Solar dryer development, efficient and user-friendly aspects

Henrik Davidsson[1], Lara Constanze Müller[1], Samten Lhendup[2], and Martin Andersson[3]

[1] Energy and Building Design, Building and Environmental technology, Lund University (Sweden)

[2] Department of Mechanical Engineering, Jigme Namgyel Engineering College, Royal University of Bhutan, Dewathang (Bhutan)

[3] Heat Transfer, Energy Sciences, Lund University (Sweden)

Abstract

Preserving fresh food for later consumption has been, and is still today, a major problem around the world. Solar drying may be a suitable method for preserving food. One issue with dryers, depending on design is uneven drying of the produce due to different environmental conditions. Uneven drying in a solar dryer creates problems for the end user as the quality of the product will be less attractive for both storing and selling. The drying time must be kept as short as possible to avoid mold and other problems with the fruit. Avoiding long drying times is essential also for the uptake of the technology as it eases the workload put in by the end user. In this work different fan solutions are tested to mitigate this problem. Results show that using a large fan to short circuit the air in the dryer may work for this purpose. The heat exchanger efficiency was evaluated showing approximately 30 % to 40 % efficiency, which can be compared to the efficiency of the collector of approximately 50 %. However, the actual temperature rise in the heat exchanger is approximately 5 °C, which is much less compared to the temperature rise in the absorber of approximately 20 °C to 25 °C.

Keywords: solar dryer, uneven drying, fruit drying, Bhutan

1. Introduction

Preserving fresh food for later consumption has been, and is still today, a major problem in many places around the world. There are many techniques to do so. However, many of these techniques are not available at many places. This can for instance be caning, freeze drying and cooling. Instead, solar drying can be a suitable method for storing food if other methods are unavailable. Even in cases where different preservation techniques are available, solar drying can also be an attractive option.

Post harvest loss is a major problem in Bhutan affecting food security, economic stability and the wellbeing of the people. Furthermore, the Ministry of Agriculture and Forests in Bhutan has set a goal to increase local food production and thus to decrease the food import that today stands for approximately 30 % of the total need. (Chhogyel and Kumar, 2018).

Research related to solar drying has been published, e.g. (Aacharya et al, 2024 a), (Aacharya et al, 2024 b), (Kumar and Sing, 2016). However, finding publications looking deeper into the evenness of the drying rate inside the solar dryer is more difficult. One issue with dryers, depending on design, can be uneven drying of the produce due to different environmental conditions. This can happen, for instance, when the hot and dry air from the absorber enters the drying chamber and passes over the initial trays of produce, the air picks up the moisture and thus becomes more humid. At the same time the temperature is reduced thus exacerbating the effect. As the air passes over the last trays in the drying chamber the air could have a very different drying potential from the air that entered the chamber. This could lead to significantly different drying rates for different parts in the dryer, i.e., uneven drying. This could be of major concern for the end user as it would require longer drying periods, or other solutions such as rotation of the produce within the dryer (Davidsson et al., 2017). This in turn would require considerable technical investment or more manual work to be put into the process of drying.

Other solutions to mitigate the problems are possible. One solution could be to short circuit the air in the drying chamber as much as possible. This could be done by introducing internal air movement that effectively rotates

10.18086/swc.2025.06.30 Available at http://proceedings.ises.org

the moist colder air mixing it with the fresh, hot and dry air. This could even out the temperature and relative humidity levels throughout the drying chamber. In this work we present a method to use various fan configurations to reduce the unevenness in the drying rate throughout the chamber. The solution should preferably not lead to more expensive dryers as this will reduce the uptake of technology.

Furthermore, the drying time must be kept as short as possible to avoid mold and other problems with the fruit. Avoiding long drying times is essential also for the uptake of the technology as it eases the workload put in by the end user. For this reason, the overall consequences from a physical point of view must be understood for the different parts of the dryer. The investigated solar dryer contains both a solar absorber and a heat exchanger that recovers parts of the energy left after passing the drying chamber.

2. Method

The solar dryer measures approximately 1.3 m · 1 m · 1 m. Its main structure is built from 20 mm plywood and the absorber is a simple black-painted metal sheet covered by a pane of glass. Details of the dryer can be found in Müller (2024). Similar dryers tested in laboratory environments are described in Davidsson et. al (2024). The dryer is illustrated in Figure 1 showing, 1 the inlet, 2 the heat exchanger, 3 the absorber, 4 the heat storage, 5 the drying chamber, 6 the internal circulation fan, 7 the second drying chamber, 8 the exhaust from the drying chambers, and 9 the exhaust from the dryer.

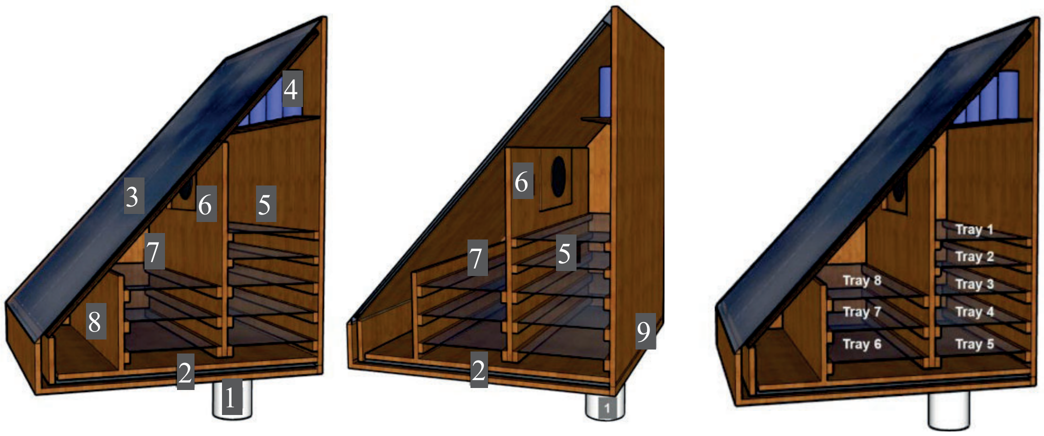

Figure 1: Different parts of the solar dryer. Left and middle illustrations show the different parts while the right picture shows the numbering of the trays.

The heat exchanger consists of two channels for air flow separated by a thin MS sheet. The heat exchanger is visible in both Figure 1 and Figure 2. The black painted metal absorber is approximately 1.5 m² large. The collector part of the dryer is a double pass collector meaning that the air can pass both in front of the absorber and on the back of the absorber. This increases the heat transfer area between solar heated absorber and air. After passing the absorber the air is let through a heat storage section. Here it is possible to place plastic bottles filled with water. The idea with the heat storage is to reduce the maximum temperature in the dryer as well as to prolong the drying time as the sun sets. Reducing the temperature can be beneficial depending on produce and temperature level. After the heat storage the air is let into the drying chamber. Here the air passes over several trays where the produce has been placed. As the air passes over the trays the hot air is cooled down as its energy is spent on evaporation and heating/drying the produce. Furthermore, as the air picks up moisture from the produce it also increases its relative humidity. This could lead to an uneven drying rate between the trays as the first tray in the airflow direction receives hot and dry air while the last tray receives considerably colder and wetter air. One way to even out this problem is to recirculate the air using an internal fan(s). This fan has the potential to short circuit the temperature and humidity levels inside the dryer at the same time as it increases the air speed in the drying chamber without pushing more air through the entire dryer. Different fans and different control strategies for the fans were tested and evaluated as part of this evaluation. Figure 2 shows the anticipated airflow from different fan configurations. Figure 2A illustrates the airflow without an internal fan. Similarly figure 2B and 2C illustrate the use of a larger forward fan, a single reversible fan and double reversible fans. All four cases were tested: no fan, forward fan, reversible fan and double reversible fans. The reversible fans switch direction every minute, resulting in an airflow pattern shown in case C of Figure 2. The last step before the air is let out of the dryer is to recover parts of the heat that remains in the air after the drying process via the heat exchanger.

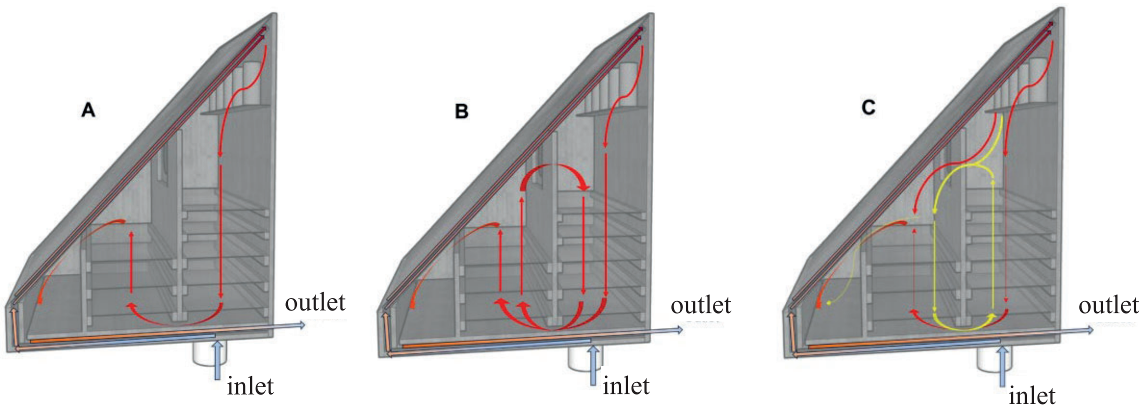

Figure 2: Air flow anticipated from different fan set-ups.

All cases were measured by individually weighing trays 1-8, as illustrated in Figure 1 to assess uneven drying. For comparison, drying was also carried out in open air and with a solar dryer previously tested at the same location during earlier development work. This slightly different solar dryer was tested by C. Rissler (2023) and by Aacharya et al. (2024a, 2024b)

Measurements were taken on the drying rate of chili put in the dryer. Each tray in the dryer was loaded with 300 g of chili. The weight of the chili was then measured and recorded at 8:00, 13:00, and 18:00. To calculate the drying rate, defined as-the weight loss per unit chili surface area per hour, where the surface area of the dried chili had to be estimated. This was done by randomly picking 116 chilies making a total weight of 300 g. The surface area per chili was estimated by measuring length and diameter of the chili. The surface area of the chili was assumed to remain constant throughout the drying period.

A Campbell Scientific CR 1000 logger and Campbell Scientific AM16/32 multiplexer was used to record measurement data. Thermocouples were used to measure the temperature in the dryer while four Campbell Scientific HygroVUE Digital Sensors were used to measure the relative humidity. A Kipp & Zonen CMP3 pyranometer was placed on the absorber to measure the solar radiation levels.

The efficiency, ε, of the heat exchanger is calculated using eq. 1 and eq. 2.

$$\varepsilon_c = \frac{(T_{c,out} - T_{c,in})}{(T_{h,in} - T_{c,in})} \qquad \text{(eq. 1)}$$

$$\varepsilon_h = \frac{(T_{h,in} - T_{h,out})}{(T_{h,in} - T_{c,in})} \qquad \text{(eq. 2)}$$

where T is for temperature, the subscript c is for the cold side, h is for the warm side, in is for inlet side and out is for the outlet side.

In principle ε_c and the ε_h should be the same. However, leakage in the dryer can lead to higher inlet flow than outlet flow. This leakage can be quantified by calculating the ratio between the flow on the hot side and cold side. This can be done by measuring the temperature difference between the warm side and the cold side according to eq. 3.

$$\frac{\dot{m}_h}{\dot{m}_c} = \frac{\Delta T_c}{\Delta T_h} \qquad \text{(eq. 3)}$$

Here, $\dot{m}$ is the mass rate, ΔT is the temperature difference. The subscript c is for the cold side, h is for the warm side.

The efficiency, η, of the collector is calculated using eq. 4

$$\eta_a = \frac{\dot{m} \cdot c_p \cdot (T_{a,out} - T_{a,in})}{G \cdot A_a} \qquad \text{(eq. 4)}$$

where c_p is the specific heat of air, G is the solar irradiation, A_a is the absorber area and the subscript a is for the absorber.

3. Results

Measurements on the efficiencies, ε_c and ε_h are presented in Figure 3. The red curve and the blue curve represent hot and cold efficiencies. The yellow curve represents the ratio between the temperature difference on the cold side and the temperature difference on the warm side. The average leakage was measured to be 31 %.

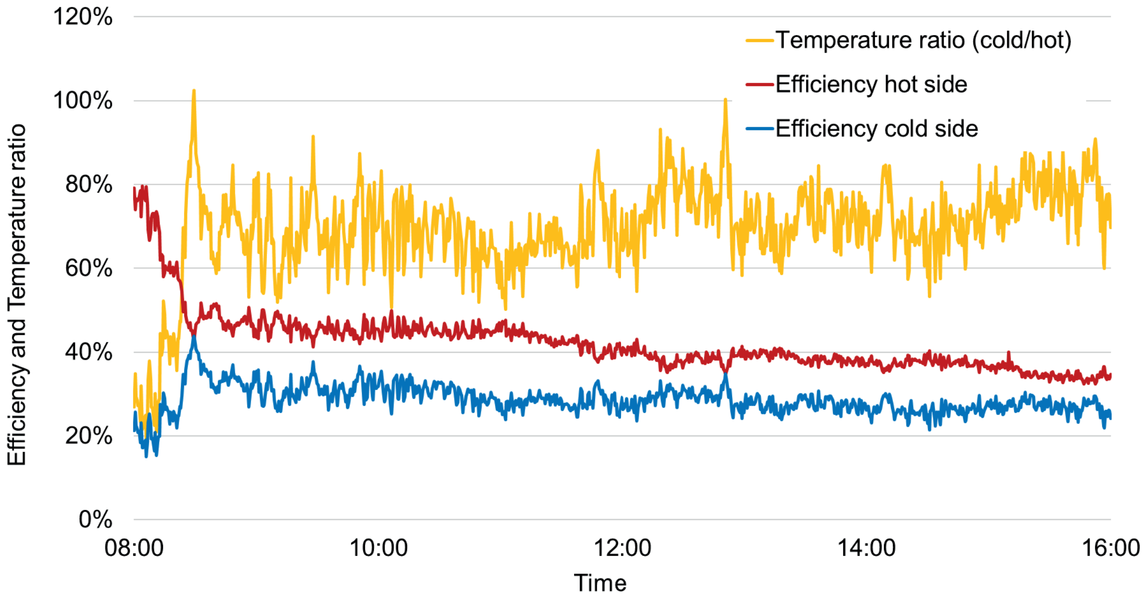

Figure 3: The blue and the red curves show the efficiency as a function of time for the cold side and the warm side of the heat exchanger. The yellow curve shows the ratio between temperature difference on the cold side to the temperature difference on the warm side.

Figure 4 shows the temperature variation on the cold and warm sides of the heat exchanger represented by the blue and orange curves respectively.The heat exchanger recovers approximately 4 °C to 5 °C during the test period.

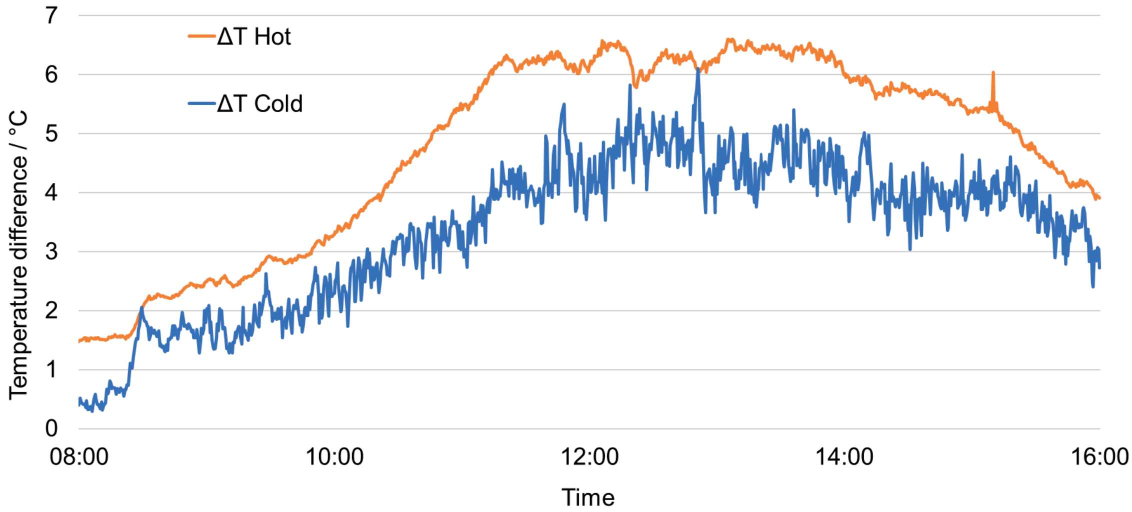

Figure 4: Temperature variation on cold and warm side of the heat exchanger.

The solar radiation and the efficiency of the absorber are shown in Figure 5. The unreasonably high efficiency is due to temporary shading of the pyranometer. The efficiency of the solar collector is approximately 50 %.

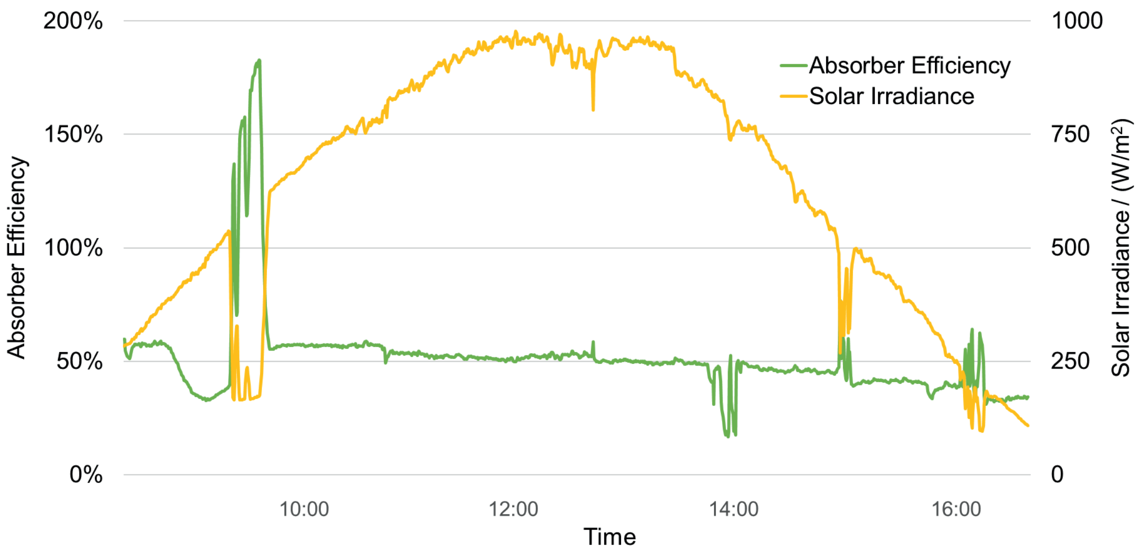

Figure 5: Solar irradiance in yellow and the efficiency of the absorber in green.

The temperature increase in the collector part is shown in Figure 6. Around midday the temperature increases somewhere between 20 °C to 25 °C.

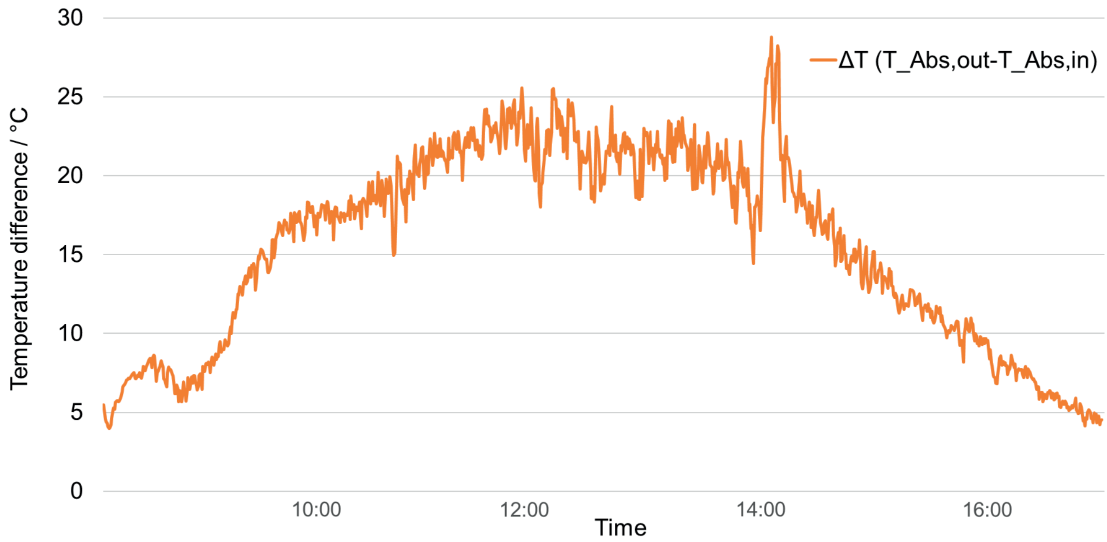

Figure 6: Temperature increase in the collector as a function of time.

Figure 7 shows the weight reduction of the chili as a function of time. The night between the two days of drying is indicated with a grey background. The weight reduction was measured also during this time. Figure 7 shows six different measurements. The anticipated airflow pattern for the different fan setups are shown in Figure 2. Results from the open air drying are shown with light blue color. Seen over the entire measurement period, this case had the lowest weight reduction. Weight reduction using the old dryer is shown in green color. Four different fan setups were used for the new dryer design. Measurement from not using an internal fan is presented in dark blue color. Using one fan in forward direction is presented in orange while using one or two reversible fans are shown in grey and in yellow. The new dryer is approximately eight hours faster than the old dryer in drying the product. However, it should be mentioned that the results from the measurements shown in Figure 7 are averages over multiple days. This means that each measurement in the graph is made up of multiple days of measurements. For instance, the "No Fan" is not only one day measurement but rather many days taken together to form an average drying rate. The weight reductions during nighttime presented in Figure 7 are averaged from four different cases of storages of the chilis during the night. The different storages are presented in Table 1. This means that the nighttime drying rates for the cases are averages of the four different storage alternatives presented in Table 1. In one of the cases the internal fans were kept off and in one of the cases there was a small heat storage made of water filled plastic bottles placed inside the dryer. As can be seen the differences in drying rate for the four different cases are small.

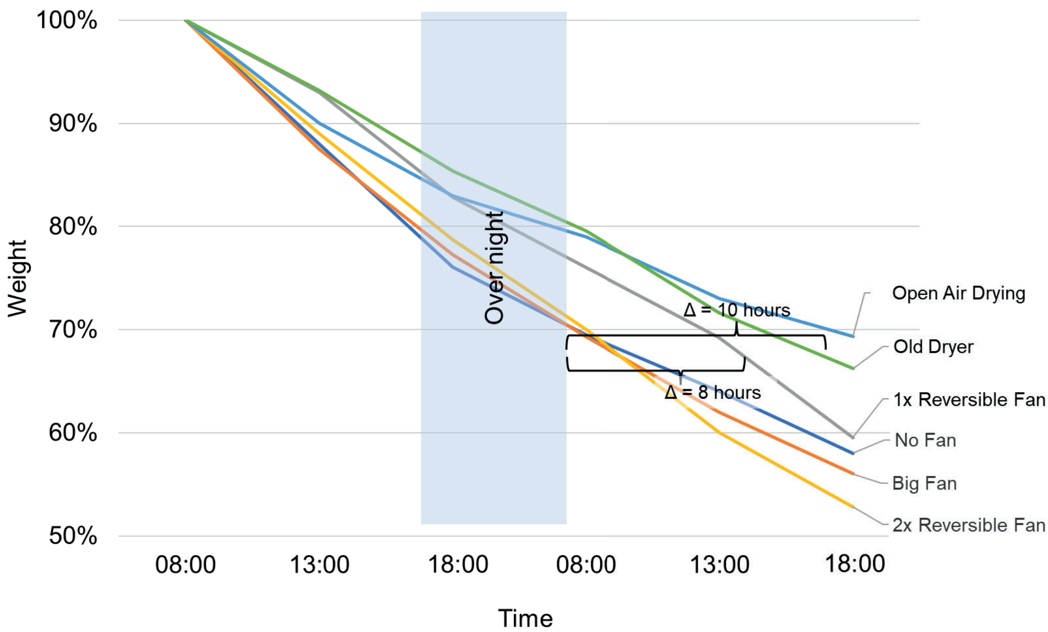

Figure 7: The graphs show weight reduction over two days of solar drying. Nighttime is indicated with grey background.

Table 1: Weight reduction through different storage overnight. The case "Outside dryer" had the chili trays placed in a plastic bag.

Case	Location of trays		Internal fan		Heat storage		Weight reduction during night
	Inside dryer	Outside dryer	On	Off	Yes	No	
1		X					7 %
2	X			X		X	6 %
3	X		X			X	6 %
4	X		X		X		5 %

Figure 8 shows the total degree of drying after two days. The cases are from left, no fan, big fan, one reversible fan and to the right is the case with two reversible fans. Drying chili on five different trays is shown for each case. The tray with the best and the worst results of dried chili in each is indicated using a crown for the best tray and a thumbs down for the worst case. The difference between the best and the worst cases is indicated on the top of each graph. The most uniform drying was achieved with a single large fan operating in forward direction, whereas the least uniform drying occurred in the absence of a fan.

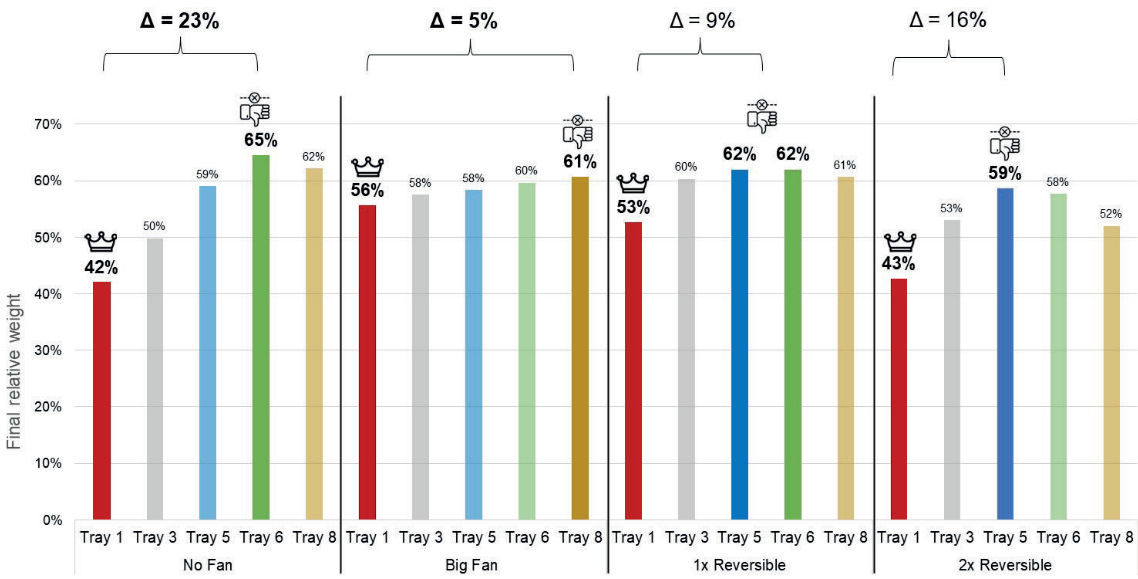

Figure 8: Weight after two days drying for all four cases. Five different individual trays are shown per test case.

Figure 9 shows a comparison between two cases where the solar dryer is loaded with different amounts of chili. The results presented using a blue line is for the case where five trays with 300 g of chili per tray have been placed in the dryer. The result shown with a green line is for putting eight such trays, each with 300 g chili, in the dryer. As shown, the total weight loss is higher for the case with eight trays. However, the drying is faster per tray using only five trays rather than the eight trays.

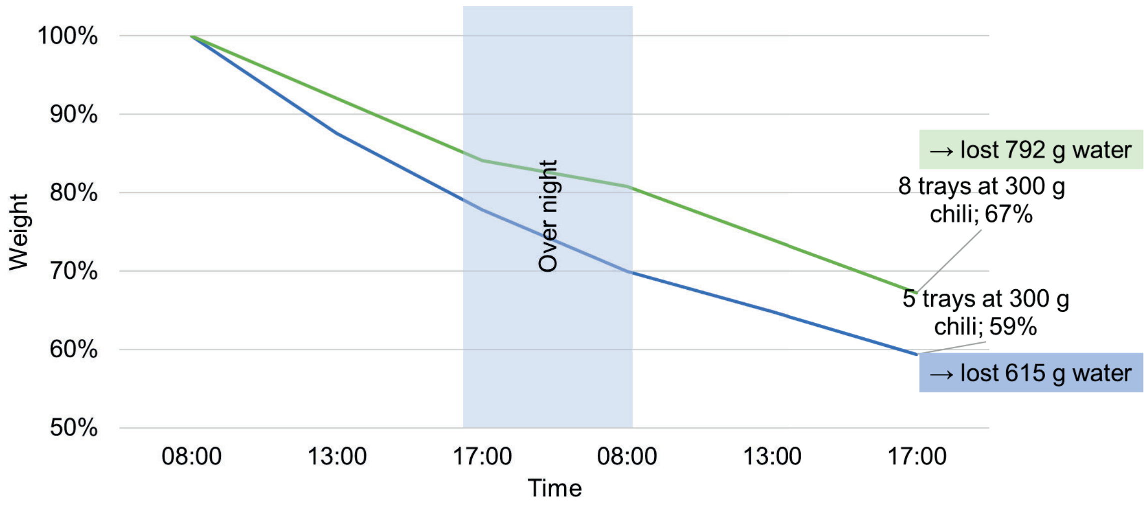

Figure 9: Fraction of starting weight as a function of time. Results from measurements with five trays in the dryer are shown with a blue colored line and with eight trays in the dryer using a green colored line.

Figure 10 represents weight reduction measurements for a period of four days. The red line represents the weight as a function of time, while the bars indicate the average drying rate during the indicated timeframe. The orange bars represent the drying rate during daytime while the grey bars represent the drying rate during nighttime. As shown, the drying rate remains relatively constant during the first three days. However, the drying rate begins to decline on the fourth day.

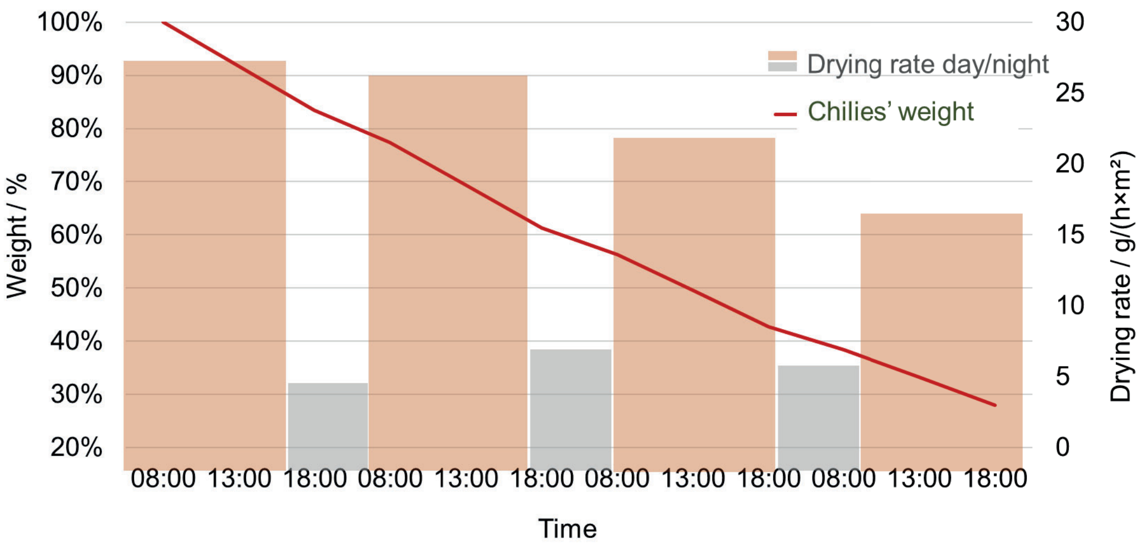

Figure 10: Fraction of starting weight as a function of time on the primary y-axis and drying rate as a function of time on the secondary y-axis.

Figure 11 shows photographs of chilies after four days drying. Browning of the chilies is low at the same time that colors are preserved. The left photo shows chilies placed on one of the trays used for drying.

Figure 11: Photography of chili after four days drying.

4. Discussion

The heat exchanger efficiency was evaluated showing approximately 30 % to 40 % efficiency. This can be compared to the efficiency of the collector of approximately 50 %. At first glance it looks like the heat exchanger is as important as the absorber. However, the actual temperature rise in the heat exchanger is approximately 5 °C, which is much less compared to the temperature rise in the absorber of approximately 20 °C to 25 °C. The reason for this is that the temperature of the air inside the drying chamber gets reduced as moisture is evaporated and transfers into the air. Therefore, even if the heat exchanger works well considering efficiency, the use of it is still limited due to the low temperature in the outgoing air from the drying chamber. However, the usefulness of the heat exchanger could vary depending on what produce is being dried. Drying leafy vegetables will differ considerably compared to drying wet fruits like watermelon. The more water available the lower the temperature and thus the lower the usefulness will be.

Results presented in Figure 7 show that the newly developed solar dryer, see Figure 2 for illustration, clearly performs better than the earlier version. Considerable time can be saved with this newer version. However, time saving as such is not the only benefit. Shortening the drying time means that the risk of getting mold on the food is reduced. The results presented in Table 1 show that the drying that happens during the night is a considerable contribution to the drying process. However, the different test cases showed small differences among each other. The results presented in Figure 8 show that using a big fan in the forward direction could reduce the uneven drying rate. Figure 8 shows that it's preferable to push more air rather than to change the direction of the fan. This conclusion could in principle change if produce other than chillis are used. If a wet produce, giving more moisture to the air, is used then changing direction could be preferable. However, for the investigated case with chili, the larger fan showed the most promising result. The results from Figure 9 show that the drying time could become considerably longer if the drying chamber is filled to a higher degree with produce to be dried. Figure 9 clearly shows that the drying time will be extended for higher loads. However, the total weight reduction is higher for higher loads. Thus, it will be faster to dry one batch with double load compared to drying single loads in two separate batches. The degree of unevenness was not tested for increased load. Figure 10 shows that the drying rate is almost constant even after three days. However, during the fourth day the drying rate is reduced. This typically happens when the produce dries on the surface and only water in the interior parts in the produce is left. That gives extra resistance to the drying and this lower drying rate.

5. Acknowledgments

The authors are grateful to The Swedish Research Council for funding the project "SolarFood: Reducing post-harvest losses through improved solar drying" with reference number 2020-04071.

The authors would like to express our sincere gratitude to Jigme Namgyel Engineering College, Royal University of Bhutan and Lund University, Sweden for providing the facilities and support necessary to carry out this research.

The authors are also grateful to carpenters from Jigme Namgyel Engineering College for their technical assistance and collaboration during the experimental work.

6. References

N.Chhogyel, L. Kumar, 2018. Climate change and potential impacts on agriculture in Bhutan: a discussion of pertinent issues. Agriculture & Food Security 7, 79. https://doi.org/10.1186/s40066- 018-0229-6

Ananta Aacharya, Christian Rissler, Bivek Baral, Tshewang Lhendup, Martin Andersson, Henrik Davidsson, Development of a novel solar dryer with an incorporated heat exchanger, Solar Energy Volume 269, February 2024, 112327, https://doi.org/10.1016/j.solener.2024.112327

Ananta Aacharya, Henrik Davidsson, Bivek Baral, Martin Andersson, Investigation of thermodynamics performance of a heat exchanger-incorporated solar dryer equipped with double-pass flat, v-corrugated, and low-e coated collectors for drying applications, Case Studies in Thermal Engineering Volume 64, December 2024, 105482, https://doi.org/10.1016/j.csite.2024.105482

P. Kumar, D. Singh, Advanced technologies and performance investigations of solar dryers: A review Renew. Energy Focus, 35 (2020), pp. 148-158, https://doi.org/10.1016/j.ref.2020.10.003

Henrik Davidsson, Tandin Jamtsho, Dechen Om, Martin Andersson, Evaluation of an Indirect Solar Dryer with Integrated Heat Exchanger, Eurosun 2024, https://proceedings.ises.org/conference/eurosun2024/papers/eurosun2024-0087-Davidsson.pdf

Lara Constanze Müller, 2024, Enhancing Post-Harvest Preservation through Improved and Even Solar Drying: A Case Study in Bhutan, LUTMDN/TMHP-24/5581-SE, ISSN 0282-1990 https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=9165837&fileOId=9165846

Christian Rissler, 2023, Mitigating Post-Harvest Losses in Bhutan through Solar Food Drying: Optimization and Analysis, id 9124967, https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=9124967&fileOId=9124974

Ananta Aacharya, Henrik Davidsson, Bivek Baral, Martin Andersson, Investigation of thermody-namics performance of a heat exchanger-incorporated solar dryer equipped with double-pass flat, v-corrugated, and low-e coated collectors for drying applications, Case Studies in Thermal Engineering, Volume 64, December 2024, 105482, https://doi.org/10.1016/j.csite.2024.105482

Ananta Aacharya, Christian Rissler, Bivek Baral, Tshewang Lhendup, Martin Andersson, Henrik Davidsson, Development of a novel solar dryer with an incorporated heat exchanger, Solar Energy, Volume 269, February 2024, 112327, https://doi.org/10.1016/j.solener.2024.112327