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SOLAR ASSISTED PERVAPORATION (SAP) FOR PRESERVING AND UTILIZING FRUITS IN DEVELOPING COUNTRIES

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ABSTRACT

The purpose of this work is to develop and implement a simple and robust preservation technology that can enhance food and economic security and thereby improve the lives of people in developing countries. The technique under development is termed “solar assisted pervaporation (SAP)”. It is a sustainable technology whereby fruit juices or purées are concentrated using reusable pouches made of “breathable textiles”. The active layer of the textile is permeable to water vapour but not liquid water, and the process is related to the techniques pervaporation and membrane distillation. The pouches are filled with the juice/purée, hung from a tree or placed on a roof or in a solar dryer, and then exposed to sun and air for a specified period of time. A storage stable concentrate can be produced within 10 to 45 hours (depending on the conditions) and the entire concentration process is done using only solar energy. The fruit juice concentrate can be stored in the household or sold, thereby increasing both food and economic security in local communities.

To demonstrate the feasibility of this technique, three different fruits/juices were concentrated by placing prototype pouches in a convective dryer to simulate a ventilated solar collector, or by exposing the pouches to a solar lamp equipped with convective air circulation to simulate ambient drying with direct sunlight exposure. Drying curves were obtained experimentally and the concentrates were analysed in terms of moisture content, water activity and degrees Brix. Depending on the drying time and type of fruit, the resulting product can be syrup-like, pasty, or have the texture of fruit leather. Under certain drying conditions, the water removal rate is actually higher for the pouch versus an open dish of the same dimensions because the pouch has two sides for mass transfer. Horizontal drying was found to be more effective than vertical drying and dissolved solids content was found to affect drying rate. Initial tests with a solar lamp have shown that drying rate increases with increasing radiant energy flux. It was also found that composition (fiber vs. sugar content) and form (purée vs. juice) of the fruit determines its compatibility with the pouch and drying technique. The results indicate that the technique is feasible and have given insight into how the bag should be designed.

NOMENCLATURE

RH	[%]	relative humidity
a_w	[-]	water activity
°Bx		degrees Brix (1 °Bx indicates density corresponding to 1 g sucrose in 100 g of solution)
W		water
L		lemon juice
W+S		water plus sugar
L+S		lemon juice plus sugar
SAP		solar assisted pervaporation

INTRODUCTION

In many developing countries, more than enough food is grown to satisfy the nutritional and caloric needs of the population, yet many still go hungry – especially children. The reason for this is that a significant amount of the food grown is not consumed due to harvest losses and spoilage before it reaches the end consumers. Estimates of post-harvest losses in Mozambique are 25-40% [1] and a large amount of fruit is never even harvested due to a short season. Households consume fruit when it is available and those who do sell fruit on the market make higher margins than for staple crops, although only for a short period. Typical small-scale farmers are only weakly linked to commercial markets, particularly due to the absence of a processing industry and preservation technology that can be adapted to the local infrastructure and prevailing economic conditions. One solution to this problem is to develop a fruit processing technology that can provide a safe and economic way to preserve the fruit when it is plentiful to be consumed at a later time. Many other preservation technologies, such as canning and aseptic processing, are economic on the large scale but also require substantial amounts of energy, clean water and a transport infrastructure, which are not always available.

The "solar assisted pervaporation (SAP)" technique would allow for small-scale farmers to preserve fruit when it is abundant using only solar energy, thereby improving food security and promoting economic growth. Pouches made of "breathable textiles" (i.e. permeable to water vapour but not liquid water) are filled with either fruit purée or juice and then exposed to sun and air. The concentration process can be done close to the point of harvest and does not require a non-renewable energy source or functioning logistics as a pre-requisite. The reusable pouches allow water to evaporate while protecting the purée or juice from contamination. The pouches can be placed on a roof, hung from a tree or set in a solar drier and within days, a storage stable (i.e. microorganisms can no longer grow) concentrate is produced. The concentrate, in its original pouch, can be stored in the household or sold. Refrigerated transport and storage are not needed which results in huge energy savings and a lower environmental impact. A simple rinse with hot water is all that is needed before the pouch can be used again. The technique has the potential to decrease malnutrition and poverty in a cost-effective way without negatively impacting the soil, water and air quality of the local surroundings.

The novel technique has never been used before for the concentration of liquid products. This paper provides the results of a feasibility study that was performed to illustrate the technique's potential.

THEORY

Theoretical understanding of the technique

The SAP technique is related to the separation techniques pervaporation and membrane distillation. With pervaporation, the transport of a chemical species from one side of a nonporous semipermeable membrane to the other occurs by diffusion of the species in the void volume of the homogeneous membrane polymer [2]. The species has an affinity for the membrane (i.e. the membrane is wetted by the species), in contrast to membrane distillation where the membrane is porous but not wetted [2, 3]. For the SAP technique, the porous membrane is the polyurethane layer coating of the textile and the chemical species is water vapour. Liquid water is not able to pass through the membrane but individual water vapour molecules can diffuse through the void volume. The transport is driven by the difference in the partial pressure of water in the fruit juice or purée, which is close to the saturation pressure even in a concentrated product, and the relative humidity (RH) of ambient air, which is usually around 60%. As long as the RH in the surrounding air is unsaturated, there will be a chemical potential gradient across the membrane and diffusion of water vapour will occur [3]. The driving force can be increased even further by heating the fruit filled bag and/or the ambient air surrounding the bag to create a larger difference in partial pressure. For example, a solar dryer could be used to increase the drying rate just by pre-heating the air that would pass along the outside of the bag [4]. By heating the air, the RH decreases and the driving force increases greatly.

With the SAP technique, evaporation of water proceeds batch-wise and the pouch shrinks as the fruit juice or purée is concentrated. This means that both sides of the membrane remain wetted and the partial pressure remains at the saturation pressure throughout almost the entire process.

Food preservation and water activity

Preserving a food product by reducing its water content is one of the oldest methods of preservation since microorganisms can only thrive if water is present. It is not the moisture content, however, that determines the microbial activity. Not all of the water present in a food is available to support microbial growth since some of the water can be adsorbed to insoluble components or bound to dissolved solutes [5]. The amount of water available for chemical reactions and microbial growth is instead related to the water activity of a product. Water activity (a_w) is the ratio of the vapour pressure of the food to the vapour pressure of pure water at the same temperature and pressure [5]. It can be related to RH by:

$$a_w = \frac{RH}{100} \tag{1}$$

For example, if a food with $a_w = 0.7$ is enclosed in a container, the RH in the air above the product would eventually reach 70%. Similarly, water has an a_w of 1 and so a glass of water in a sealed container would eventually cause the RH in the air to become 100%.

Foods with a_w below 0.7 are considered storage stable at ambient conditions since bacteria, yeasts and molds are unable to grow. Therefore, in order to preserve fruit so that refrigerated storage is not of acidic fruits to $a_w < 0.7$ provides the lowest food safety needed, the fruit must be dehydrated to an a_w of at least 0.7. Fruits that are naturally acidic also have an additional advantage since bacterial pathogens are not able to grow below pH 4.6 [6]. Therefore, dehydration risk for the end user.

MATERIALS AND METHODS

Three different fresh fruits were concentrated to make a preliminary assessment on fruit compatibility. The fruits tested were mango (Brazil), apple (Ingrid Marie variety, Sweden) and lemon (Spain). Mango is not usually processed among farmers in Mozambique yet large quantities are produced. It has one of the highest losses of all fruits produced due to its rapid maturation and from lack of proper storage facilities post-harvest. Lemon juice was chosen as a citrus fruit simulant. Large quantities of citrus fruits, such as tangerine, are produced in Mozambique but a large portion is never harvested. Apple was tested because it has a different structure and physicochemical properties compared to mango purée and citrus juice.

Mango and apple (without peel) purées were prepared with a kitchen-scale food processor (Koninklijke Philips N.V., The Netherlands). Fresh lemon juice was prepared by first squeezing the lemons with an electric juicer (Empire AB, Sweden) and then filtering the juice to remove pulp and seeds.

Breathable pouches were produced using a prototype textile with a polyurethane coating (F.O.V. Fabrics AB, Borås, Sweden) and a Multivac vacuum sealer (model A300/11, Multivac, Sepp Haggenmüller KG, Germany). All bags used were rectangular with dimensions 20.0 cm x 9.0 cm. Bags were prepared by first sealing three sides, washing with 15% v/v ethanol, rinsing with water and then drying in a 70°C oven. The juices (with or without added sugar) and purées were added to the pouches using a funnel, after which the fourth side was sealed. The dimensions of the surface area available for mass transfer on each side of the bag were 18.5 cm x 7.5 cm. Since the bag has two sides, the total surface area available for mass transfer was 0.028 m^2. The filled bags were then placed either horizontally on a rack with adequate ventilation under the bag or hung vertically.

Two different experimental setups were used to assess the concept. A convective dryer was used to simulate a ventilated solar collector and a solar simulating lamp was used to mimic drying under ambient conditions with direct exposure to sunlight. The temperature and RH-controlled pilot plant scale convective dryer was equipped with a scale (Satorius BP 4100, Bradford, MA, USA) to continuously measure the water loss for horizontally-oriented samples. The mass of vertical hanging samples was measured manually at specific time intervals using a second scale (Mettler Toledo B3001-S, Switzerland) external to the dryer. Temperature and RH were monitored inside the dyer using a Humidprobe connected to PicoLog data logging software (Pico Technology, Cambridgeshire, United Kingdom). Wind speed inside the dryer was verified using a Testo 416 vane anemometer (Testo, Hampshire, United Kingdom). The second experimental setup made use of a solar simulating sulphur plasma lamp (Fusion Lighting, Inc., USA) with a wavelength range of 400 to 900 nm and maximum irradiance of 1 kW/m^2. Bags were placed horizontally on ventilated racks or hung vertically from a frame and exposed to the radiation. Irradiance was measured using a Hand Pyranometer type 105hp (resolution ± 1 W/m^2, SolData Instruments, Silkeborg, Denmark). Ambient temperature and RH were measured using a Humidprobe and logged with PicoLog software. Concentrates were vacuum packed after drying using a Multivac sealer and stored at 4°C until analysed.

Concentrates were analysed in terms of water activity (a_w), moisture content and degrees Brix. a_w was measured at 20°C using an AquaLab Series 3TE water activity meter (Decagon Devices, Inc., Pullman, Washington, USA) calibrated using standard salt solutions (13.41m LiCl: a_w = 0.245, 8.57m LiCl: a_w = 0.496, 6.0m NaCl: a_w = 0.760 and 0.5m KCl: a_w = 0.984 at 20.0°C). The standard deviation of a_w values was ±0.003. Moisture content of the initial and dried samples was determined by heating in a Gallenkamp vacuum oven (Fistreem International Ltd., Leicestershire, United Kingdom) at 70°C until constant weight. These measurements were performed in triplicate. The dissolved solids content at 20°C was measured using a digital HI 96801 Refractometer (HANNA Instruments Inc.,Woonsocket, RI, USA) and expressed as degrees Brix (°Bx), which represents the amount of sucrose in an aqueous solution. When other dissolved solids are present in addition to sucrose, °Bx can be used to estimate the total amount of soluble solids. The analysis was carried out in triplicate.

RESULTS AND DISCUSSION

Drying curves for open dish and pouch with water

Experiments were first performed with water to compare the drying curve for open dish drying to that of the pouch. Figure 1 shows the cumulative mass loss per time observed for open dish vs. bag drying at ambient conditions (20.7 ± 0.1°C and 51.1 ± 1.3% RH) with no additional wind or energy input. The mass flux in both cases is constant, with the open dish flux approximately 1.6 times higher than that of the bag. Another case that was explored is shown in Figure 2. The drying curves in this plot were produced by evaporating water from an open dish and pouch using a convective dryer. The temperature and RH were set to 40.9 ± 0.1°C and 13.9 ± 1.5%, respectively, and the air velocity to 2.0 m/s. For this case, the mass flux was 3.8 times higher for the open dish vs. the bag. Compared to the conditions in Figure 1, the open dish and bag mass fluxes are 22 and 9 times higher, respectively, at 40°C and 2 m/s compared to 20°C and 0 m/s.

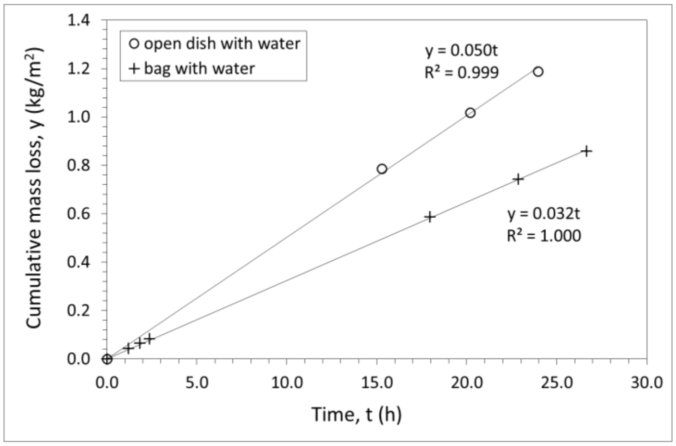

Figure 1 Open dish vs. bag drying at 20.7 ± 0.1°C and 51.1 ± 1.3% RH (no additional wind or energy input).

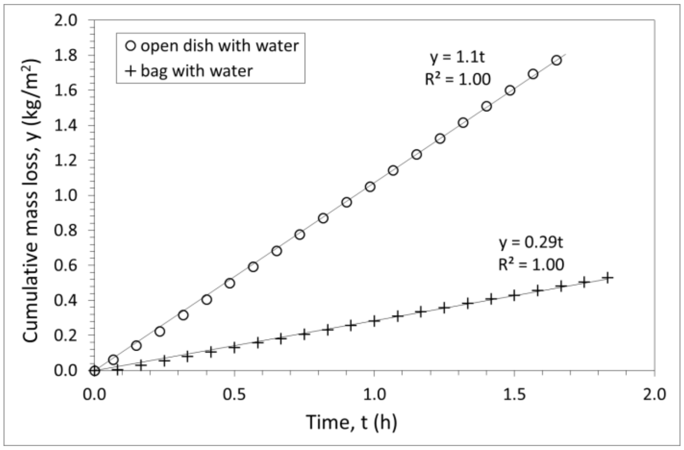

Figure 2 Open dish vs. bag drying at 40.9 ± 0.1°C and 13.9 ± 1.5% with 2.0 m/s air flow.

These initial tests show that water evaporates more quickly from an open dish compared to a bag on a per m^2 basis, but because a bag of the same dimensions has twice the surface area (i.e. two sides), the drying rate in kg/h can be higher for the bag. This is shown in Table 1. For the first case at ambient conditions, more water is actually evaporated from the bag per hour than from the open dish. For the second case where convection and a higher temperature are used, the rate is higher for the open dish. These results show that the bag can have a larger overall evaporation rate depending on the drying conditions because it has two sides for mass transfer. A next step is to determine how the drying rates for open dish and bag drying compare as a function of solar irradiance.

Table 1 Evaporation fluxes/rates for open dish (OD) vs. bag.

	Temperature (°C)	Relative humidity (%)	Air velocity (m/s)	Evaporation mass flux (kg/m^2/h)	Evaporation rate for OD (SA = 1m^2) and bag (SA = 2 m^2) (kg/h)
OD	20.7	51.1	0	0.050	0.050
Bag	20.7	51.1	0	0.032	0.064
OD	40.9	13.9	2.0	1.1	1.1
Bag	40.9	13.9	2.0	0.29	0.58

Vertical vs. horizontal bag orientation

An important question related to the optimization of the design is how the bag should be oriented during drying. Figure 3 shows the results of a trial that was performed to compare the drying rate for bags filled with lemon juice and either hung vertically or placed horizontally in a convective dryer at 40.9 ± 0.1°C and 13.9% ± 1.5%. The drying rates are similar in the beginning, but then the rate for the vertical bag gradually decreases with time. This is because when the bag is hung vertically, the liquid collects at the bottom of the bag and a “tear-drop” shape results. Instead of a constant evaporation rate along the entire wetted height of the bag, the upper part dries out and is no longer active, resulting in less surface area available for mass transfer during the drying process. This insight about the problems with vertical orientation is of great importance and will assist with optimizing the bag design.

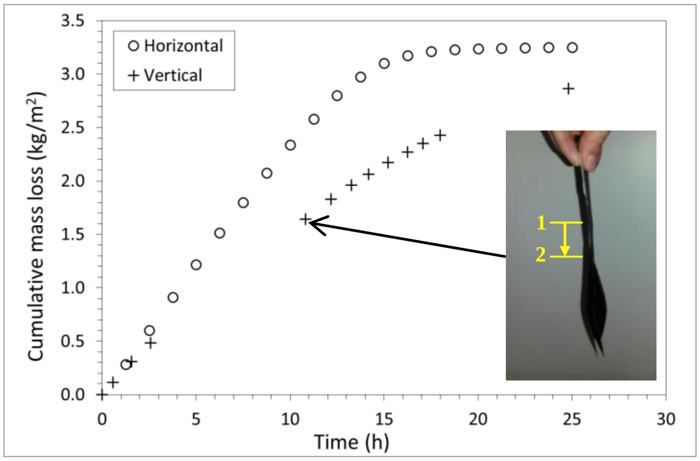

Figure 3 Horizontal versus vertical bag orientation for lemon juice drying (40.9 ± 0.1°C and 13.9 ± 1.5%). The tear-drop shape observed using the vertical orientation is shown. After 10.8 h, the height of the active area had decreased from 1 to 2.

Effect of temperature, RH and dissolved solids on drying

The effect of temperature, RH and dissolved solids on drying rate was studied using a convective dryer by drying pouches with water (W), lemon juice (L), water plus 20% w/w sugar solutions (W+S20) and lemon juice plus 20% w/w sugar solutions (L+S20). The drying conditions used were 40.9 ± 0.1°C and 13.9 ± 1.5% (Figure 4) and 51.6 ± 0.1°C and 7.5 ± 0.5% (Figure 5). The air velocity was kept constant at 2.0 m/s. In almost all cases, the drying rates are relatively constant (i.e. linear) until near the end of the drying process. The initial rates at 51.6°C and 7.5% RH for W, L and W+S20 are similar for the first four hours, whereas for the 40.9°C and 13.9% RH case, the rates for W, L, and W+S20 are only similar for about two hours, after which each sample maintains a relatively constant drying rate with the magnitude of the rate corresponding to the dissolved solids concentration (i.e. more dissolved solids = lower evaporation rate). L+S20 is an exception at both temperatures as the rate begins to decrease much earlier than with the other samples. The decreased drying rate in relation to increased dissolved solids concentration can be explained by the ability of solutes to decrease the vapour pressure of a food (e.g. through hydrogen bonding) and by a decreased diffusion coefficient for water in the fruit matrix [7, 8]. Since vapour pressure in a food is represented by a_w and the driving force for the convective mass transfer is the difference between a_w and the surrounding RH, a lower a_w reduces the driving force and therefore decreases the evaporation rate.

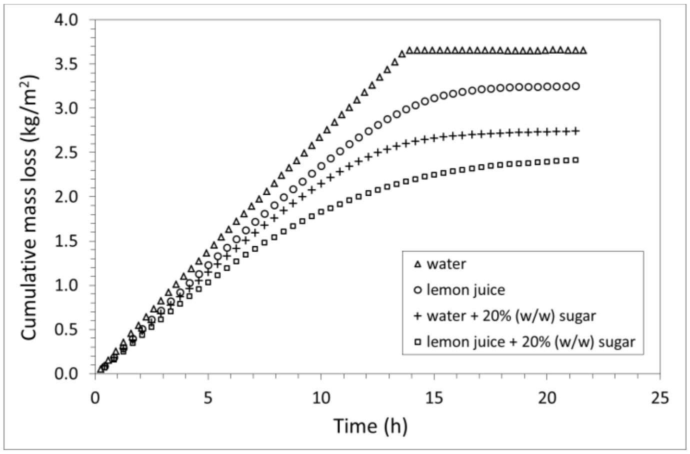

Figure 4 Drying curves from a convective dryer at 40.9 ± 0.1°C and 13.9 ± 1.5% with 2.0 m/s air velocity.

Evaporation with a solar simulator

Pouches filled with L+S20 solutions were concentrated using a solar simulating lamp to prove that dehydration is possible with the help of radiation. Four different radiant fluxes were used and convection was provided by a fan at 1.1 m/s. Figure 6 shows that the sweetened juices were effectively dehydrated after approximately 30 hours. The solar lamp was turned off overnight to simulate night conditions, but the fan remained on during this time. Drying continued but at a slightly lower flux that was approximately equal for all four samples (i.e. 0.054 ± 0.001 kg water/m^2/h). It can be seen in Figure 7 that the evaporation flux increases significantly and almost proportionally with magnitude of irradiance.

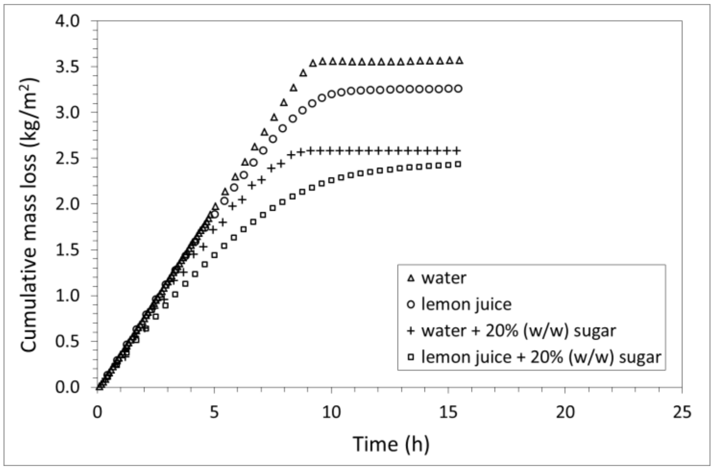

Figure 5 Drying curves from a convective dryer at 51.6 ± 0.1°C and 7.5 ± 0.5% with 2.0 m/s air velocity.

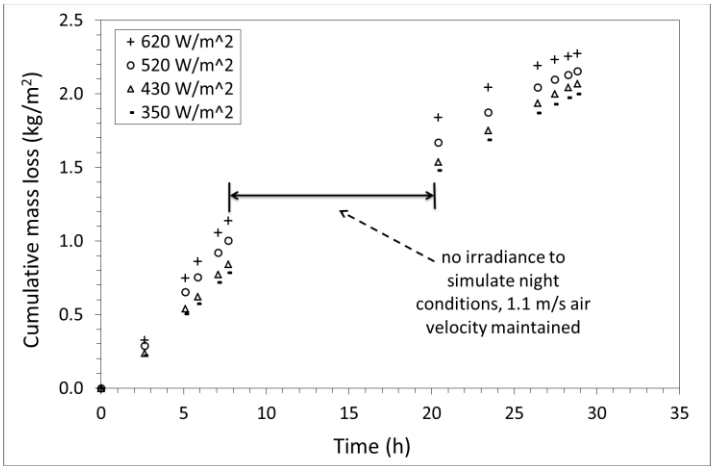

Figure 6 Drying curves for horizontal pouches filled with lemon juice + 20% w/w sugar solutions and exposed to a solar radiation simulator and 1.1 m/s air flow (surrounding air was at 20.7 ± 0.1°C and 51.1 ± 1.3% RH).

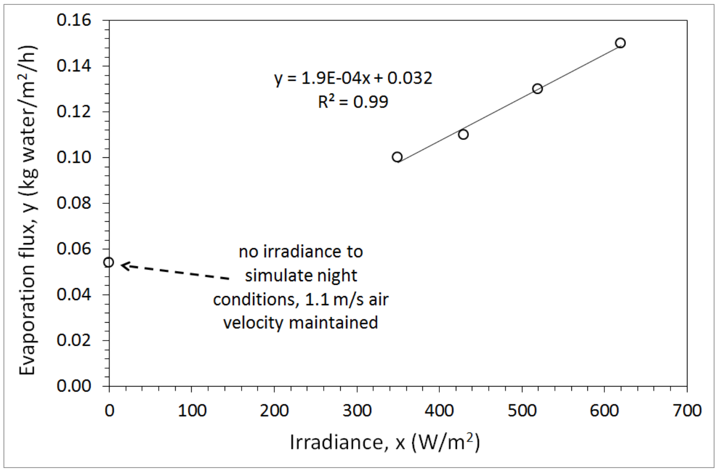

Figure 7 Effect of irradiance on evaporation flux for lemon juice + 20% w/w sugar solutions under ambient conditions (20.7 ± 0.1°C and 51.1 ± 1.3% RH) with 1.1 m/s air flow.

Compatibility of different fruits with the pouch

Three fruits (i.e. mango, apple and lemon) were tested to assess their compatibility with the pouch. In all cases, water was evaporated from the pouch and a concentrate was produced. The concentrates were produced with the bags in a horizontal orientation due to the difficulties in drying with a vertical orientation, as described above.

Diluted mango purée was concentrated for 45 hours at 40.5 ± 0.0°C and 21.3 ± 1.9% RH to see what degree of concentration could be achieved. From Table 2, it can be seen that the resulting mango “leather” had a moisture content of 9.1% and a water activity of 0.48. The leather peeled away from the textile easily and had a smooth, glossy surface. The water activity was well below the 0.7 needed for a microbiologically stable product.

Fruit leather was also produced using apple purée. One set of pouches was removed after 14.8 hours of drying at 52.0 ± 0.2°C and 10.6 ± 1.5% RH and then a second set of pouches was removed after 16.4 hours. The average moisture content and water activities for these samples are given in Table 2. It can be seen that after 14.8 hours of drying, the average water activity in the concentrate did not yet reach 0.7 but after 16.4 hours, a microbiologically stable product was achieved. An optimal drying time to reach 0.7 would therefore be between 14.8 and 16.4 hours with the given drying conditions. The apple leather was stickier than the mango leather and could not be removed as easily from the textile. One observation was that the resulting apple leather did not dry evenly. The middle parts of the leather were moister than the edges and a thin skin formed on the top and bottom parts of the leather in contact with the bag. This skin may have been a result of faster drying since 50°C air was used for this trial. The uneven drying is illustrated by the large standard deviations for both moisture content and water activity for the apple leather samples. Even after 16.4 hours, there is some variation in moisture content (less variation in water activity), but since all water activity values are below 0.7 (i.e. 0.55 to 0.62), there is no food safety risk and the variation is less of a concern. These results indicate that when the starting material is a purée, the concentrate will likely be more fruit leather-like rather than syrup or jelly-like and the drying temperature needs to be chosen carefully to avoid skin formation.

Table 2 Moisture content and water activity of the mango and apple purées and concentrates (mango: 40.5 ± 0.0 °C and 21.3 ± 1.9% RH; apple: 52.0 ± 0.2°C and 10.6 ± 1.5% RH).

Sample description	Moisture content (wt%)	Water activity
Diluted mango purée (64% w/w mango)	88.5 ± 0.0	1.00 ± 0.00
Mango leather after 45 h drying	9.1 ± 0.3	0.48 ± 0.02
Fresh apple purée (Ingrid Marie variety)	85.1 ± 0.0	0.99 ± 0.00
Apple leather after 14.8 h drying	25.9 ± 5.1	0.78 ± 0.13
Apple leather after 16.4 h drying	14.4 ± 4.3	0.55 ± 0.04

Lemon juice with added sugar (25% w/w) was concentrated to compare with the two purée examples given above. The results are shown in Table 3. After 10 hours drying at 51.9 ± 0.2°C and 9.0 ± 0.9% RH, the water activity had almost reached 0.7 and the °Bx had increased significantly from the original value of the juice/sugar solution. After 19 hours of drying, a microbiologically stable concentrate was achieved and the °Bx was close to 80. In both cases, fruit leather did not result and instead the concentrate was more syrup/jelly-like. No skin developed near the inside walls of the pouch and the concentrate could be squeezed out. Lemon juice without sugar was also dried (see previous section for drying curves) but it was found that lemon juice alone does not have enough dissolved solids for binding the amount of water needed to create a syrup or jelly. Instead, the result was a gooey paste attached to the inside of the bag. It may be better to add a small amount of sugar to the juice before concentrating to arrive at a microbiologically safe product faster and produce more user-friendly syrups or jelly-like products (i.e. squeezable).

Table 3 Moisture content, a_w and °Bx of lemon juice + 25% w/w sugar pre- and post-drying (51.9 ± 0.2°C, 9.0 ± 0.9% RH).

Sample description	Moisture content (wt%)	Water activity	°Bx
Before drying	64.4 ± 0.0	0.98 ± 0.00	34.9 ± 0.2
After 10 h drying	27.1 ± 0.1	0.78 ± 0.00	70.9 ± 0.1
After 19 h drying	18.4 ± 0.2	0.63 ± 0.00	79.5 ± 0.2

One traditional approach to preserving fruit as a jam or jelly is by boiling to evaporate the water. Converting liquid water to vapour via boiling is very energy intensive due to the latent heat of evaporation required to remove the water. For example, if 1 kg of a lemon juice plus sugar (25% w/w) solution is to be concentrated to a final moisture content of 18.2% (i.e. to achieve a water activity of 0.63 as shown in Table 4), 0.6 kg of water would need to be removed which would require an energy input of approximately 1.4 MJ. By using the SAP technique, this energy would be provided by the sun, which would not only save on costs but also eliminate the need for finite resources and result in less harm to the environment. The amount of sensible heat required to bring the juice temperature to 100°C was not accounted for in the above value which means the total energy input would be slightly higher. Compared to latent heat of evaporation, the amount of sensible heat is an order of magnitude less (approximately 240 kJ to bring 1 kg of the L+S solution from 30 to 100°C). Depending on the pH of the fruit and the temperature that the juice inside the bag reaches during drying, a pasteurisation step may not be necessarily before adding the juice to the pouches. If it is necessary, one option could be to use a solar cooker to heat up the juice, thereby eliminating any need for finite resources.

Initial conclusions can be drawn about the behaviour of juices versus purées during drying from the tests that have been conducted with mango, apple and lemon juice. The L+S solution was concentrated using nearly identical drying conditions as the apple purée, but uneven drying and skin development were not an issue for the L+S solution. This may mean that there is a risk of uneven drying if the starting material is too fibrous and/or the drying rate is too fast. There are also other benefits of producing syrups or jellies rather than leathers. With a syrup or jelly, the residual material left in the bag after squeezing can be removed with water and still used. Leather, however, has to be removed carefully from the bag and could potentially destroy the bag if there is too much adhesion at the bag-fruit interface.

CONCLUSION

The results of the feasibility study show that the SAP technique is effective both in a convective dryer and with direct solar radiation exposure. As long as the RH outside the bag is not 100%, water vapour will migrate out of the bag – even at 20°C and 50% RH. Under certain drying conditions, the bag can remove more water per hour than an open dish because of the two sides available for mass transfer. Horizontal drying is much faster than vertical drying because the entire surface is used for mass transport. Drying rate was found to decrease as a function of dissolved solids. Initial tests with a solar simulator indicate that drying rate increases significantly and almost proportionally to irradiance. It is possible to concentrate fruit juices and purées to water activities below 0.7 using the SAP technique. If the starting material is a fruit juice with a low fiber content, the final concentrate can be squeezed from the bag. Fibrous fruits may not be suitable due to uneven drying and because the bag might be destroyed upon removal of the leather-like concentrate. Next steps include a more detailed parametric study with a solar simulator, optimization of the bag design and field tests in Mozambique with local fruits.

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