBlue WS08 Smart Hygrometers. At the end of each experiment, we placed the 8 samples in a drying oven at 100°C and left them overnight to desiccate completely before weighing again. Finally, for experiment 1 samples, we weighed the fish again after they had been left for 4.5 h open to the air after desiccation to determine mass of water reabsorption.

Modelling

A physics-based model of Silver cyprinid drying was developed to enable us (a) to consider our empirical observations in the context of the drying processes that should, in theory, be in action, and (b) to explore options for optimizing the drying process energetically (e.g. to explore whether additional air-flow or heat or both would be beneficial). The drying characteristics of Silver cyprinid have been studied in detail (Oduor-Odote et al., 2010). Drying occurs in two stages: an initial constant rate, followed by a decreasing rate. In the initial constant-rate period, evaporation occurs from the fish surface and can be reasonably well approximated as the rate of evaporation from a free water area (Oduor-Odote et al., 2010; Hisatake et al., 1995). In the second phase, the limiting factor is internal diffusion of water from the inside of the fish to the outer surface: the rate of this reduces over time and so the drying rate also decreases over time.

Our model is framed around the moisture content per dry weight M of fish (sometimes referred to as dry basis). M has units of kg/kg$_{dw}$ corresponding to kg water per kg dry weight (dw), and is defined as:

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

With W_w being the wet weight and W_d the dry weight of the fish. Initially, fish have a moisture content of $M_0 =$ 0.8 kg/kg$_{dw}$ and this decreases toward 0 kg/kg$_{dw}$ at full desiccation. During the constant-rate drying phase, the drying rate $\mathrm{d}M/\mathrm{d}t$ is a function of the relative humidity h_r of the surrounding air, temperature T (we assume for simplicity that the fish are at the same temperature as the air within the tented enclosure in experiment 1 and as ambient air outside), and air velocity v (which is wind velocity outside, and blown air velocity in the enclosure in the respective experimental conditions). Under the turbulent flow conditions in our experiments $\mathrm{d}M/\mathrm{d}t$ for a single fish is given by the following semi-empirical formula (Hisatake et al., 1995):

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -C_1 n_s (1 - h_r) \left(\frac{v}{v_1}\right)^{0.9} \left(\frac{D_{fish}^{eff}}{D_1}\right)^{1.8} \quad (2)$$

Where, n_s is the saturation water vapour density at temperature T (Foken, 2021), h_r the relative humidity, v the air velocity and

D_{fish}^{eff} is the effective average fish length. C_1 is an empirical constant that was determined by Hisatake et al. (1995) to be 4 mg h^{-1} for a wind velocity v_1 = 1 m s^{-1} and dimension D_1 = 1 cm, with the scaling laws for air velocity v (0.9) and dimension D (1.8) being determined experimentally as well.

In the decreasing drying-rate period, drying is most likely limited by the diffusion of residual moisture from the interior tissue of the fish. In this regime, the moisture content M is modelled by a form of Newton's model for thin layer drying (Oduor-Odote et al., 2010):

$$M = M_0 \exp(-kt) \quad (3)$$

Where, k is the drying rate constant, and t the time. The drying rate $\mathrm{d}M/\mathrm{d}t$ in the falling rate phase is therefore:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -kM_0 \exp(-kt) \quad (4)$$

From a meta-analysis of the available literature (Abdulamjid et al., 2015; Oduor-Odote et al., 2010; Mujaffar and Sankat, 2005, 2014), k was found to have no significant dependence on the relative humidity, but to follow a linear relationship with temperature:

$$k = 0.0030\ \mathrm{h}^{-1}\ \mathrm{K}^{-1}\ T - 0.7805\ \mathrm{h}^{-1} \quad (5)$$

Equations 4 and 5 as well as the environmental conditions determined on the days of the experiments (temperature, humidity and estimated wind velocity) for the ambient (outside) simulations were utilised to model ambient drying.

In order to simulate drying in the heat pump system, we took the following additional effects into account. First and foremost, the heat pump raised the temperature of the air within the enclosure by approximately 15°C. We therefore modelled the air temperature within the tent as being the outside air temperature plus 15°C. The main effect of this elevated temperature is a corresponding reduction of the relative humidity h_r by c. 20%.

Air speed inside the tent is driven by the heat-pump fan at approximately 1 ms^{-1} at the location of the fish, compared to the prevailing conditions outside of approximately 2 ms^{-1} (windspeeds obtained from weather data for the location and time of the experiment (Hersbach et al., 2022)). In addition, we took into account that the evaporated moisture increases the humidity in the tent while moisture is furthermore continuously removed via the intake of fresh air and the ejection of moist air from the enclosure. For our experiment in the small, prototype enclosure, this led to a minor increase in relative humidity of only about 1%, but increased relative humidity within the enclosure may become an important factor in an upscaled version. The aforementioned model was implemented in Matlab Simulink.

RESULTS

Experiment 1: Enclosure + heat pump versus open air

February 24th started as an overcast day with nil wind. At the start of the experiment, at around 8 a.m. local time, air temperature was c. 23°C outside and 26°C inside the enclosure. Relative humidity was similar inside and out (c. 75%). Fish had a mean length of 25.1 mm (range 18 to 36 mm, mode 25 mm; Figure 4) which, according to length-mass relationships in Yongo et al. (2016) would equate to a mean mass of c. 0.10 g per fish.

Temperature outside the enclosure climbed steadily to a maximum of about 38°C at around 1 p.m., and relative humidity fell to a low of about 40% by that time (Figure 5). Temperature inside the enclosure rose to a maximum of around 52°C by noon, with relative humidity dropping to 30% by that time (Figure 5). The mass of the fish samples inside the enclosure dropped rapidly hour by hour, reaching a floor of around 22 g after about 4.5 h. The fish outside lost mass (water) more slowly, reaching a low of around 24 g after 7 h when the experiment ceased. Mass-loss trajectories are as shown in Figure 5.

Mean final oven-dry sample masses were 20.00 g taking this to be 0% moisture content, the mean final mass of the fish dried with the heat pump in Experiment 1 of 21.12 g equated to a moisture content of 5.29%. The moisture content of the fish dried outside as the control in Experiment 1 equated to a moisture content of 17.07%. Oven-dried (at 100°C) samples left in the open post drying for 4.5 h increased in mass by between 0.61 and 0.87 g (mean 0.72 g), increasing moisture content from 0% to a mean of 3.45%.

Figure 6 shows the output of our Matlab Simulink model under the same environmental conditions as Experiment 1 (Figure 5B and C). The physical model captures the drying characteristics outside and inside the enclosure qualitatively and quantitatively. The transition from the constant-rate drying regime to the decreasing-rate drying regime is evident after c. 4 h in the tented enclosure and c. 6.5 h under ambient conditions outside, and modelled drying times are consistent with the experimental data. This close agreement provides evidence that the model captures well all the relevant experimental parameters and processes. We are therefore confident that the model provides a good basis for the optimisation of the system under constrained energy budgets.

Experiment 2: Enclosure + fan versus open air

February 25th started as a bright day with clear sky and a light wind. At the start of the experiment, at around 8.30 a.m. local, air temperature was c. 26°C outside and 29°C inside the enclosure. Relative humidity was 65% outside and 70% inside. Fish available for Experiment 2 were larger than those landed the previous day, with a mean length of 28.3 mm (range 17 to 42 mm, mode 30 mm, equivalent to a mean mass of c. 0.15 g; Figure 4). Temperature outside climbed steadily to a maximum of about 39°C at around 1 p.m., and relative humidity fell to a low of about 36% by that time (Figure 5), and wind

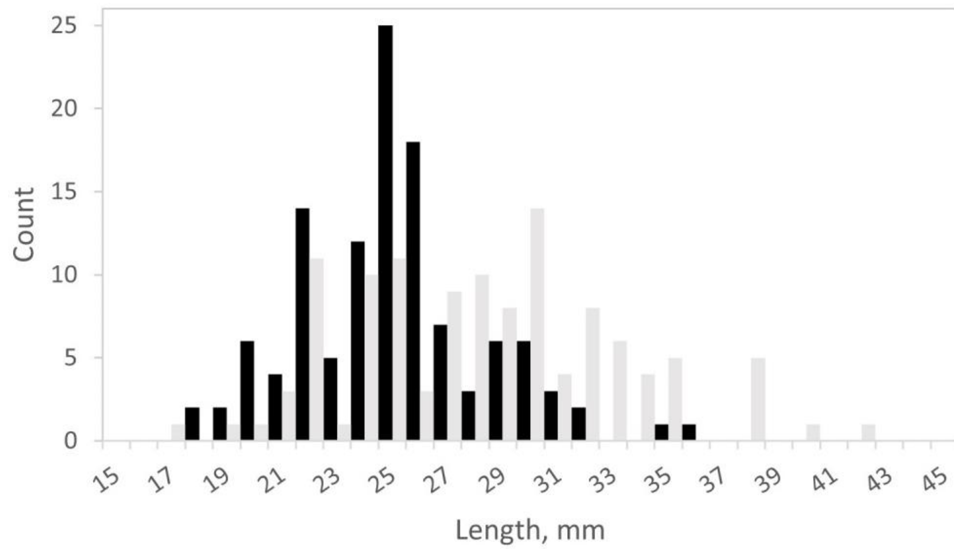

Figure 4. Length distributions of fish used in Experiment 1 (black bars) and Experiment 2 (grey bars). N = 117 fish in both plots.
Source: Authors

velocity increased through the day.

Temperature inside the enclosure rose to a maximum of around 42°C by 1 p.m. (this maximum was c. 10°C cooler and occurred 1 h later than in Experiment 1 with the heat pump), with relative humidity dropping to 39% by that time (Figure 5): humidity inside the enclosure was marginally higher than out, possibly due to evaporation of water from the fish into the confined space of the enclosure. The mass of the fish samples inside the enclosure dropped slightly more rapidly than outside over the first 3 h, but by 4 h samples outside and in had a similar range of masses, with both sets of samples reducing rapidly in mass hour by hour, reaching a floor of around 24 g. Mass-loss trajectories are as shown in Figure 5.

Mean final oven-dry sample masses were 20.17 g. Taking this mass to be 0% moisture content, the mean final mass of the fish dried with the fan in the enclosure in Experiment 2, and outside as the control (both means were 24.13 g), equates to a moisture content of 16.42%.

DISCUSSION

Heat pump versus ambient drying

The water-source heat pump was able to increase the temperature in the enclosure on February 24 2022 to 52°C, or some 14°C above ambient. At the same time, it reduced relative humidity between 10 and 20% relative to ambient conditions to a minimum of around 30%. Fish outside the enclosure dried on February 24 to a moisture content of around 17.1% after 7 h. Fish inside the enclosure reached this level of dryness around 3 h sooner, and over the 7-h duration of the experiment dried in the enclosure to moisture content of 5.3%. The enclosure and heat pump together clearly provided substantially better drying conditions than those outside on February 24. Indeed, it would have been possible to dry two batches of fish in sequence that day on the single rack in the enclosure to the moisture content achieved on the control rack over the full 7 h.

February 24 started off overcast, but there were sunny intervals through the day, and it did not rain: the drying-time gains provided by the enclosure and heat pump would likely be relatively much greater during the wet season. Furthermore, our control was an elevated rack, with air circulating above and below fish. In practise much drying is on the ground, with evaporation therefore principally from the upper surface only, so likely to be at a slower rate than in our control: the relative gain of the tent compared to standard ‘field’ drying conditions is therefore likely to be greater than portrayed here. The enclosure provided the added advantage of protecting the drying fish from birds and insects.

Fan versus ambient

Although the fan used in experiment 2 on February 25 was able to blow air over the fish in the enclosure at the same rate as had been achieved by the heat pump, this

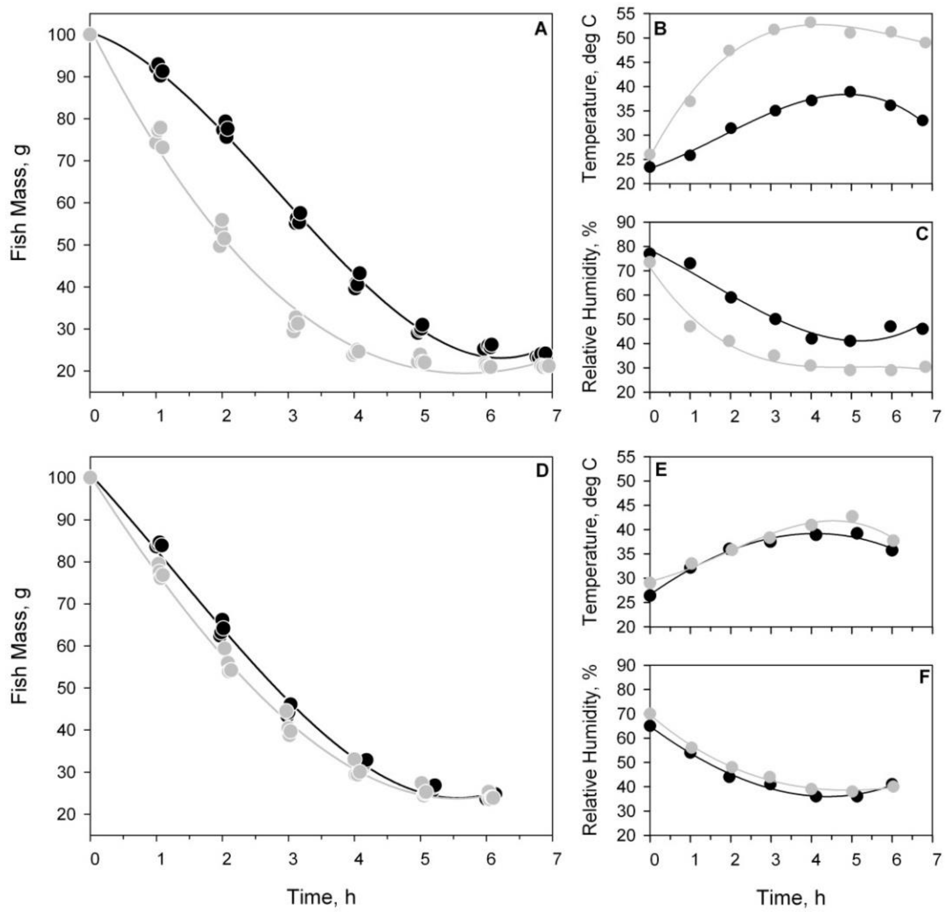

Figure 5. Drying (mass-loss) trajectories, and temperatures and humidities (C) inside and outside the enclosure for Experiment 1 with the heat pump (panels A, B and C) and Experiment 2 with the fan (panels D, E and F). Trajectories inside the enclosure are shown by grey symbols and lines. Trajectories outside in the open air are shown by black symbols and lines. The lines are simple smooths to guide the eye, and are not intended to suggest statistically significant relationships. Drying trajectories tend towards asymptotes slightly above 0% moisture content.
Source: Authors

blown ambient air did not deliver improvements in fish-drying rate or final moisture content compared to the control samples outside (wind velocities outside and air velocities within the tent were of the same order of magnitude). This is consistent with model expectation, given the closely similar temperatures and humidities inside and outside on February 25. Although the fish in the enclosure lost mass initially more quickly than those outside, there was no difference between drying floor or time to drying floor. Fish inside the enclosure were however free of from ants, whereas those outside were not.

Comparison between experiments

The weather on February 25 (Experiment 2) was warmer and with a stronger breeze than on February 24 (Experiment 1). Fish outside reached the drying floor between 5 and 6 h on February 25, which was about an hour sooner than on February 24, and this was even though fish available to us on February 25 were larger, and hence had a lower surface area to volume ratio than those used on February 24. Evaporation of moisture from the fish will take place from the surface, and moisture from the fish interior will diffuse towards the surface as the surface dries: larger fish with lower surface area to volume ratios would be expected to dry more slowly than smaller fish under the same conditions. The differences in drying between our 2 experiments reveal the likelihood of considerable day-to-day variability: season to season variability should be expected to be considerably more marked.

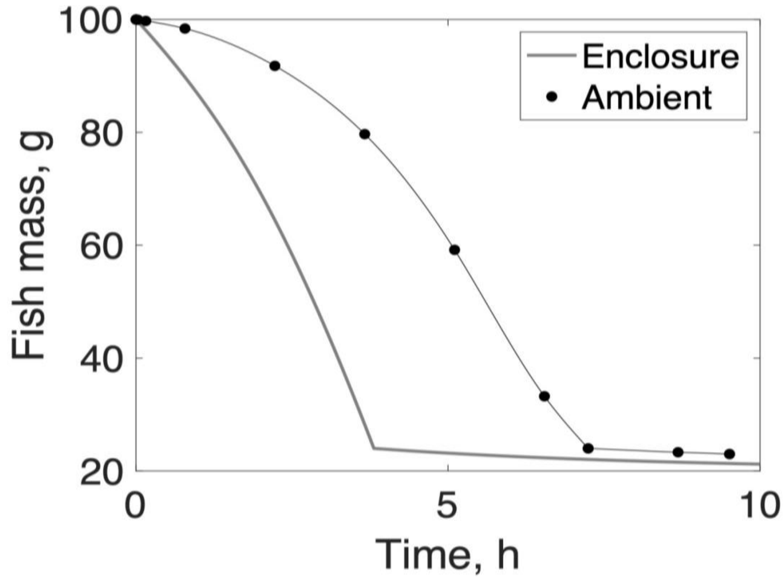

Figure 6. Simulated drying (mass-loss) trajectories for conditions prevailing during Experiment 1. Trajectories equivalent to inside the enclosure are in grey, and outside the enclosure in black.
Source: Authors

Modelling evaporation and drying

Given that evaporation is a function of temperature, air-flow and relative humidity (Hisatake et al., 1995), it is instructive to examine from a physics standpoint where energy should most effectively be invested to maximise drying. Given a limited electrical energy input (limited by the size of the photovoltaic array used to generate solar electricity, and the capacity of batteries to store it), should the available energy budget be directed towards raising temperature or increasing the rate of air flow, or some combination? The heat pump generated an air displacement of approximately 2,000 m^3 h^{-1} which, for a standalone fan of similar capacity requires about 160 W. If this energy was doubled (to 320 W) it would result to first order in a 40% increase in air flow. Providing the same amount of additional energy to the heat pump would increase the air temperature by ~2°C. Figure 7 shows the behaviour of the model in these two scenarios, that is; (a) increasing the air velocity by 40% (blue) or (b) increasing the temperature of the air by 2°C (red) relative to the conditions in the tent during Experiment 1 (grey). It is evident that under these conditions, additional energy expended on increasing the air velocity will decrease the trying time more than twice as much than expanding the same energy on increasing the air temperature.

Furthermore, we ran a simulation for weather data with hourly resolution available for the whole year via the ERA5 climate database (Hersbach et al., 2022). This revealed that it was possible to dry fish to the 'safe' moisture content of 15% dry weight in less than 10 h using the prototype drying enclosure on every day of the year, including during the rainy season (when higher humidity and lower temperature would be expected). Initial calculations suggest that similar levels of performance could be achieved in an upscaled version suitable for processing 50 kg of fish.

Potential for increasing energy efficiency

The results suggest that elevated temperature is important for accelerated drying. Our basic swimming-pool heat pump was able to achieve temperatures in the enclosure of around 55°C. Above about 60°C fish begin to 'cook', so rather than trying to deliver substantially more heat, improved efficiency in capture of heat from water should be sought. We used a basic, cheap (£1,000) and rather inefficient water-source heat pump for this proof-of-concept study. The heat pump had a specified maximum coefficient of performance (COP) of 6. It was observed that, under full load, the water temperature dropped by 1°C from inlet to outlet across the heat pump at a flow rate of 2 m^3 per hour. This indicates that further efficiency could have been achieved if larger water pump was used (ideally the temperature drop across the heat pump should be negligible, which can be achieved by greater water flow). An 'off the shelf' heat pump with a specified maximum COP of 15 can be purchased for around £2,500. This would deliver over

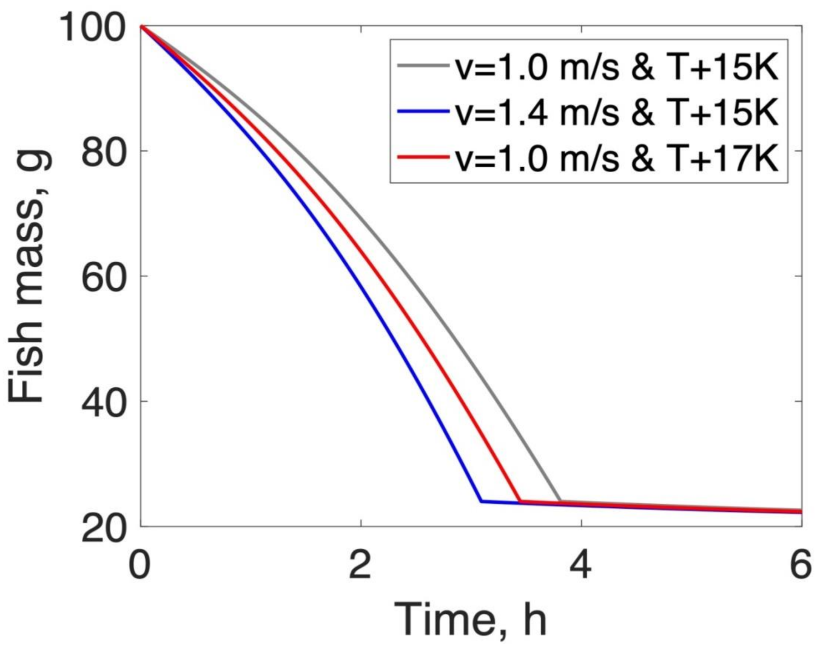

Figure 7. Modelled fish drying as a function of time for the conditions in Experiment 1 (grey), a temperature raise of 2°C (red) or alternatively wind velocity increase of 40% (blue).
Source: Authors

double the heat output for the same electrical input. Calculations indicate that a heat pump specifically designed for our application could have bettered the COP of 15 by an additional ca. 25%. Air-source heat pumps are much less energy efficient than water-source heat pumps; this is due to the inherently variable temperature of the source air and its lower density and lower heat capacity. Ground source heat pumps have similar energy efficiency to water source heat pumps because the temperature of these two sources is relatively constant and their heat capacity is high. Ground source heat pumps would add flexibility in cases where drying operations were carried out away from Lake Victoria.

Further improvements in drying rate could also perhaps be achieved by drying the air before blowing it over the fish: this air drying could be achieved by a condensing heat pump, but the condensing process would cost energy. In our setup with a tent erected on grass, we may have been able to achieve a reduction in humidity in the tent by placing a groundsheet on the floor: some of our heat energy probably served to dry the NaFiRRI lawn rather than the fish!

Gains to be made by improved drying

Post-harvest loss due to spoil following inadequate drying - which may exceed 50% of landed fish by mass - has been identified as one of the major impediments to community Silver cyprinid processors (LVFO 2016b). Although a moisture content of only 15% is desired for long-term preservation (<15% moisture content is required to stop the growth of mould, and <25% content required to stop the growth of bacteria; Oduor-Odote, 2010), this low level might not be required if fish are to be eaten locally quite soon after capture. Indeed, economic analyses presented by LVFO (2016b) suggests a wet-to-dry weight conversion ratio of 1:0.4, which equates to a 50% moisture content (from our measurements here, 1 kg of fresh fish would dry fully to 0.2 kg; 0.4 kg of product from 1 kg of fresh fish would therefore contain 0.2 kg of desiccated fish and 0.2 kg water). In the conditions provided in our enclosure by the heat pump, 50% moisture content was achieved in around 2 hours (Figure 5). Such rapid processing would enable dryers to process multiple batches of fish per day. In the wet seasons, when fish are abundant, open-air drying typically takes 2.5 days (LVFO, 2016b): reducing the drying time by use of renewable energy could reduce wastage, particularly in the wet seasons, deliver more fish of a quality suitable for human consumption, and improve value along the entire catch and processing chain.

Although drying to 15% moisture content by mass is apparently not always required (indeed, perhaps not desired by dryers since 'dried' fish are sold by weight, and dryer fish are lighter), very dry fish that can be stored for long periods - and hence transported substantial distances from Lake Victoria - can command a high price. Mukene Industries, for example, ask UGX 7,000 per kg for clean, high-quality air-dried product, which is more than double the beach-dried price. In some circumstances, then, drying to 15% could be a sensible business choice. With access to sufficient space in a heat-pump-driven facility, dryers could dry fish to desired levels in wet seasons and dry seasons, and make choices around product quality, longevity or value - in the security of renewable energy- to optimise food availability or income.

Nutritional quality

This study did not include any measures of nutritional quality of fish. A useful avenue for future research would be analytical comparison of fish dried in the open and fish dried in the enclosure. This could provide reassurance that gains made in reduced drying time, and reduction of spoil-rate (in the wet season), were not negated by reductions in nutritional quality. It is unlikely, however, renewable-energy-mediated drying would impact nutritional quality adversely. Studies on the effects of four different artisanal processing methods (smoking, salting, sun-drying and deep-frying) on the lysine content of Silver cyprinid found that only deep-frying reduced the content of this essential amino acid significantly (Margaret and Edgar, 2016). Deep-frying exposes fish to temperatures around 180°C and, using methods employed in Uganda, temperatures during smoking may exceed 120°C (Margaret and Edgar, 2016): lysine losses increase markedly with temperature, exceeding 80% at 120°C. In our experiments, by contrast, temperatures with the heat pump did not exceed 55°C, and with the fan alone did not exceed 45°C. The fact that use of the enclosure produced dried fish with a very low final moisture contents may actually result in *increased* lysine content weight for weight. Other work has reported moisture-loss leading to concentration of protein (Akinwumi, 2014).

Conclusion

Our experiments have shown that considerable gains in drying rate and final moisture content can be achieved in the dry season using an enclosure and water-source heat pump compared to ambient conditions outdoors. Improvements in the wet season are likely to be much better. Individual fish dryers typically work an area of few tens of square m, and are able to dry 1 batch of fish per day in the dry season. An agricultural polytunnel could be used to cover an area greater than this, and use of heat pumps could enable multiple batches of fish to be dried per day. The quality of the product (in terms of contamination) would likely be higher than for product dried outside on the ground. This would lead to increased availability of fish for human consumption, add value to the product, and bring better income for fishers and fish-dryers. Application of the sort of sustainably powered technology demonstrated here could improve food security, nutrition and economic wellbeing around Lake Victoria. Furthermore, since small pelagic fish are caught from many African lakes (e.g. Malawi, Tanganyika, Mweru, Kivu, Kariba) (Kolding et al., 2019), this technology could bring considerable benefits across Africa.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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