Solar Energy Advances 1 (2021) 100006

Contents lists available at ScienceDirect

Solar Energy Advances

journal homepage: www.elsevier.com/locate/seja

Combined solar and membrane drying technologies for sustainable fruit preservation in low-income countries – prototype development, modelling, and testing

Ricardo Bernardo[*], Henrik Davidsson, Peter Samuelsson, Gustaf Bengtsson, Viktor Döhlen, Joakim Olsson, Randi Phinney, Pia Otte, Lucas Tivana, Martin Andersson, Marilyn Rayner

Energy and Building Design, Architecture and Built Environment, Sövegatan 24, P.O. Box 118, 221 00 Lund, Skåne, Sweden

ARTICLE INFO

Keywords:
Solar drying
Fruit preservation
Membrane drying
Low-income countries

ABSTRACT

This investigation consisted of developing and evaluating solar dryers together with semi-permeable membrane pouches for drying juicy fruits in low-income tropical countries.

Two design iterations were carried out including prototype modelling and testing. The latest developed solar dryers were a passive and an active solar dryer. Modelling was initially carried out mathematically using an equation solver software followed by computational fluid dynamics. Preliminary measurements were carried out on a small-scale solar dryer. Thereafter, full-scale models were developed and tested, both in laboratory and in real conditions in Mozambique.

Results from modelling were validated against measurements in laboratory in Sweden and field trials in Mozambique. Prototype building and testing in Mozambique was undertaken in collaboration with local farmers and a university. Measurement results show that the dryers help to prevent microbial growth through increased temperatures. The drying flux was increased by 50% for the passive, and by 100% for the active solar dryers compared to the ambient controls that did not use a solar dryer. The total drying time was below four days for all pouches in the dryers. The active solar dryer was shown to have the shortest drying time and the highest capacity (more pouches) but also the highest costs.

Mould growth and juice fermentation were observed on control pouches drying in open air. These problems were solved with the use of solar dryer technology. However, some challenges with the membrane pouches require further development including degradation of the membrane when exposed to direct sunlight.

Introduction

Relevance

Enough food is grown in many low-income countries to satisfy the needs of the population. One such country is Mozambique. Despite this, many people still go hungry. One reason for this is because large amounts of fruit ripen during a very short period, which means that much of the uneaten fruit spoils before reaching the end consumers. In Mozambique, post-harvest losses are estimated to be 25-40%, with this estimate only accounting for harvested fruits [1]. Since some fruits are never harvested, the total amount of spoiled fruit would be even greater. Canning and aseptic processing are two options for preservation, but they are often not feasible unless carried out on a large scale. They also require large energy inputs, large capital investments and a transport infrastructure, which are often not available in low-income countries. Several studies have identified the need for a simple and affordable fruit processing technology that can safely preserve fruits close to the harvest point when the fruit is ripe [2–7]. Solar dryers that can be used at large scale for a large variety of agricultural products would greatly benefit small and marginal farmers [2].

Traditional fruit dehydration methods and solar assisted drying

Food has been preserved with drying and dehydration methods for thousands of years. Reducing the amount of available moisture in a product has two effects: pathogenic and spoilage microorganisms are no longer able to grow, and the nutritional value of the food is conserved.

Existing small-scale dehydration methods include oven drying; wood, charcoal or diesel burning evaporators; osmotic dehydration; and open-air sun drying. Oven dryers require an expensive energy source (i.e. electricity or gas) and contribute to CO_2 emissions. Wood, charcoal, or diesel burning evaporators also contribute to the release of CO_2

---

[*] Corresponding author.
E-mail address: Ricardo.Bernardo@ebd.lth.se (R. Bernardo).

https://doi.org/10.1016/j.seja.2021.100006
Received 19 February 2021; Received in revised form 5 October 2021; Accepted 6 October 2021

Nomenclature

$Aabs$	Collector absorber area (= glass area) m^2
$Abag$	The effective area for evaporation of a SAP-pouch m^2
$Abags$	Total effective evaporation area of SAP-pouches per shelf m^2
$Aeff$	Effective cross section area for the dryer air flow m^2
$Ainlet$	Collector inlet area m^2
$Asides$	Collector side area m^2
aw	Water activity no units
CP, air	Specific heat capacity for air J/(kg•K)
$CP, H2O$	Specific heat capacity for steam J/(kg•K)
DH	Hydraulic diameter of the collector m
$Evap$	Total power required for evaporation for all SAP-pouches placed on a shelf in the dryer W
G	Total solar irradiation W/m^2
Ge	Effective solar irradiation (heat absorbed by the absorber) W/m^2
$hcon, in$	Heat transfer coefficient for internal convection W/(m^2•K)
$hcon, out$	Heat transfer coefficient for external convection W/(m^2•K)
$hrad, in$	Heat transfer coefficient for internal radiation W/(m^2•K)
$hrad, out$	Heat transfer coefficient for external radiation W/(m^2•K)
mh	Water mass flow kg/s
$mvap$	Water mass flow from SAP-pouch kg/s
n	Number of bags per shelf in the dryer no units
Nu	Nusselt number for uniform surface heat flux no units
$Prair$	Prandtl number for air no units
Pw	Vapour pressure for water Pa
Pws	Water saturation pressure Pa
$Rabs$	Absorber reflectance no units
$Reair$	Reynolds number for air no units
$Rglass$	Glass reflectance no units
RH	Relative humidity no units
RV	Specific gas constant for water vapour J/(kg•K)
S	Number of shelves in the dryer no units
$Tabs$	Absorber temperature in the collector K
$Tair$	Mean temperature of Tin and $Tout$ K
$Tamb$	Ambient temperature K
$tbottom$	Bottom insulation thickness m
$Tglass$	Glass temperature in collector K
Tin	Inlet temperature for a section K
$Tout$	Outlet temperature for a section K
$tside$	Side insulation thickness m
$Tsky$	Sky temperature K
$Twall$	Wall temperature of dryer K
$Twall$	Outer wall temperature in the collector K
$Twall, in$	Inner wall temperature in the dryer K
$Twall, out$	Outer wall temperature in the dryer K
$uair$	Collector inlet air velocity m/s
$ubags$	The air velocity surrounding the SAP-pouches m/s
X	Air constant ($\rho air \bullet CP, air \bullet uair \bullet Ainlet$) W/K
X	Air constant ($\rho air \bullet CP, air \bullet uair \bullet Ainlet$) W/K
z	Additional heat gains for the outer walls of the dryer W/m^2
αabs	Absorber absorbance no units
$\Delta hvap, H2O$	Enthalpy of vaporization for water J/kg
εabs	Absorber emissivity no units
$\varepsilon glass$	Glass emissivity no units
$\varepsilon wall$	Collector outer wall emissivity no units
$\varepsilon wall, dryer$	Dryer outer wall emissivity no units
λair	Air thermal conductivity W/(m•K)
$\lambda bottom$	Collector bottom insulation thermal conductivity W/(m•K)
$\lambda side$	Collector side insulation thermal conductivity W/(m•K)
$\lambda wall$	Dryer wall thermal conductivity W/(m•K)
μair	Air dynamic viscosity kg/(m•s)
ρair	Air density kg/m^3
σ	Stefan-Boltzmann constant W/ (m^2•K^4)
$\tau glass$	Glass transmissivity no units

and have a time and/or economic burden. Open-air sun drying of food is a preservation method widely used in developing countries as part of local ancient traditions but also has a significant limitation. It is not suitable for preserving juicy fruits because 1) it is difficult to handle large open trays of liquid and 2) juices/purées dried in open trays attract dust, insects and pests and are therefore easily contaminated by microorganisms and toxins as a result of the product being directly exposed to the environment [4].

In addition to open-air sun drying, two solar assisted food processing applications are solar drying and solar cooking. There are numerous types of solar dryers ranging from simpler greenhouse types to complex solar dryers that use heat exchangers and large solar storages [2, 4, 5, 8]. Its applicability goes beyond food processing such as drying cement mortar for building applications [9]. Solar dryers are normally divided into two main categories: passive or natural-circulation and active or forced convection [8]. Since they are susceptible to weather changes, hybridization is often needed, i.e., combination with backup energy sources that uses solar energy to decrease its consumption. A recent review article identified five categories of hybrid solar dryers: hybrid thermal storage-solar dryer, hybrid heat pump–solar dryer, hybrid biomass–solar dryer, hybrid solar with novel drying techniques, and hybrid photovoltaic solar dryers [7]. These type of dryers provide better control over drying conditions and can be used on a wider range of agricultural products [7]. Efficiency and cost vary significantly depending on the technology [10].

Solar cooking is used to prepare food in real time. One of the most well-known solar cooking technologies is the Scheffler collector that consists of a parabolic reflector concentrating solar radiation towards a cooking pot [11]. The reflector needs to be constantly adjusted to follow the sun during the day and when the sun is not available, fuel is normally used instead [12].

Even though these techniques have been developed and tested for decades, the development in solar food processing has been limited. Two of the main reasons are the necessity of hybridization (combination with backup fuel) and acceptance by the end-users [13]. Hybridization implies technical complexity and high investment costs, which are major hindrances in developing countries [4, 12]. Also, backup fuels and infrastructure are not available in many cases.

Solar drying technology is most commonly used to further improve traditional drying techniques with fruits, such as open-air drying of raisins, dates, figs, mangoes, etc [2–6]. However, solar drying of a large range of juicy fruits such as oranges, tangerines, lemons, and grapefruits, are not commonly described in literature. Furthermore, investigations of solar dryers are frequently either experimental [2, 6, 14, 15] or theoretical [16, 17] lacking an integrated approach to the design process. Additionally, literature identifies the need for further research on efficient designs at low costs [4, 8, 10].

Earlier studies on the implementation of solar energy technologies, such as solar cookers, in developing countries, have shown that there are also multiple non-technical factors that strongly influence the adoption of these technologies [18–20]. These can be, for example, an inappro-

Fig. 1. Left: schematics of the solar assisted pervaporation process. Middle: membrane pouches before drying. Right: final product (jam) after drying on the far right.

priate time-schedule for cooking or changes in the social organization [21]. The quality of the final product in terms of sensory quality (taste, aroma, colour and acceptability of the dried fruit products) and nutritional composition of the dried fruit products are also important factors for larger acceptance in the market [6].

Solar assisted pervaporation (SAP)

Solar Assisted Pervaporation (SAP) involves the use of a pouch or sealed bag made of a food-grade breathable membrane (i.e. permeable to water vapour but not liquid water) to concentrate fruit juices/purées with the help of solar radiation and ambient air [22]. The SAP technique is related to the separation process pervaporation, with the mass transport driven by the difference in partial pressure of water vapour in the fruit juice/purée to the partial pressure of water vapour in ambient air [23,24]. The phenomenon of pervaporation was first documented by Kober in 1917 [25]. If the relative humidity (RH) in the surrounding air is unsaturated, there will be a chemical potential gradient across the membrane, allowing for the diffusion of water vapour to occur. The driving force can be increased even further by heating the air around the bag (e.g. with a solar collector). The membrane pouch allows water to evaporate but protects the juice from contamination. Fig. 1 illustrates the SAP process and the product before and after drying. If the amount of water in the juice decreases below a certain level, the juice concentrate becomes storage stable for up to a year, i.e. due to a low water activity that prevents microbial growth [26, p. 2]. The final product can then be consumed as jam or re-hydrated again into nutritious fruit juices.

Although promising, the SAP method used in open air drying does not reach high enough temperatures to decrease the risk of microbial growth in the product. Furthermore, the drying time is relatively long. These are crucial factors for the successful practical implementation of the process. In short, controlling the drying parameters around and inside the pouches - air temperature, relative humidity, fruit temperature and air flow - is critical to make the method safe and practically feasible [26,27].

Purpose and scope

The main purpose of the project behind this article was to investigate the combination of solar collector technology with the SAP pouches described above, using Mozambique as a case-study. The investigated solution consisted of adapting and combining solar collector technology that produces solar heat with semi-permeable membrane pouches for drying and thus preserving and utilizing juicy fruits in developing countries to a higher extent than today. The final product of the drying is a shelf-stable fruit marmalade or juice concentrate that can be later consumed or sold for up to one year. The SAP pouch technology is innovative and therefore not as developed as solar dryers. This article contributes to the testing of SAP pouches in combination with newly developed solar dryers.

The investigation followed an integrated transdisciplinary research approach that is able to include diverse sets of knowledge relevant for the design of user-friendly solar dryers [28]. The project consisted of an interdisciplinary research team with backgrounds from solar energy technology, food technology and social sciences with previous research experience in Mozambique. Furthermore, the project worked with two farmer associations in an iterative process throughout the research process. The project included 3 phases of fieldwork in Inharrime district between 2016 and 2019.

In the first phase the project started by assessing local fruit drying traditions and practices of the communities, existing know-how, culture, and routines [2]. This assessment was carried out by engaging groups of farmers in participatory exercises to identify their needs and preferences related to solar fruit drying [29]. Furthermore, the importance of gender roles and relationships were also assessed in the scope of technology development and implementation [30]. In parallel, the food technology investigation focused on factors affecting food safety risk and quality. This was carried out by evaluating the drying flux [27, p. 1], [31] and microbiological quality [26, p. 2] of the fruit juices in membrane pouches for several drying conditions. These results were then used as input for the technology development in the form of several design criteria that were tested in phase 2 and then modified and implemented in phase 3.

This paper focuses on the solar technology part of the research namely the development, modelling, and testing of solar dryers, in laboratory and in real conditions. To grasp the complete technology development and testing, the current paper comprises findings from several master theses [32–35].

Methods

Since the farmers participating in this study did not have any experience on solar drying, careful selection of the methodology was needed for successful adoption of the technology. To avoid a “technical push” the selected workflow was to start with a social investigation including participatory research exercises [29, 30]. This approach allows for an active involvement of the farmers instead of treating them as passive recipients [36]. Together with food technology investigations, the design criteria for the solar dryers were established (Fig. 2). Two design iterations for solar dryer prototypes were carried out. For each of the two design phases, models and measurements were performed. Modelling was carried out mathematically and using advanced computational fluid dynamic tools. Results from modelling were validated against measurements in laboratory in Sweden and in rural areas in Mozambique. Prototype building and testing in Mozambique was undertaken in collaboration with local farmers and a university. Finally, the performance of the solar dryers was evaluated. Results from the first design influenced the second design. Fig. 2 illustrates the workflow of the entire study. The influence of several design criteria in the drying were analysed during this study: direct/indirect solar radiation; passive or active driven solar dryer; air flow and velocity; temperature levels; drying time for storage

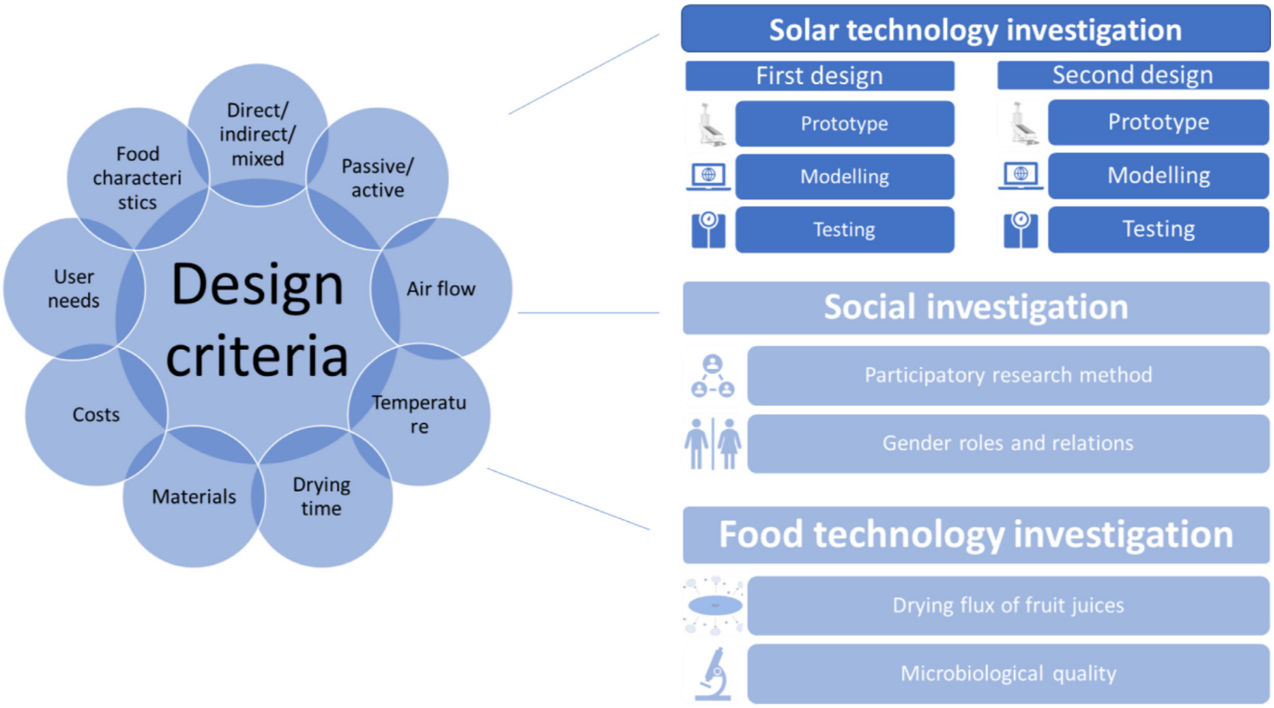


Fig. 2. Illustration of the workflow of the whole investigation. This paper focuses on the solar technology investigation.

Table 1
Dimensions of the miniature indirect solar dryer used for preliminary tests.

Collector Parts	Dimensions (m)
Length, l	0.700 m
Outer width, w	0.424 m
Width absorber plate, w_a	0.376 m
Width glass, w_g	0.376 m
Height collector, h_c	0.082 m
Distance absorber glass, h_{ag}	0.035 m
Height heat storage, h_{hs}	0.035 m
Thickness absorber, t_a	0.012 m
Thickness glass, t_g	0.003 m
Drying cabinet parts	Dimensions (m)
Height, h_{dc}	0.500 m
Width, w_{dc}	0.400 m
Depth, d_{dc}	0.200 m

stable product and drying flux; materials used in the prototypes; costs for two prototypes.

First design

Prototype design

Preliminary trials of a small-scale solar dryer were made. The goal was to get a practical understanding of the drying process of the membrane pouches inside a conventional solar dryer. More specifically, the small-scale solar dryer was intended to identify the most relevant parameters influencing the drying process of the pouches. An indirect solar dryer was chosen since it was uncertain whether the membrane pouch would resist direct sunlight and high temperatures. To simplify the test procedure at the very beginning of the investigation, water was used inside the pouches instead of fruit juice. The small-scale indirect solar dryer and the membrane pouches filled with water are illustrated in Fig. 3 and Fig. 4, respectively. The corresponding dimensions are illustrated in Table 1.

The solar dryer consists of two main parts: the solar collector and a drying cabinet. The solar collector consists of a glass pane on the top, insulation on the sides and the bottom and an absorber plate on top of the bottom insulation layer. The absorber plate consists of a simple plywood painted black. The drying cabinet is insulated on the sides and contains shelves with pouches. The air gets heated in the solar collector and rises by natural convention into the bottom of the drying cabinet. At the outlet of the drying cabinet moist air is released.

Modelling

The previously described solar dryer prototype was mathematically modelled and analysed using an equation solver software [37]. The goal at this stage was to build a deeper understanding of the critical design features of the solar dryer to consider when improving the drying process. Based on this model, the design of the solar dryer was improved. An illustration of the modelled solar dryer is shown in Fig. 5. The modelled energy flows and temperatures in the solar collector and drying cabinet are illustrated in Fig. 6 and Fig. 7, respectively.

To limit the complexity of the numerical equations some assumptions were made. The most important were: the collector and dryer were assumed in steady state for constant solar irradiation; no air leakages; the temperatures of the pouches were assumed equal to the surrounding air temperature and that the bags do not dry out (constant part of the dry rate); the inner sides of the collector do not reflect any radiation; no

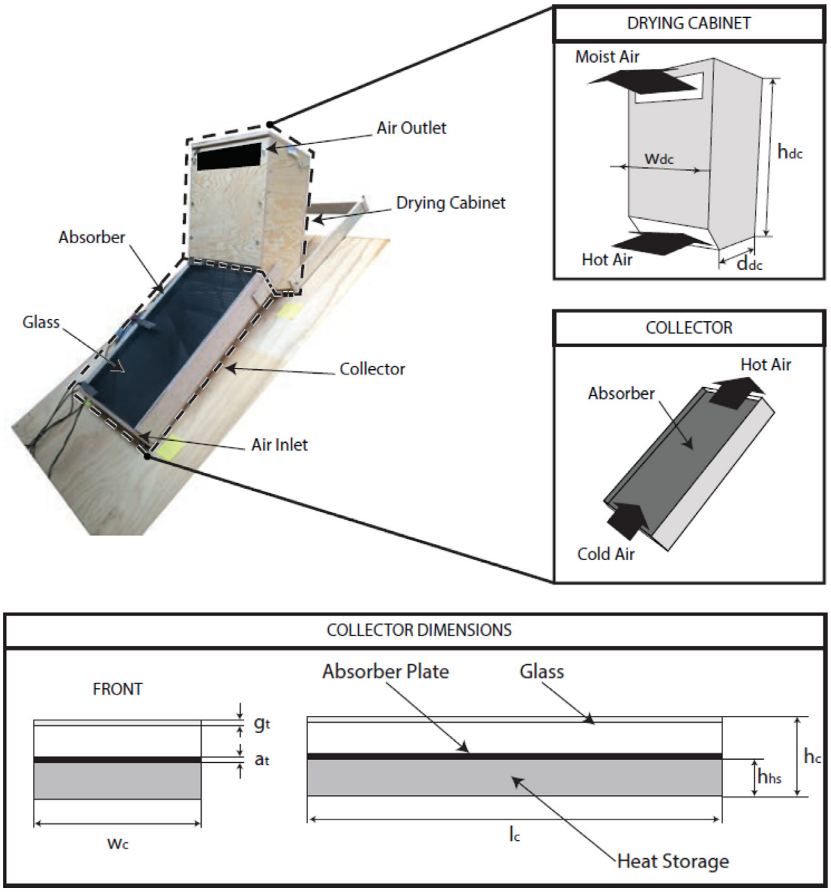


Fig. 3. Miniature indirect solar dryer used for preliminary tests.

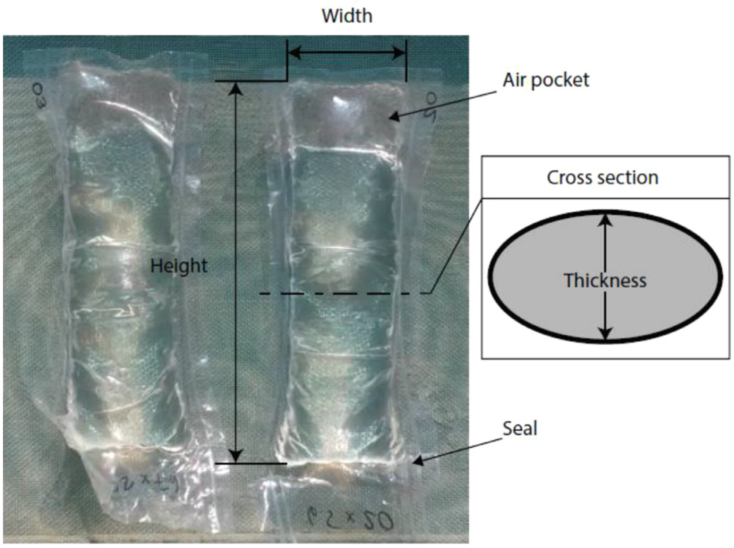


Fig. 4. Membrane pouches filled with water for preliminary tests.

heat transfer was taken into consideration between pouches; the glass does not absorb any sunlight ($\alpha_{\text{glass}} = 0$).

The modelling procedure resulted in four energy balances to be solved for four variables. The energy balances correspond to the glass cover in Equation 1, the air flow in Equation 2, the absorber in Equation 3, and the outer walls in Equation 4. The variables are T_{out}, T_{glass}, T_{abs} and T_{wall}. The whole procedure is described in detailed in [38].

Equation 1. Energy balance of the glass cover.

$$h_{con,in} \cdot A_{abs} \cdot \left(\frac{T_{in}+T_{out}}{2} - T_{glass} \right) + h_{rad,in} \cdot A_{abs} \cdot \left(T_{abs} - T_{glass} \right)$$
$$- h_{con,out} \cdot A_{abs} \cdot \left(T_{glass} - T_{amb} \right) - h_{rad,out} \cdot A_{abs} \cdot \left(T_{glass} - T_{sky} \right) = 0$$

Equation 2. Energy balance of the air flow.

$$h_{con,in} \cdot A_{abs} \cdot \left(T_{abs} - \frac{T_{in}+T_{out}}{2} \right) + h_{con,in} \cdot A_{sides} \cdot \left(\frac{T_{abs}+T_{glass}}{2} - \frac{T_{in}+T_{out}}{2} \right)$$
$$- h_{con,in} \cdot A_{abs}$$
$$\cdot \left(\frac{T_{in}+T_{out}}{2} - T_{glass} \right) - (T_{out} - T_{in}) \cdot \rho_{air} \cdot Cp_{air} \cdot u_{air} \cdot A_{inlet} - (T_{out} - T_{in})$$
$$\cdot Cp_{H2O} \cdot m_h - h_{con,out} \cdot A_{abs} \cdot \left(T_{glass} - T_{amb} \right) = 0$$

Equation 3. Energy balance of the absorber.

$$G - h_{con,\ in} \cdot \left(T_{abs} - \frac{T_{in}+T_{out}}{2} \right) - h_{rad,in} \cdot \left(T_{abs} - T_{glass} \right) - \frac{\lambda_{bottom}}{t_{bottom}}$$
$$\cdot \left(T_{abs} - T_{wall} \right) - \frac{\lambda_{side}}{t_{side}} \cdot \frac{A_{sides}}{A_{abs}}$$
$$\cdot \left(\frac{T_{abs}+T_{glass}}{2} - T_{wall} \right) - h_{con,in} \cdot \frac{A_{sides}}{A_{abs}} \cdot \left(\frac{T_{abs}+T_{glass}}{2} - \frac{T_{in}+T_{out}}{2} \right) = 0$$

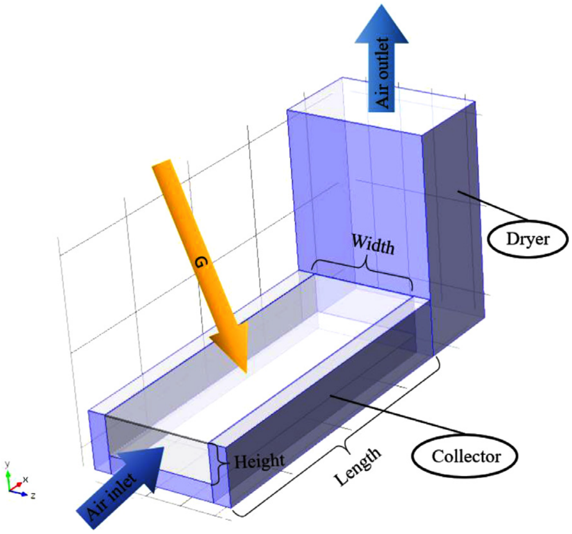


Fig. 5. Schematic figure of the model. The solar dryer is consisting of two parts: the solar collector and the dryer.

Equation 4. Energy balance of the outer walls.

$$\frac{\lambda_{bottom}}{t_{bottom}} \cdot \left(T_{abs} - T_{wall}\right) + \frac{\lambda_{side}}{t_{side}} \cdot \frac{A_{sides}}{A_{abs}} \cdot \left(\frac{T_{abs}+T_{glass}}{2} - T_{wall}\right) - h_{con,out} \cdot \frac{(A_{abs}+A_{sides})}{A_{abs}} \cdot \left(T_{wall} - T_{amb}\right) - h_{rad,out1} \cdot \left(T_{wall} - T_{amb}\right) - h_{rad,out1} \cdot \frac{A_{sides}}{2\cdot A_{abs}} \cdot \left(T_{wall} - T_{amb}\right) - h_{rad,out2} \cdot \frac{A_{sides}}{2\cdot A_{abs}} \cdot \left(T_{wall} - T_{sky}\right) = 0$$

Convective heat transfer calculations followed methods and equations based on well-established literature [39]. The convection heat transfer coefficient on the inside of the solar collector, $h_{con,in}$, was calculated using Equation 5.

Equation 5. Nusselt number.

$$Nu = \frac{h_{con,in} \cdot D_H}{\lambda_{air}}$$

where D_H is the hydraulic diameter calculated using Equation 6. λ_{air} is the thermal conductivity for air and Nu is the dimensionless Nusselt number.

Equation 6. Hydraulic diameter.

$$D_H = \frac{2 \cdot h \cdot w}{h + w}$$

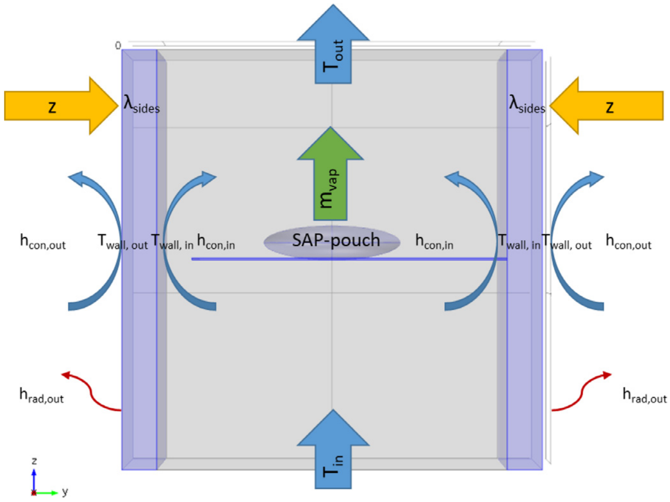


Fig. 7. Schematic figure for all energy flows and temperatures modelled of the drying cabinet. Energy balances for the air flow, inner and outer wall of the collector were modelled according to this figure. Blue arrows represent convective heat transfer and red arrows radiative heat transfer. The yellow arrows represent solar energy absorbed by the drying cabinet.

where h and w are the height and width of the cross section for the air passage in the solar collector.

The Nusselt number, Nu, is strongly dependant on the Reynolds number, Re_{air}, calculated using Equation 7. In these calculations the flow was assumed to be fully developed turbulent if $Re_{air} > 3000$. Otherwise, a laminar flow was assumed. More detailed descriptions for these calculations can be found in [32].

Equation 7. Reynolds number.

$$Re_{air} = \frac{\rho_{air} \cdot u_{air} \cdot D_H}{\mu_{air}}$$

where ρ_{air} is the density of air, $\cdot u_{air}$ is the air velocity inside the solar collector and μ_{air} is the dynamic viscosity for air.

Results from these calculations led to Re_{air} above 4000 [32]. The airflow can therefore be considered to be turbulent. Nu could therefore be calculated using the Gnielinski's correlation and the friction factor f according to Equation 8 and Equation 9.

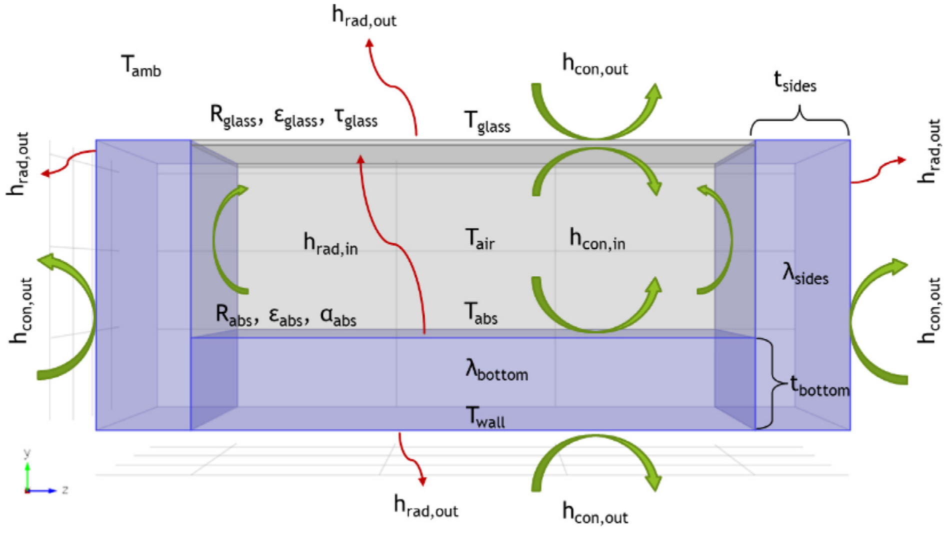


Fig. 6. Schematic figure for all energy flows and temperatures that are included in the model of the collector. Energy balances for the glass, air flow, absorber and outer wall of the collector were modelled according to this figure. Green arrows represent convective heat transfer and red arrows radiative heat transfer.

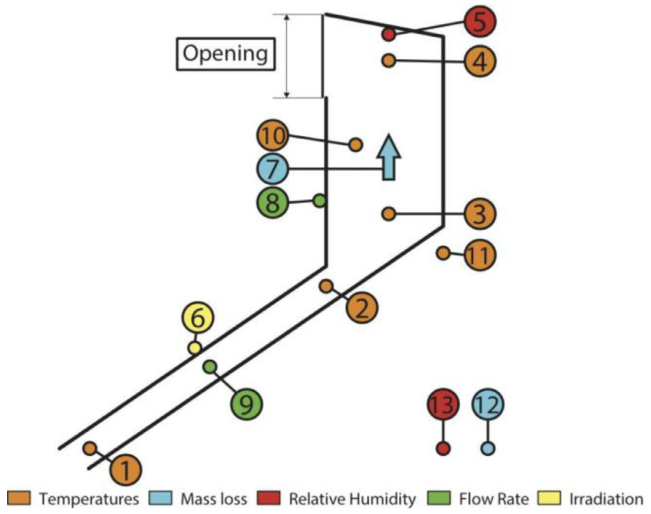


Fig. 8. Illustration of the measurement setup of the miniature indirect solar dryer used for preliminary tests. (colour)

Equation 8. Gnielinski's correlation for the calculation of Nusselts number.

$$Nu = \frac{\frac{f}{8}\cdot\left(Re_{air}-1000\right)\cdot Pr_{air}}{1+12,7\cdot\left(\frac{f}{8}\right)^{\frac{1}{2}}\cdot\left(Pr_{air}^{\frac{2}{3}}-1\right)}$$

Equation 9. Friction factor.

$$f = (0,790\cdot\ln\left(Re_{air}\right)-1,64)^{-2}$$

where Pr_{air} is the Prandtl number for air.

With the parameters used in this example $h_{con,in}$ was calculated to be:

$$h_{con,in} = \frac{Nu\ \cdot\ \lambda_{air}}{D_H} = \frac{13.75\ \cdot\ 0.0263}{0.324} = 1.12\ \frac{W}{m^2\cdot K}$$

A parametric analysis was performed assuming that the $h_{con,in}$ could be increased by a multiplication factor in the range 1 to 5 between the air and absorber. $h_{con,in}$ between air and glazing was kept the same. This was assumed to be possible using fins to increase the convective heat transfer or by any other means possible. This calculation should thus be viewed as an investigation to see how much an increased convection heat transfer coefficient could affect the temperature of the outlet air from the solar collector. The convection heat transfer coefficient was assumed to be 20 W/(m^2•K) on the outside of the collector [41].

Several parametric studies were carried out regarding the design of the solar drying. The base case for the simulations is the following. Collector: 0.22 m high; 0.60 m wide; 1.70 m long. Sides of collector: 1 cm plywood. Bottom and sides of collector: 1 cm plywood + 1 cm Styrofoam. Dryer: 0.60 m high; 0.60 m wide; 0.40 m long. Sides of dryer: 1 cm plywood + 1 cm Styrofoam. Six shelves, 10 pouches per shelf. Ambient conditions: solar irradiation 700 W/m^2; outdoor temperature 25°C; air velocity in collector 0.2 m/s.

Prototype testing

Based on the knowledge gained from the results of modelling (shown further ahead in this article under 'Results and analysis') the design of the solar dryer was improved. Fig. 8 and Table 2 illustrate the experimental setup of the small-scale indirect solar dryer used for preliminary tests. The most trustworthy indicator found to characterize the performance of the drying was the drying flux expressed in weight loss of the pouches per hour. However, opening the cabinet to weigh the membrane bags would disrupt the drying conditions. Therefore, a load cell was mounted into the drying cabinet to regularly monitor the weight of the pouches (illustrated by number 7 in Fig. 8). The drying flux of the pouches inside the dryer was compared to that of a control pouch in open-air drying conditions.

The influence of varying air velocity passing through the pouches was investigated in practice by decreasing the cross-section area of the drying cabinet (Fig. 9). This was done by installing an air-tight wall.

Second design

Prototype design

Based on the results from the small-scale solar dryer described under "First design" (further ahead in the paper under 'Results and analysis') the following design criteria were set for the second design (Table 3). Results from the first design showed the importance of making use of direct solar radiation, to increase air velocity, and to achieve a higher heat transfer between absorber and air. Hence, during the second design stage two solar dryers were built: one passive and one active (Fig. 10).

The purpose of building a passive dryer was to achieve a simple and cheap design where the air flow is thermally driven. The dryer was tilted to maximize incoming radiation and to increase thermally driven air flow. However, placing the pouches on a tilted surface would pose a problem for the drying. As water evaporates from the pouches the remaining juice flows to the bottom to form the pouch into a teardrop shape. This decreases surface area compared to volume which makes drying more difficult. This problem was solved using an extension at the end of the dryer in the form of a horizontal platform where the pouches could lay horizontally during the entire drying process.

The purpose of building an active dryer was to achieve higher performance and capacity (larger number of pouches). The active dryer was closed, and air flow was forced by photovoltaic driven fans. Consequently, high temperature and air velocity could be reached simultaneously. The fans force a circular flow inside the dryer and around all pouches. The axial fans are driven by 12V DC current, 0.28 A, and the size is 120 × 120 × 25 mm. The rated airflow is 35 l/s [40]. Four fans are powered by a photovoltaic module of 20 W_p peak power. Controllable side openings were used to exchange the air and regulate the relative humidity inside the dryer. The fan speed increases with increased solar radiation which provides a certain degree of 'self-regulation' to the drying process. The pouches were placed on a grate for support and to make sure that the air flows on both sides of the pouches.

Both dryers were built in the same way and using the same locally available materials, expect the photovoltaic fans in the active dryer (Fig. 11). Besides the elements illustrated in the figure, an additional black net was added to the passive dryer between the absorber and the transparent cover. The aim was to force the air through it and increase heat transfer.

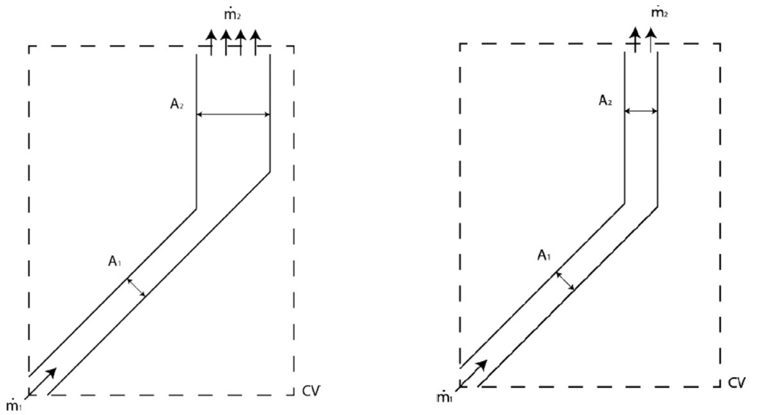
The tilt angle of the passive solar dryer was chosen considering the solar distribution along the day during the harvest season. The harvest season in Mozambique for most citruses is between March to June when solar altitudes are lower in the southern hemisphere. To achieve more balanced drying conditions during the day redistribution of solar radiation throughout the day is desired. The total solar energy received throughout the day for several inclinations was investigated and a 55° tilt from horizontal was chosen.

Modelling

Modelling of computational fluid dynamics (CFD) was carried our using the software COMSOL 5.2 [41]. CFD is the simulation of fluids engineering systems using modelling (mathematical physical problem formulation) and numerical methods (discretization methods, solvers, numerical parameters, and grid generations, etc.) This was carried out in parallel to the measurements performed on the second design. The simulations assumed steady state and constant solar radiation. The plastic net on top of the absorber was neglected and the plastic cover was assumed to not absorb any visible radiation. For a more detailed description of the COMSOL simulations see [35].

Table 2
Measurement equipment, accuracy, and nomenclature. The right-hand column with numbers is connected to the previous figure to illustrate where the measurement equipment is placed. Measurement equipment from Vernier is used (if nothing else is stated). 'C_{max}' is the maximum capacity of the load cell, 15kg.

Measurement Equipment	Abbreviation	Accuracy	Number in illustration
Stainless steel temperature probe	$T_{Ambient}$	±0.4°C	11
Stainless steel temperature probe	$T_{C,In}$	±0.4°C	1
Stainless steel temperature probe	$T_{C,Out}$	±0.4°C	2
Surface temperature sensor	$T_{DC,Bottom}$	±0.4°C	3
Surface temperature sensor	$T_{DC,Top}$	±0.4°C	4
Surface temperature sensor	$T_{DC,Bag}$	±0.4°C	10
RH sensor	RH_{DC}	±2 %	5
RH sensor	$RH_{Ambient}$	0.2 %	13
Pyranometer	I	W/m^2 ±5 %	6
Scaime load cell	$V_{Mass\ Loss}$	±0.017 % Cmax	7
Anemometer	v_{wind}	±0.15 ms^{-1}	8
Hand anemometer TSI 8330	v	±0.05 ms^{-1}	9
Scale House – HS-3000	m_{RB}	±2 g	12



(a) The original cross-section of the drying cabinet

(b) The decreased cross-section used for the tests in Maputo to increase the airflow over the bags.

Fig. 9. Schematic illustration of the cross-section modification in the drying cabinet shown before in (a) and after in (b).

Table 3
Summary of the design criteria as a result of the tests for the first design and taking into account the social and food technology investigations carried out in parallel.

Design Parameters	Requirement
Direct/Indirect/Mixed	Dryer Direct or Mixed
Passive/Active Dryer	Both
Air flow (Speed, characteristics, direction)	Velocity: As high as possible, except if slowing the process Characteristics: better turbulent (higher heat transfer) Direction: Parallel to the biggest dimension of the bag
Temperature Interval	50°C – 65°C
Drying time	Two to three sunny days
Material	No wood, has to be available in Mozambique
User friendliness	As high as possible

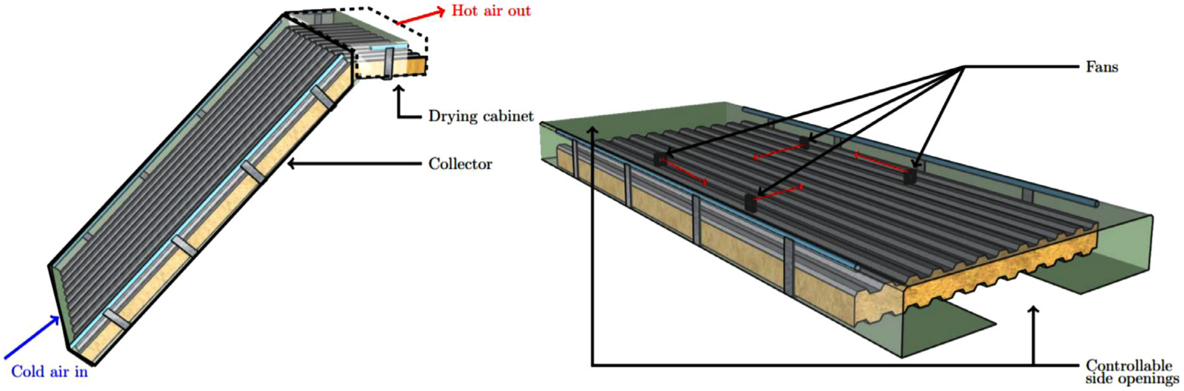


Fig. 10. Left: illustration of the passive solar dryer. Right: illustration of the active solar dryer.

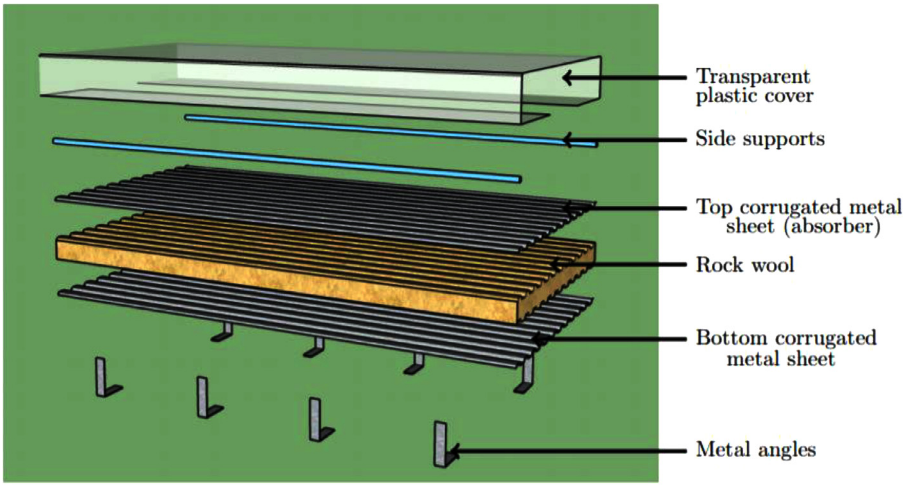


Fig. 11. Local available materials used in both solar dryers.

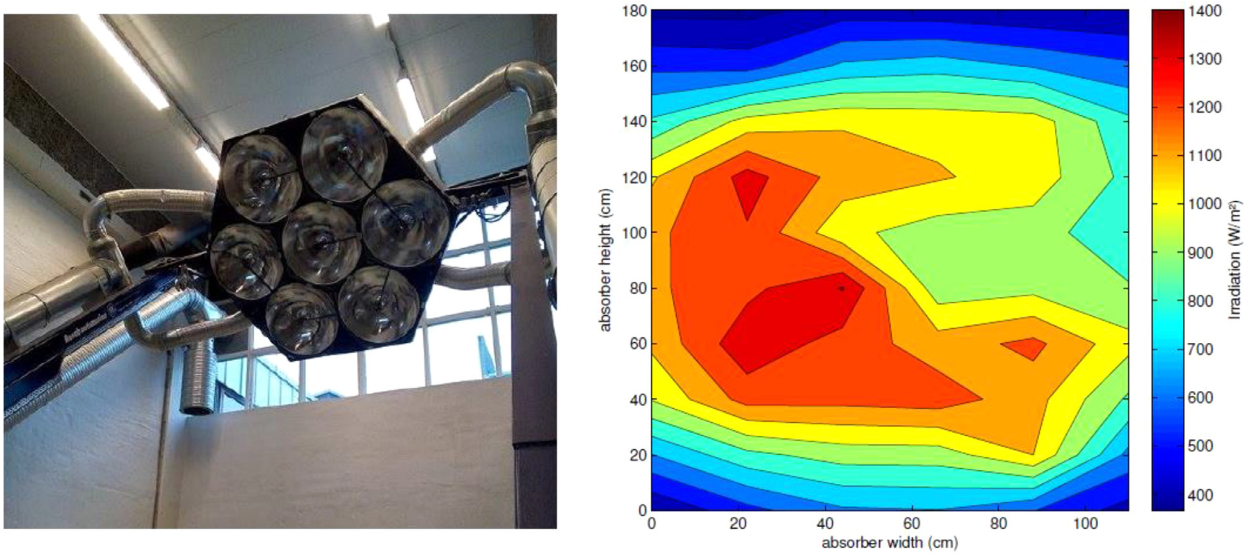


Fig. 12. Left: indoor solar simulator in laboratory. Right: level of irradiation on the leaning collector in laboratory. (colour)

The simulation model was validated against field measurements carried out in Mozambique. Temperature sensors placed on the plastic cover, in the air, on the absorber, inside the insulation and at the bottom of the collector were used for the validation.

Prototype testing

Laboratory in Sweden

Before performing tests in Mozambique, the passive and active solar dryer prototypes were built and tested in a laboratory at Lund University in Sweden. The laboratory is equipped with a full-scale artificial solar simulator which allows performance testing under controlled conditions such as radiation, room temperature and relative humidity. Fig. 12 shows the levels of incoming radiation on the leaning part of the passive dryer. The average incoming radiation was 905 W/m^2 which is close to full solar radiation. However, as illustrated in Fig. 12, the variation of the incoming radiation was significant, specially far from its centre. For instance, the incoming irradiation at the top was close to 400 W/m^2 while its highest value was approximately 1400 W/m^2. A list of measuring equipment, their accuracy, range, and placement are described in Table 4. Fig. 13

Field testing in Mozambique

After the tests in laboratory in Sweden, the passive and active solar dryer prototypes were built and tested in real conditions in Mozambique (Fig. 14). Ambient conditions were monitored regularly with the logger: temperature, relative humidity, wind speed and solar irradiation. The juice inside the pouches was made from local tangerines from the farmer association collaborating with the research group. The sugar content of the juice influences not only the microbiological quality of the final product [26] but can also affect the drying process. Therefore, tests were performed with and without added sugar (i.e., sucrose). The pouches with added sugar were prepared so that 10% of all weight was added sugar and 90% juice.

Cost estimates and availability of materials

The cost estimates for each dryer were based on the retail price of its individual components in local shops in Mozambique. At this stage, no cost was attributed to labour. The dryers are thought to be built by farming associations that will use them. Also, availability of materials was a requirement for the prototype design.

Results and analysis

First design

Modelling

Results from modelling of the small-scale dryer showed that its performance could be significantly improved since the vast majority of in-

Table 4
Measuring equipment, accuracy, and range of each device.

Device	Measures	Accuracy	Range	Location
Testo 435-2	Airspeed	± (0.3 m/s + 4 % of mv)	0 to 20 m/s	Bag
	Temperature	± 0.3°C	-20 to 70°C	Bag
	RH	± 2 %	0 to 100 %	Bag
Vernier LabQuest	Temperature	± 0.5°C	-40 to 135°C	Ambient
	RH	± 2 %	0 to 85°C	Ambient
	Irradiation	± 5 %	0 to 1100 W/m^2	Ambient
	Temperature	± 0.5°C	-25 to 125°C	Absorber
Scale	Weight	± 1 g	0 to 3000 g	Bag
Pyranometer (Vernier)	Irradiation	± 1.29 %	0 to 1100 W/m^2	Collector

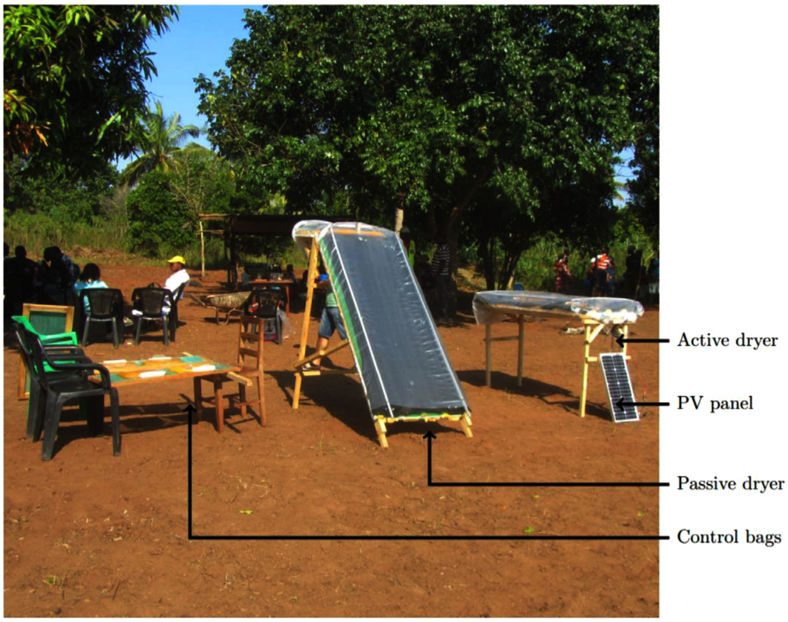


Fig. 13. Solar dryers and control pouches in rural area in Mozambique.

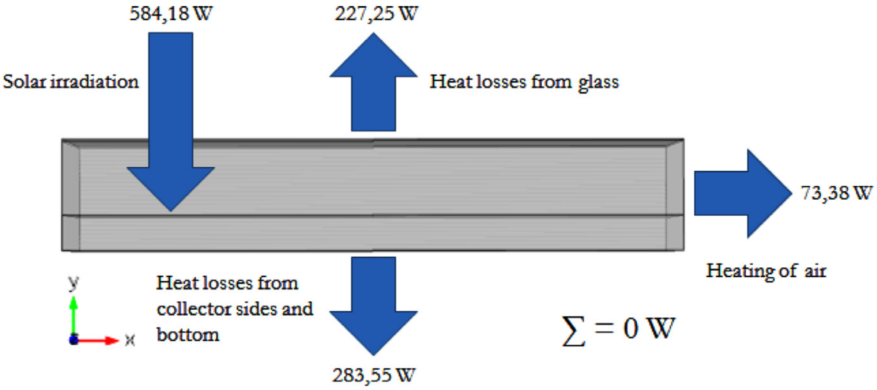


Fig. 14. Estimated heat balance of the solar collector.

coming solar radiation was estimated to be lost by heat losses from the bottom, glass and sides of the collector (Fig. 14). Heat from the absorber was estimated to be mainly transferred to the glass and backside and further lost into ambient. Consequently, only 13% of incoming solar radiation was estimated to be transferred to air flow which meant low temperature and high relative humidity.

Several parametric studies were carried out to investigate increase of convective heat transfer of the absorber. One possibility was to add convective fins to the absorber or other type of surface (Fig. 15). The figure shows a parametric analysis of the outlet air temperature from the solar collector as a function of the effective convective heat transfer between the air and absorber increased by a multiplication factor in the range 1 to 5 resulting from the possibility of adding fins. The convective heat transfer was calculated according to Equation 5 to Equation 9 in the method section. A higher air velocity can be achieved by decreasing the cross-section height of the solar collector (Fig. 16).

A higher air temperature results in a lower relative humidity inside the dryer, which increases the drying flux. A higher air velocity increases the drying flux due to higher heat transfer between the pouch and the air and makes the drying along the drying cabinet more even. The pouches placed on the first shelf, closest to the entrance, will be exposed to a lower relative humidity than the pouches placed further up in the dryer [42]. This occurs due to the absolute humidity being higher further up in the dryer as well as the temperature being lower since heat will be

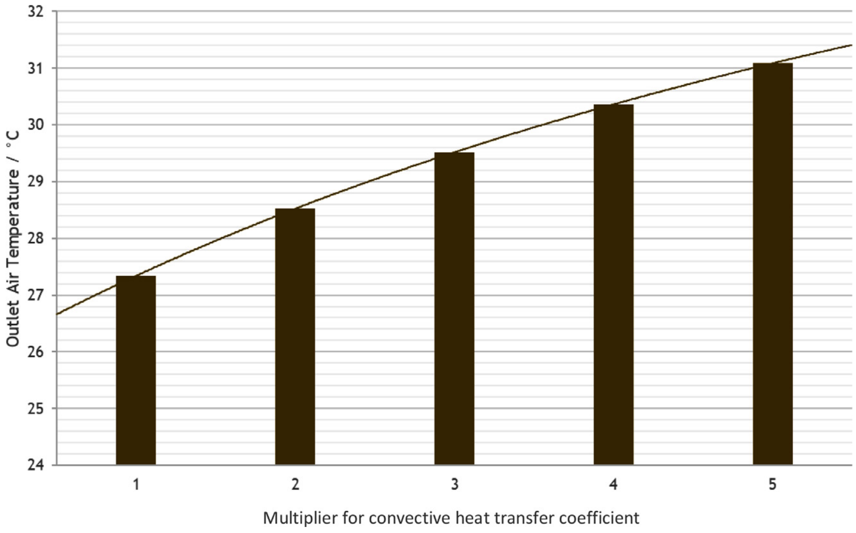


Fig. 15. Parametric analysis on the outlet temperature of the solar collector depending on convective heat transfer between air and absorber.

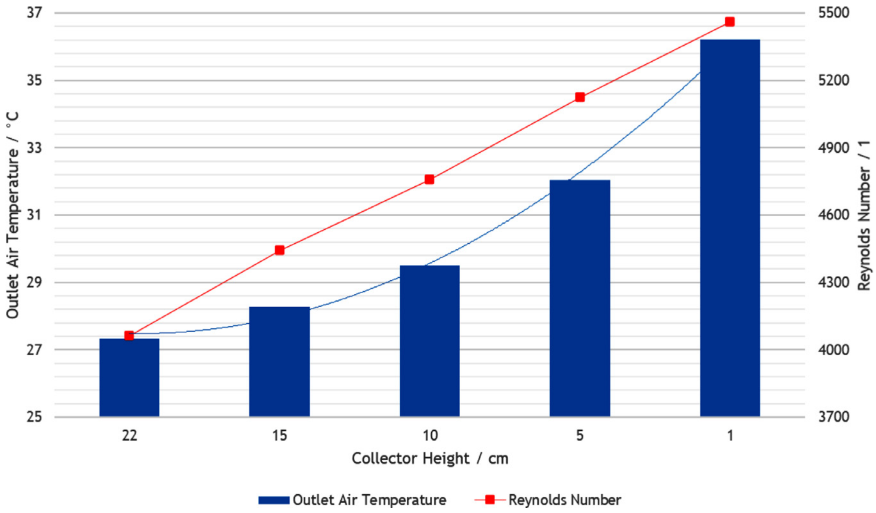


Fig. 16. Expected influence of cross-section height on the outlet temperature of the solar collector.

absorbed by the pouches and lost through the walls. However, air temperature and velocity are inter-dependent where a higher volumetric air flow results in lower temperature. A balance between these factors is therefore needed.

Prototype testing

Field testing in Mozambique

Measurement results for the control pouch showed that the drying flux was 150 g/h/m^2 in the shade and 372 g/h/m^2 in direct sunlight showing the importance of making use of direct radiation.

Fig. 17 illustrates 6 runs in the small-scale solar dryer. During run 4 to 6 the cross-section of the drying cabinet was decreased according to Fig. 9. During run 1 to 3, before the cross-section was reduced, the run with the highest drying flux was run 3 with 247 g/h/m^2. This value is lower than that of the control pouch under direct sunlight, which was unexpected. However, the drying flux of run 6, with a smaller cross-section area and therefore higher air velocity, was 370 g/h/m^2 which was close to that of the control pouch in open-air drying and under direct sunlight. The decrease in cross-section caused an increase of air speed of about 44% and an increase of drying flux of approximately 33% while the temperature interval for most of the runs was comparable.

Based on the results obtained, the air velocity had a larger impact on the drying flux than expected. When drying less juicy and more intact fruits and vegetables, the impact of air velocity on the drying flux is often less significant due to the high internal mass transfer resistance inside the food. For example, in [4] it is stated that "*… the most effective factor on the drying rate is the temperature of the air inside the cabinet; the effect of variation of speed of air inside the drying cabinet is small and can be neglected…* "; in [43] one can read "*…Studies on the drying of fruits and vegetables indicate that the air velocity has little influence on the drying kinetics of most of them…"; and in* [44] *"The air drying temperature is a principal factor influencing the drying kinetics … the air velocity had a small impact on the drying kinetics"*. Even with the additional mass transfer resistance provided by the membrane in the pouch, the external mass transfer resistance at the surface of the pouch showed to be higher and therefore a different drying behaviour was observed compared with the solar drying of more in-tact fruits and vegetables.

An interesting and important observation was that at lower air velocities the pouches inside the dryer were wet all around. Droplets of water were seen dropping from the drying cabinet. Furthermore, the temperature of the pouches inside the dryer was relatively high and increasing during the drying process. In comparison, the control pouches in open-air were dry and colder due to evaporative cooling and lower ambient air temperatures.

From the analysis of these results, it seemed that the higher temperature and lower relative humidity inside the solar dryer were not enough to increase the drying flux above the level of the reference bag placed in ambient conditions where wind and direct sunlight were available. The solar dryer seemed to be missing the capacity to remove the vapour from

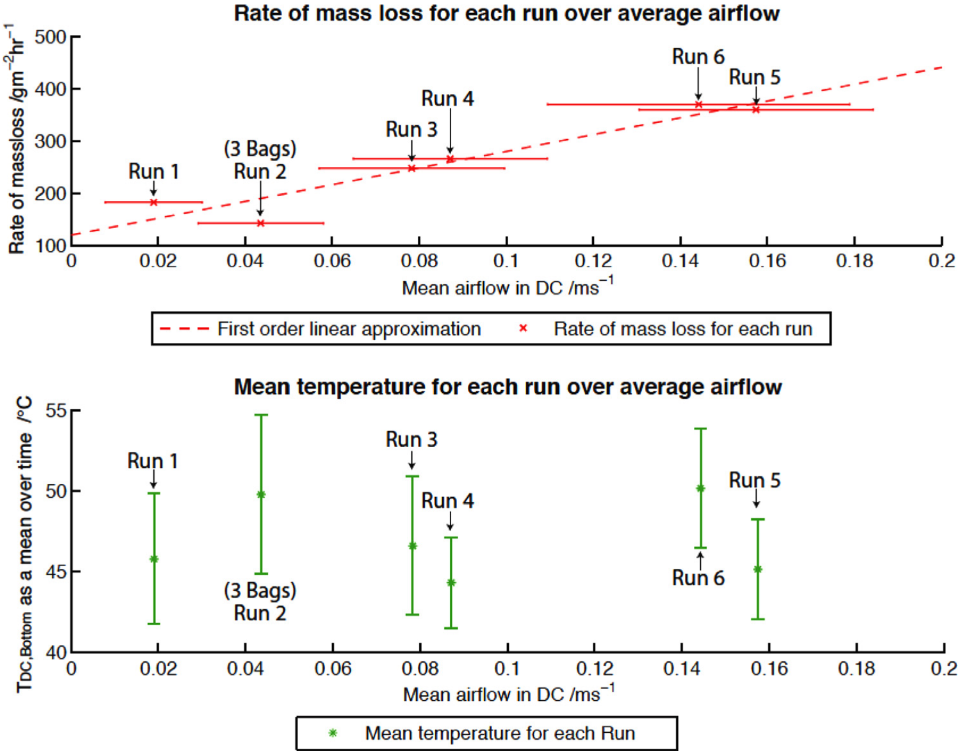


Fig. 17. A comparison of the drying fluxes and temperatures. Average drying fluxes and temperatures are plotted against air velocity. The horizontal bars represent the deviation of the air velocity while the vertical bars represent the deviation of the temperature in the drying cabinet. A first order linear approximation is drawn for the rate of mass loss.

the surface of the bag to continue the pervaporation process through the membrane. The air flow velocity was low and seemed to be limiting drying. Therefore, the next design of solar fruit dryer took this important outcome into consideration.

Second design

Modelling

Results show that measurements and simulations are mainly in good agreement. The larger difference for temperatures on the plastic cover was most likely due to sensors heating up directly from the sun. This problem occurred throughout the evaluation measurements. However, other measurements carried out away from direct sunlight had significantly higher correlation to the simulation results.

The models give a sufficient estimation of the temperature and relative humidity in a direct and in an indirect solar dryer with a maximum relative error of 10% for the outlet air temperature and approximately 30% for the relative humidity. Guidelines to improve the design were provided by the model. An adequate balance between the air flow velocity, the relative humidity and the convection provided on the absorber plate and around the bags was found to significantly improve the drying flux.

Prototype testing

Laboratory in Sweden

The influence in the drying process of closing the active solar dryer was investigated in laboratory by monitoring temperature and relative humidity of the air inside. Pouches containing orange juice were used to mimic real conditions. Results are shown in Fig. 18. After 4 hours, when the parameters were stable, it was observed that the temperature of the closed active dryer was close to that of when the plastic cover was open. However, a much higher relative humidity was measured (35% compared to 10%). Furthermore, condensation was seen in several places inside the dryer. It was therefore concluded that the absence of openings does not allow the relative humidity to be low enough to avoid saturation. Therefore, testing in Mozambique was carried out with openings on the plastic cover. Results from the drying flux in laboratory for both solar dryers are shown further ahead in Table 6. The air flow could not be measured in the active design solar dryer. The reason is that to be able to measure an air flow using an anemometer the air flow direction must be known. As the flow is turbulent and chaotic this measurement could not be performed.

Field testing in Mozambique

Measurements of the air temperature inside the passive and active solar dryers during clear sky conditions along the day are illustrated in Fig. 19. The illustrated air temperatures were measured inside the solar dryers. The air temperature inside the passive dryer was measured at the warmest point located at the outlet of the solar collector at its top. The airflow in the active solar dryer is turbulent and therefore the air temperature is fairly homogeneous inside the drier. As expected, the air temperature of the passive dryer was shown to be less stable due to its sensitivity to wind conditions while the incoming solar radiation was higher due to its favourable inclination towards the sun. As illustrated below, between 11:00 and 14:00 temperatures in the range of 70°C-78°C and 58°C-65°C were measured, for the passive and active solar dryer respectively, during clear sky conditions and for that period of the year. Such results are consistent with laboratory measurements as illustrated in Fig. 18 (left) for the active solar dryer and measurements during other days as illustrated in [34]. It should be noted that the sharp temperature increase of the active dryer at 12:00 is explained by an air-leakage from the plastic cover that was corrected.

Large pouches of over 1.5 kilograms of juice each were dried in the solar dryers. This represents a 330ml pot of jam of final product for each bag. Table 5 shows the drying flux for both solar dryers and control pouch during a three-day period. The pouches used for all days were the same.

During the first day a significant increase in drying fluxes was observed when the bags are placed in the solar dryers compared to when they are placed outside in ambient conditions was observed. The drying fluxes for the second day were not has high as during the first day, but still higher compared to the control pouch. Finally, the drying fluxes for the third day were lower than the second day. The drying flux of the

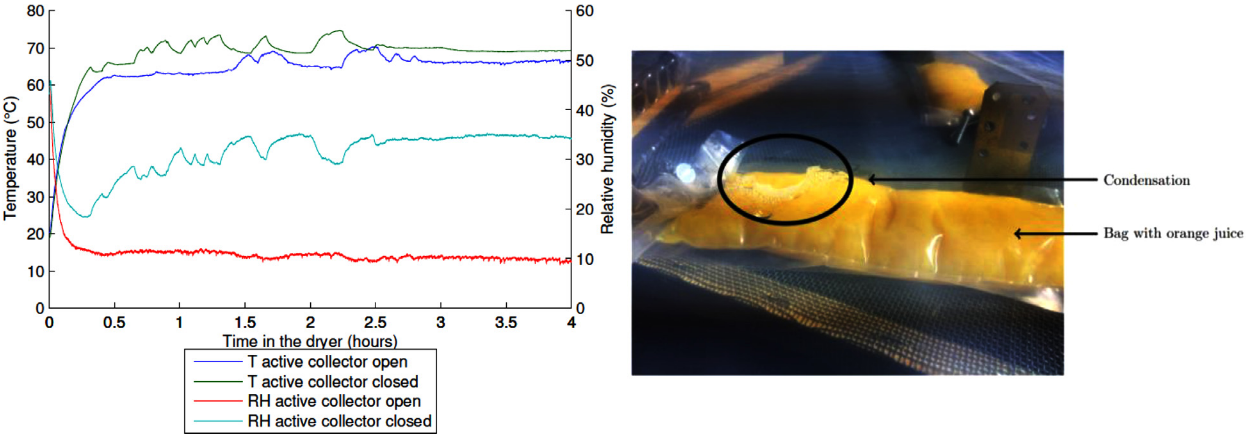


Fig. 18. Left: comparison of relative humidity and temperature in the active collector when plastic cover was opened and closed. Right: condensation on the plastic as a result of no air exchange. (colour)

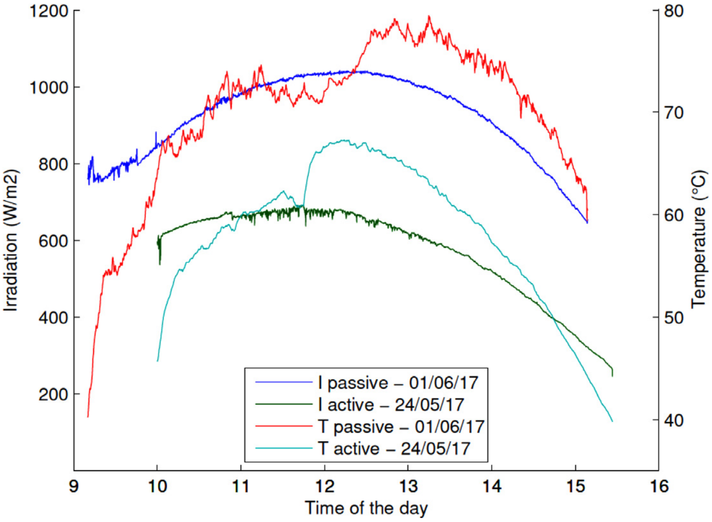


Fig. 19. Illustration of air temperatures inside the passive and active solar dryers and corresponding solar radiation at the surface of each collector during clear sky conditions.

Table 5
Drying fluxes for both solar dryers and control pouch during three days, with and without added sugar.

	Day 1 Sugar	No Sugar	Day 2 Sugar	No Sugar	Day 3 Sugar	No Sugar
Active ($g/m^2/h$)	497	609	320	390	187	220
Passive ($g/m^2/h$)	465	457	325	354	216	287
Control ($g/m^2/h$)	293	311	246	264	192	227
Active (ratio to control)	1.70	1.96	1.30	1.48	0.97	0.97
Passive (ratio to control)	1.59	1.47	1.32	1.33	1.12	1.26
Control	1	1	1	1	1	1

pouch inside the active dryer was even lower than that of the control pouch. This means that the drying flux decreases as cumulative weight loss increases as expected, since the mass transfer driving force decreases as the moisture concentration in the juice decreases and as the juice is turning into a more viscous product. For the active and passive dryers, the moisture concentration decreased more rapidly explaining why the drying fluxes also decreased substantially from days 1 to 3.

The percentage cumulative weight loss of pouches inside the passive and active solar dryers is shown in Fig. 20 and Fig. 21, respectively. Pouches with and without added sugar were tested and compared to control pouches. The minimum cumulative weight loss when microbiological growth is prevented was calculated for the pouches with and without sugar and is represented by the horizontal lines [26, p. 2]. These lines represent the target for drying. The pouches were weighed at the start and end of each day, this is shown by the crosses in the figures. The sudden increase from end of one day to start the next day is due to drying during night.

Results show that pouches dry faster inside the solar dryers than their respective control pouches. Furthermore, pouches without sugar dry faster than the ones with, as expected. Sugar was noticed to slow down the drying process but the threshold for cumulative weight loss where microbiological growth is prevented is also lower. Consequently, pouches with and without sugar are thought to complete the drying process approximately at the same time. Finally, results show that the pouches inside the active collector almost reached the goal for cumulative weight loss during the three-day period.

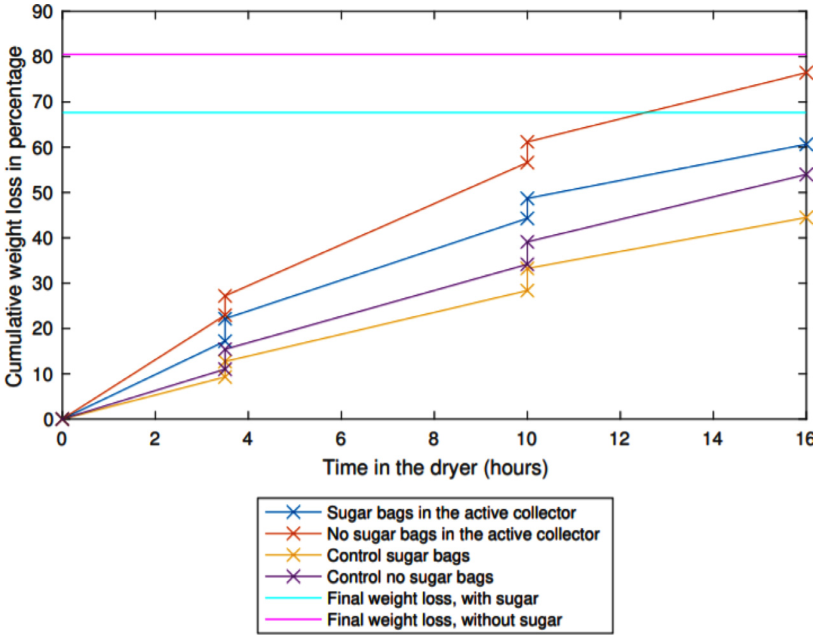


Fig. 20. Cumulative weight loss in the active solar dryer and control pouch for a three-day period, with and without added sugar. (colour)

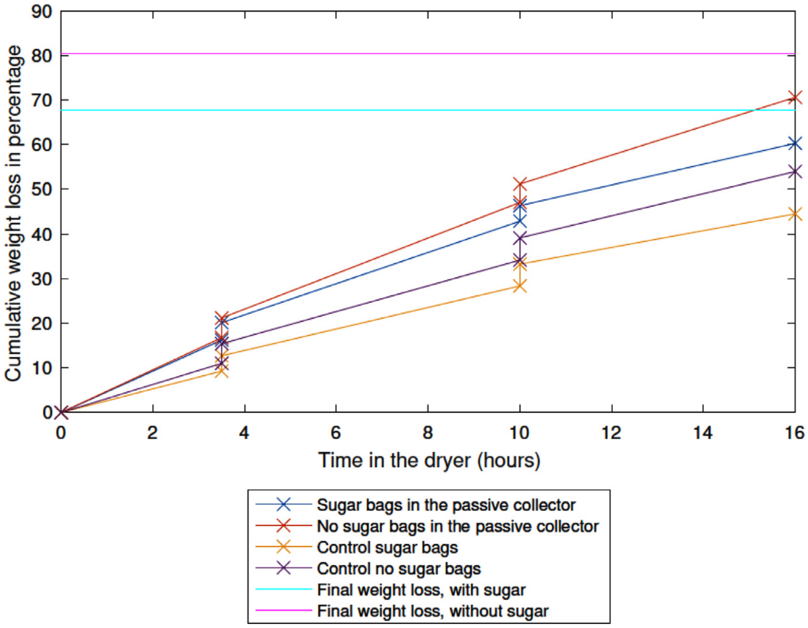


Fig. 21. Cumulative weight loss in the passive solar dryer and control pouch for a three-day period, with and without added sugar. (colour)

In summary, the mean drying flux for the pouches without sugar inside the passive and active solar dryers in comparison with the control pouches, both in laboratory and in Mozambique, are shown in Table 6. Both dryers consistently achieved the target temperature of at least 50°C during most of the days, which prevents bacterial growth and lowers the relative humidity significantly. An increase of the drying flux from approximately 50 % (passive dryer) to 100% (active dryer) was measured in real conditions in Mozambique which means that all pouches in the solar dryers significantly outperform the pouches that do not use a solar dryer. The total drying time was below four days for all bags in the dryers, even when the weather was not optimal. The active solar dryer was shown to have the shortest drying time and the highest capacity (more pouches) but also the highest price (Table 7).

It is important to notice that mold growth on the outside and fermentation of the juice was consistently observed on the control pouches drying in open air. These factors compromise drying without a solar dryer. Furthermore, during field measurements in Mozambique it was discovered that the pouch material degrades when exposed to direct solar radiation both with and without a solar dryer and, as manufactured at the time, could not resist more than 5 days of drying.

Cost estimates and availability of materials

The materials used to build the solar dryers were based on local availability, costs and inputs from the farmers [29]. The cost estimate for each solar dryer was based on the retail price of its individual components in local shops in Mozambique is presented in Table 7. As shown, the active solar dryer costs approximately 2.4 times more than the passive collector. This is mainly due to the cost of fans (most expensive component) and solar cells which, together, made up 61% of the total price. The mean drying flux is increased by approximately 33%. This could indicate that the passive collector is more cost-effective. However,

Table 6

Comparison of the mean drying fluxes for the passive and active solar dryers in comparison with the control pouches, both in laboratory and in Mozambique, for the pouches without sugar.

Place of testing	Type of drying method	Mean drying flux ($g/m^2/h$)	Ratio (solar dryer / without)
Laboratory in Lund	Solar passive dryer	678	1.65
	Solar active dryer	924	2.25
	Without solar dryer	411	1.00
Field tests in Mozambique	Solar passive dryer	457	1.47
	Solar active dryer	609	1.96
	Without solar dryer	311	1.00

Table 7

The retail price of all the components used in both dryers. (1 MZN = 0,0138589 €, as of 2017-08-08).

Product	Size	Unit price	Qt. active	Price active	Qt. passive	Price passive
Metal sheet (mm)	800*3600*0.4	14.4 EUR	1	14.4 EUR	1	14.4 EUR
Net (m)	3*1	7.6 EUR	1	7.6 EUR	1	7.6 EUR
Styrofoam (cm)	100*200*2	12.4 EUR	1	12.4 EUR	1	12.4 EUR
Fillinf foam (ml)	750	5.3 EUR	2.5	13.3 EUR	2.5	13.3 EUR
Plastic sheet (m)	4*5	15.5 EUR	0.5	7.7 EUR	0.5	3.9 EUR
Metal angles (cm)	8 pcs 10*10	0.5 EUR	8	4.0 EUR	1	4.0 EUR
Plastic support (m)	10*2500	0.7 EUR	2	1.4 EUR	2	2.7 EUR
Nuts and bolts (mm)	50 pcs, 6*75	6.5 EUR	1	6.5 EUR	1	6.5 EUR
Wood for frame (mm)	38*38*5400	3.4 EUR	3	10.1 EUR	4	40.4 EUR
Wood screws (mm)	50 pcs, 4*45	1.4 EUR	1	1.4 EUR	1	1.4 EUR
Fans (mm)	120*120	18.4 EUR	4	73.6 EUR	0	0 EUR
PV-panel (W)	20	47.8 EUR	1	47.8 EUR	0	0 EUR
Cables	N/A	N/A	N/A	0 EUR	0	0 EUR
Total				200.3 EUR		78.6 EUR

the active collector has a significantly larger capacity, and the solar cells could potentially also be used for other purposes outside the juicy fruit period.

Discussion

The evaluated solar dryers were found to decrease drying time and increase productivity, to increase food safety, and to provide additional protection from external environment.

However, an important constraint was encountered. The successfulness of the use of the pouch membrane is a requirement to successfully dry juicy fruits according to the investigated concept. The observed degradability of the pouch in direct sunlight might be an important hurdle for successful implementation. This challenge needs to be overcome before the pouches can become suitable for widespread use. Moreover, mold growth on the outside and fermentation of the juice was observed on the control pouches drying in open air. Open air sun drying with pouches increases the risk of mold growth on the outside of the pouch, which further emphasizes the usefulness of a solar dryer. Some open-air samples experienced mold growth on the outside of the pouches, while all passive and active samples had no visible mold growth on the outsides of the pouches. In another study, for the pouches with mold on the outside, the juice was not contaminated which shows that the pouches have the ability to act as a barrier to mold [22]. Despite this, drying with a solar dryer is still preferred over open sun drying to reduce the risk of any mold growth during the process and also decrease the drying time. By using solar dryers to avoid mold growth, the person handling the pouches also avoids touching mold that may have accumulated on the outside of the pouch. Even if a pouch is not used, the concept of protecting liquid food in a container is good to prevent as much microbial contamination as possible.

Concerning measurements, the higher uncertainty on measurements relates to air flow velocity on the passive solar dryer. This was measured at the outlet under controlled conditions in laboratory in Sweden. The measured value depends on flow characteristics and how far the measurement is taken from the absorber and sides. Approximately 1 m/s can be considered as a reference value. As the accuracy of the anemometer is ± 0.3m/s, the relative error is large. On the other hand, large pouches of over 1500 grams of juice each were dried and since the accuracy of the scale is ± 1 grams, the correspondent relative error in weight measurements is small. Hence, drying flux was used as a key performance indicator for the drying process.

Regarding future work, it is believed that even if the pouch is not used the solar dryers may have potential to be used. Since the association of farmers do not carry out any fruit drying today, there is a large potential on solar fruit drying for all non-juicy fruits and herbs. Further development of the concept could focus on designing holistic solar photovoltaic systems for active solar food drying and other uses such as lighting and cooking. Another possible development is to design more advanced solar dryers that include thermal storage, for example. When it comes to profitability, the cost estimates show a significantly higher cost for the active dryer but also shorter drying time. It becomes therefore difficult to accurately estimate the most cost-effective design. To do so, several other factors should be accounted for such as the cost of building the dryers, the quantity of juice that can be dried at once, and the selling price of the finished product. Regarding modelling of the solar dryer, it should be noted that the calculations for the Nusselt number contains approximations. Using the Gnielinski's correlation is suitable as it is valid for $0{,}5<Pr<2000$ and $3000<Re<5 \times 10^6$. No effects due to entry length were included in the calculations, which could lead to a less accurate estimation of Nu which would be interesting to include in future work.

Conclusions

A holistic development, implementation and evaluation of solar dryers combined with semi-permeable membrane pouches for drying juicy fruits was carried out. Two prototype design iterations were carried out including modelling and testing in Mozambique. The latest version of solar dryers were a passive and an active solar dryer.

Results from modelling showed that the accuracy was sufficient to estimate levels of temperature and relative humidity with a maximum relative error of 10% and 30%, respectively. The models were used to improve the design of the dryers for a faster and safer drying process.

One of the main technical challenges was to increase convective heat transfer from the absorber to the air flow in a simple manner, which was tested in several manners.

Measurement results show that both dryers consistently achieved the target temperature of at least 50°C during most of the days, which prevents bacterial growth and significantly lowers the relative humidity. An increase of the mean drying flux of the passive dryer from 457 $g/h/m^2$ to 609 $g/h/m^2$ of the active dryer was measured in real conditions in Mozambique. The mean drying flux of the control pouches that did not use a solar dryer was 311 $g/h/m^2$. Hence, the drying flux of the passive and active dryers is approximately 50% and 100% higher than without a solar dryer, respectively. The total drying time was below four days for all bags in the solar dryers, even when the weather was not optimal. It was found that, besides temperature, air velocity had a large impact on the drying flux of the membrane pouch suggesting that, under the drying conditions tested, the external mass transfer resistance at the surface of the pouch was greater than the internal mass transfer resistance inside the membrane and juice. This observed drying behaviour differs from solar drying of more in-tact fruits and vegetables [4,43,44]. It was found that an adequate balance between air flow velocity, relative humidity, and convection on the absorber plate and around the pouches has significant impact on the drying flux. For future research it is recommended that special focus is set on air velocity and its impact on solar drying of the pouches [45]. Furthermore, it was concluded that the evaluated solar dryers decrease drying time and increase productivity, increase food safety, and provide additional protection from the external environment, when compared to open-air sun drying.

The active solar dryer was shown to have the shortest drying time and the highest capacity (more pouches) but also the highest costs. The active solar dryer costs approximately 2.4 times more than the passive dryer while the mean drying flux was increased by approximately 33%.

Mold growth on the outside and fermentation of the juice was observed on the control pouches drying in open air. It was also observed that the pouch material degrades when exposed to direct solar radiation and, as manufactured at the time, could not resist more than 5 days of drying. Also, the current pouch material is not biodegradable. These factors point out that further development of the membrane pouch is needed.

Acknowledgments

The Swedish Research Council for Sustainable Development is acknowledged for financing this research study (project number 2015-00633). The authors are also thankful to local associations of farmers in Inharrime and to Eduardo Mondlane University, Mozambique. Etienne Deslandes and Juliette Chaignon are also acknowledged by their contributions during their master thesis work.

References

[1] 'Mozambique FY 2011-2015 Multi-Year Strategy', 2011. Accessed: Jun. 30, 2020. [Online]. Available: https://docplayer.net/190631-Mozambique-fy-2011-2015-multi-year-strategy-u-s-government-document.html
[2] K.S. Jairaj, S.P. Singh, K. Srikant, A review of solar dryers developed for grape drying, Sol. Energy 83 (9) (Sep. 2009) 1698–1712, doi:10.1016/j.solener.2009.06.008.
[3] D.R. Pangavhane, R.L. Sawhney, P.N. Sarsavadia, Design, development and performance testing of a new natural convection solar dryer, Energy 27 (6) (Jun. 2002) 579–590, doi:10.1016/S0360-5442(02)00005-1.
[4] S. VijayaVenkataRaman, S. Iniyan, R. Goic, A review of solar drying technologies, Renewable Sustainable Energy Rev. 16 (5) (2012) 2652–2670.
[5] O.V. Ekechukwu, B. Norton, Review of solar-energy drying systems II: an overview of solar drying technology, Energy Conversion (1999) 41.
[6] S. Mohammed, M. Edna, K. Siraj, The effect of traditional and improved solar drying methods on the sensory quality and nutritional composition of fruits: A case of mangoes and pineapples, Heliyon 6 (6) (Jun. 2020), doi:10.1016/j.heliyon.2020.e04163.
[7] A. Jha, P.P. Tripathy, Recent Advancements in Design, Application, and Simulation Studies of Hybrid Solar Drying Technology, Food Eng Rev 13 (2) (Jun. 2021) 375–410, doi:10.1007/s12393-020-09223-2.
[8] O. Prakash, A. Kumar, Historical Review and Recent Trends in Solar Drying Systems, Int. J. Green Energy 10 (7) (Aug. 2013) 690–738, doi:10.1080/15435075.2012.727113.
[9] Y. Bahammou, et al., Evaluation of the influence of ambient air temperature and air velocity on mortar cement durability using a forced convection solar dryer, International Journal of Building Pathology and Adaptation (Jan. 2021) vol. ahead-of-print, no. ahead-of-print, doi:10.1108/IJBPA-08-2020-0069.
[10] B. K. Bala and S. Janjai, 'Solar Drying Technology: Potentials and Developments', in *Energy, Environment and Sustainable Development*, M. A. Uqaili and K. Harijan, Eds. Vienna: Springer, 2012, pp. 69–98. doi: 10.1007/978-3-7091-0109-4_10.
[11] A. Munir, O. Hensel, W. Scheffler, Design principle and calculations of a Scheffler fixed focus concentrator for medium temperature applications, Sol. Energy 84 (8) (Aug. 2010), doi:10.1016/J.SOLENER.2010.05.011.
[12] N.L. Panwar, S.C. Kaushik, S. Kothari, State of the art of solar cooking: An overview, Renewable Sustainable Energy Rev. 16 (6) (Aug. 2012) 3776–3785, doi:10.1016/j.rser.2012.03.026.
[13] P.P. Otte, Sunrise or sunset?: -A comparative study on the successfuladoption of institutional solar cookers inthe developing world, LAMBERT Academic Publishing, Saarbrücken, 2014 Accessed: Jan. 03, 2021. [Online]. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/268793 .
[14] M. Augustus Leon, S. Kumar, S.C. Bhattacharya, A comprehensive procedure for performance evaluation of solar food dryers, Renewable Sustainable Energy Rev. 6 (4) (Aug. 2002) 367–393, doi:10.1016/S1364-0321(02)00005-9.
[15] V.K. Sharma, A. Colangelo, G. Spagna, Experimental investigation of different solar dryers suitable for fruit and vegetable drying, Renewable Energy 6 (4) (Jun. 1995) 413–424, doi:10.1016/0960-1481(94)00075-H.
[16] E.A. Arinze, S. Sokhansanj, G.J. Schoenau, Simulation of natural and solar-heated air hay drying systems, Comput. Electron. Agric. 8 (4) (Jun. 1993) 325–345, doi:10.1016/0168-1699(93)90019-W.
[17] 'Technical and financial feasibility of a solar dryer in Bhutan | Elsevier Enhanced Reader'. https://reader.elsevier.com/reader/sd/pii/S0973082608604962?token=2D7B853DE1D4112B502C445409D1EBFD5D5991479D29918A0F2BAB9B4C09228D3FFFF57CA36EA9FE1458CECAFD6B5826&originRegion=eu-west-1&originCreation=20210824112841 (accessed Aug. 24, 2021).
[18] E.R. Carmody, A.U. Sarkar, Solar box cookers: Towards a decentralized sustainable energy strategy for sub-Saharan Africa, Renewable Sustainable Energy Rev. 1 (4) (1997) 291–301.
[19] P.P. Otte, Solar cookers in developing countries—What is their key to success? Energy Policy 63 (C) (2013) 375–381.
[20] M. Wentzel, A. Pouris, The development impact of solar cookers: A review of solar cooking impact research in South Africa, Energy Policy 35 (3) (2007) 1909–1919.
[21] P.P. Otte, A (new) cultural turn toward solar cooking—Evidence from six case studies across India and Burkina Faso, Energy Res. Soc. Sci. 2 (Jun. 2014) 49–58, doi:10.1016/j.erss.2014.04.006.
[22] R. Phinney, M. Rayner, I. Sjöholm, L. Tivana, and P. Dejmek, 'Solar assisted pervaporation (SAP) for preserving and utilizing fruits in developing countries', 2015, Accessed: Jun. 30, 2020. [Online]. Available: https://portal.research.lu.se/portal/en/publications/solar-assisted-pervaporation-sap-for-preserving-and-utilizing-fruits-in-developing-countries(1ce79ba8-e17b-436c-abb9-06f3bb13a70e).html
[23] J.A. Howell, V. Sanchez, R.W. Field, Membranes in Bioprocessing: Theory and Applications, Springer Science & Business Media, 2012.
[24] G.D. Saravacos, A.E. Kostaropoulos, Handbook of Food Processing Equipment, Springer US, 2002, doi:10.1007/978-1-4615-0725-3.
[25] P. Kober, Pervaporation, Perstillation and Percrystallization, J. Am. Chem. Soc. 39 (5) (1917) 944–948.
[26] R. Phinney, et al., Concentration of citrus fruit juices in membrane pouches with solar energy Part 2: How solar drying setup and juice pretreatment determine the microbiological quality, J. Food Process Eng. 43 (4) (Apr. 2020) e13377, doi:10.1111/jfpe.13377.
[27] R. Phinney, et al., Concentration of citrus fruit juices in membrane pouches with solar energy Part 1: How solar drying setup and juice pretreatment determine the drying flux, J. Food Process Eng. 43 (1) (2020) e13335, doi:10.1111/jfpe.13335.
[28] A. Fleming, et al., Reflections on integrated research from community engagement in peatland restoration, Humanit Soc Sci Commun 8 (1) (Aug. 2021) 1–11, doi:10.1057/s41599-021-00878-8.
[29] P.P. Otte, R. Bernardo, R. Phinney, H. Davidsson, L.D. Tivana, Facilitating integrated agricultural technology development through participatory research, The Journal of Agricultural Education and Extension 24 (3) (May 2018) 285–299, doi:10.1080/1389224X.2018.1461662.
[30] P.P. Otte, L.D. Tivana, R. Phinney, R. Bernardo, H. Davidsson, The importance of gender roles and relations in rural agricultural technology development: a case study on solar fruit drying in Mozambique, Gender, Technol. Dev. 22 (1) (Jan. 2018) 40–58, doi:10.1080/09718524.2018.1444442.
[31] R. Phinney, I. Sjöholm, K. Östbring, M. Rayner, Method to assess the drying performance of water vapour-permeable membrane pouches for fruit juice preservation, Chem. Eng. Res. Des. 152 (Dec. 2019) 433–446, doi:10.1016/j.cherd.2019.09.045.
[32] J. Olsson, Modelling of a solar dryer for food preservation in developing countries Master thesis, Lund University, 2016.
[33] G. Bengtsson, V. Döhlen, Performance Testing of a Solar Thermal Fruit Drying - a Case-Study to Reduce Food Waste in Mozambique Master thesis, Lund University, 2016.
[34] P. Samuelsson, E. Deslandes, Testing of solar fruit driers in laboratory and in Mozambique Master thesis, Lund University, 2017.
[35] J. Chaignon, Modeling of a solar dryer for fruit preservation in developing countries Master thesis, Lund University, 2017.
[36] C. Massey, F. Alpass, R. Flett, K. Lewis, S. Morriss, F. Sligo, Crossing fields: the case of a multi-disciplinary research team, Qualitative Research 6 (2) (May 2006) 131–147, doi:10.1177/1468794106062706.

[37] *Maple - The Essential Tool for Mathematics*. 2015. Accessed: Jul. 01, 2020. [Online]. Available: https://www.maplesoft.com/products/Maple/

[38] J. Olsson and H. Davidsson, 'Modelling of a Solar Dryer for Food Preservation in Developing Countries', in *Proceedings of EuroSun2016*, Palma de Mallorca, Spain, 2016, pp. 1–12. doi: 10.18086/eurosun.2016.02.19.

[39] F.P. Incropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, 5th Edition, 5th edition, Wiley, New York, 2001.

[40] 'Open circuit webshop - fan 12V DC', *Opencircuit*. https://opencircuit.shop/product/Fan-12vdc-sleeve-120-x-120-x-25mm (accessed Oct. 04, 2021).

[41] 'COMSOL: Multiphysics Software for Optimizing Designs', *COMSOL Multiphysics*®, 2016. https://www.comsol.se/ (accessed Jul. 14, 2020).

[42] H. Davidsson, J. Olsson, R. Phinney, R. Bernardo, P. Otte, and L. D. Tivana, 'Towards a Homogenous Drying Rate Using a Solar Fruit Dryer', in *Proceedings of SWC2017/SHC2017*, Abu Dhabi, 2017, pp. 1–7. doi: 10.18086/swc.2017.24.01.

[43] D.I. Onwude, N. Hashim, R.B. Janius, N.M. Nawi, K. Abdan, Modeling the Thin-Layer Drying of Fruits and Vegetables: A Review, Comprehensive Rev. Food Sci. Food Safety 15 (3) (2016) p. n/a-n/a.

[44] Y. Bahammou, et al., Water sorption isotherms and drying characteristics of rupture-wort (Herniaria hirsuta) during a convective solar drying for a better conservation, Sol. Energy 201 (May 2020) 916–926, doi:10.1016/j.solener.2020.03.071.

[45] R. Phinney, 'Solar Assisted Pervaporation : A process for the concentration of fruit juices in membrane pouches with solar energy', thesis/doccomp, Lund University, 2019. Accessed: Aug. 23, 2021. [Online]. Available: http://lup.lub.lu.se/record/0d282e19-c7ee-4e02-94ff-cc4e87aae3c3