Solar Assisted Pervaporation

A process for the concentration of fruit juices in membrane pouches with solar energy

Phinney, Randi

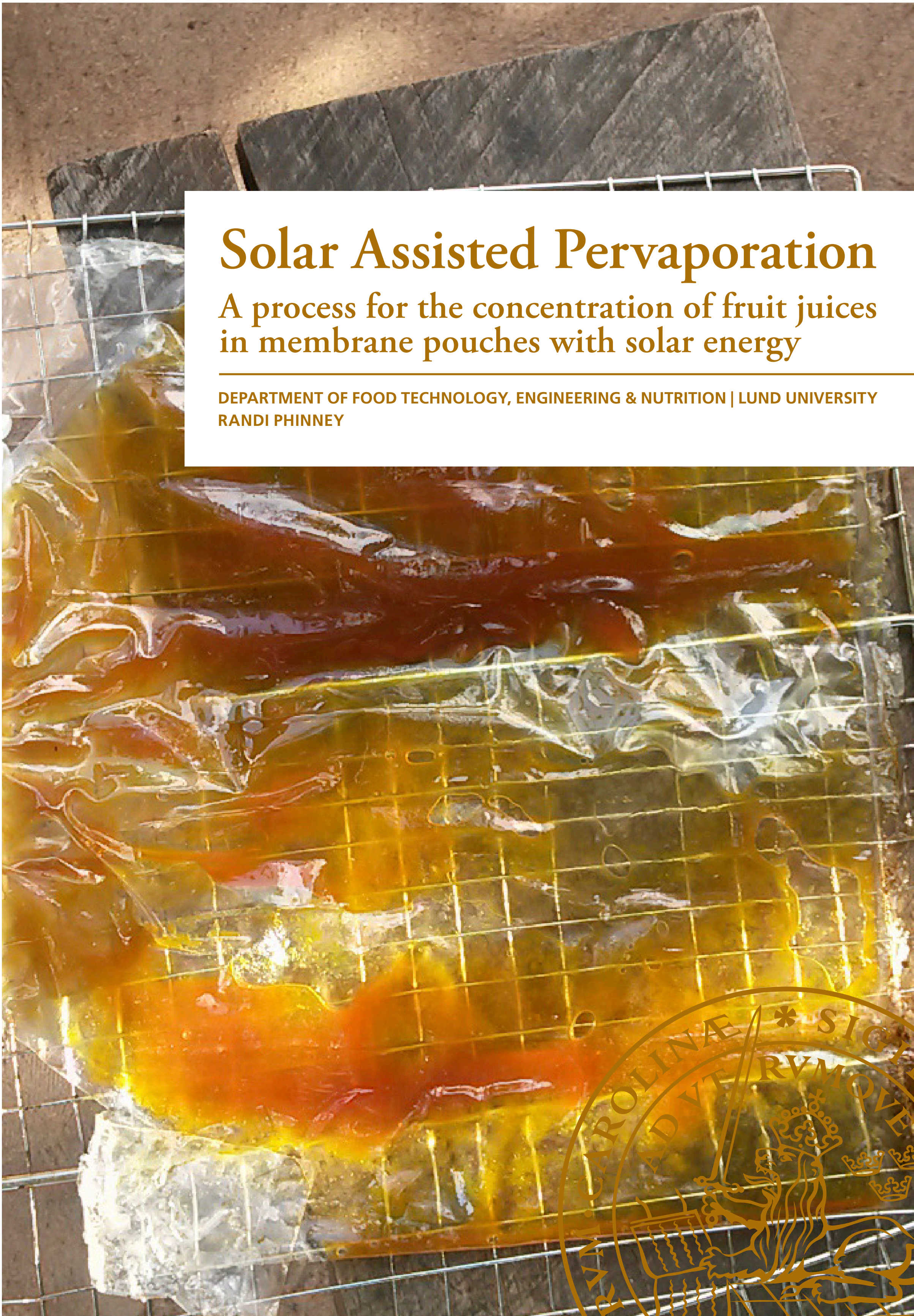
2019

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Phinney, R. (2019). *Solar Assisted Pervaporation: A process for the concentration of fruit juices in membrane pouches with solar energy*. Department of Food Technology, Engineering and Nutrition, Lund University.

Total number of authors:
1



Solar Assisted Pervaporation

A process for the concentration of fruit juices in membrane pouches with solar energy

DEPARTMENT OF FOOD TECHNOLOGY, ENGINEERING & NUTRITION | LUND UNIVERSITY
RANDI PHINNEY

Solar Assisted Pervaporation

A process for the concentration of fruit juices in membrane pouches with solar energy

Randi Phinney

2019

LUND UNIVERSITY

DOCTORAL DISSERTATION

which, by due permission of the Faculty of Engineering, Lund University, Sweden, will be publicly defended at the Center for Chemistry and Chemical Engineering, Naturvetarvägen 14, Lund, on Friday, June 14th, 2019 at 10:15 in Lecture Hall B, for the degree of Doctor of Philosophy in Engineering

Faculty opponent

Associate Professor Francesco Marra, PhD
Department of Industrial Engineering, University of Salerno, Fisciano, Italy

Organization
LUND UNIVERSITY
Department of Food Technology, Engineeing and Nutrition
Faculty of Engineering
P.O. Box 124, SE-221 00 Lund, Sweden

Author: Randi Phinney

Document name
DOCTORAL DISSERTATION

Date of issue: 2019-06-14

Sponsoring organization: Swedish Research Council (Vetenskapsrådet, VR), Dr.n. 2013-6290, 2017-05625

Title and subtitle
Solar Assisted Pervaporation
A process for the concentration of fruit juices in membrane pouches with solar energy

Abstract

Drying has been used for thousands of years to preserve foods. One of the first methods used was open air sun drying which exposes foods directly to solar radiation and ambient air. This method is still used today around the world but it remains underdeveloped on a small-scale for two main reasons. The first is that it can be unhygienic since the food is easily contaminated by pests, dust or microorganisms in the air or surroundings. The second is that it is difficult to control due to changing weather patterns and unpredictable cloud cover. Solar dryers are one alternative as they provide some protection from larger pests in the surroundings and can be used to gain more control over the process. However, there is still a risk of contamination since microorganisms in the air can be transferred to the product during the drying process. This means there is a need for improved solar drying practices that can prevent contamination from the air during drying, especially if the weather conditions are poor or drying is to continue over many days and nights.

The overall aim of this research was to develop and evaluate a safe and practical fruit juice concentration process that is suitable for rural and remote areas of tropical countries, where solar energy is abundant and fruit spoilage rates are high. The process has been termed Solar Assisted Pervaporation (SAP) and involves the concentration of fruit juices in membrane pouches with solar energy to create shelf-stable fruit juice concentrates or marmalades. The membrane pouches are permeable to water vapour but not liquid water or other nutrients. The hygienic membrane layer of the pouch also prevents the product from contamination during drying because it is impermeable to microorganisms. The process is meant for small-scale use and is especially suitable for rural and remote areas of low-income countries where infrastructure is limited.

This doctoral thesis has focused on evaluating the SAP process under controlled laboratory conditions and under realistic, outdoor conditions in Mozambique. In terms of process feasibility, the findings indicate that it takes 3 to 6 days to produce a marmalade with a soluble solids content of at least 65 degrees Brix when membrane pouches are solar dried in an outdoor, tropical environment. With regards to food safety, it was found with neutron imaging that viscous, fibrous and starchy fruit purées dry inhomogeneously compared to fruit juices. Local regions of high moisture were also observed in the purées, which means there is an increased probability of microbial growth and spoilage in these regions. The mass transport in the purées was also found to be by diffusion. The results of the field study show that by using a solar dryer, the total drying time can be reduced by 50%. The field study results are in-line with the results obtained under controlled laboratory conditions using a climate chamber, where it was shown that increasing the air velocity had a positive on the drying flux. A resistance-in-series model could be used to model the overall mass transfer resistance and assess how changing internal conditions (i.e. viscosity changes) affect the SAP process. In terms of the microbiological quality, active and passive solar drying were found to significantly reduce the probability of fermentation by yeast during drying. Pasteurisation as a juice pre-treatment was found to significantly reduce the total aerobic count, whereas solar drying setup had a negligible effect on the aerobic count. For all samples tested in Mozambique, mold, lactic acid bacteria and Enterobacteriaceae were not a concern. Mold was visible on the exteriors of some pouches yet not detected in the final samples, which indicates that the pouches provided a hygienic barrier during drying. The recommended SAP process is to add sucrose and pasteurise the tangerine juice before adding it to the pouches and then use an active solar dryer to reduce the drying time and the probability of spoilage and fermentation during drying. Pasteurisation and hot filling into sterilised jars is recommended after drying, if the marmalades are to be sold commercially.

Key words: pervaporation, solar drying, membrane pouch, juice concentration, fruit preservation, marmalade, tangerine, *Vangueria infausta*, microbiology, water activity, soluble solids, Brix

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language: English

ISSN and key title

ISBN (print): 978-91-7422-666-9

Recipient's notes

Number of pages: 159

Price

Security classification

Signature Randi Phinney   Date 2019-05-09

Solar Assisted Pervaporation

A process for the concentration of fruit juices in membrane pouches with solar energy

Randi Phinney

2019

Department of Food Technology, Engineering and Nutrition
Faculty of Engineering
Lund University, Sweden

Department of Food Technology, Engineering and Nutrition
Faculty of Engineering, Lund University

ISBN (print) 978-91-7422-666-9
ISBN (digital) 978-91-7422-667-6

Printed in Sweden by Media-Tryck, Lund University
Lund 2019

Printed matter 3041 0903

Media-Tryck is an environmentally certified and ISO 14001:2015 certified provider of printed material.
Read more about our environmental work at www.mediatryck.lu.se

MADE IN SWEDEN

To those who believed in me

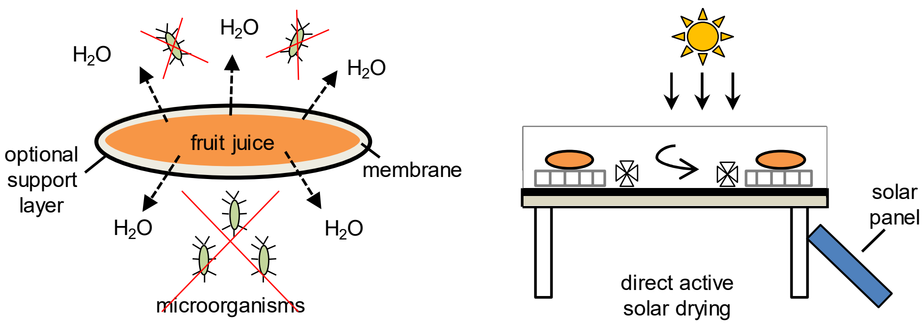
Abstract

Drying has been used for thousands of years to preserve foods. One of the first methods used was open air sun drying which exposes foods directly to solar radiation and ambient air. This method is still used today around the world but it remains underdeveloped on a small-scale for two main reasons. The first is that it can be unhygienic since the food is easily contaminated by pests, dust or microorganisms in the air or surroundings. The second is that it is difficult to control due to changing weather patterns and unpredictable cloud cover. Solar dryers are one alternative as they provide some protection from larger pests in the surroundings and can be used to gain more control over the process. However, there is still a risk of contamination since microorganisms in the air can be transferred to the product during the drying process. This means there is a need for improved solar drying practices that can prevent contamination from the air during drying, especially if the weather conditions are poor or drying is to continue over many days and nights.

The overall aim of this research was to develop and evaluate a safe and practical fruit juice concentration process that is suitable for rural and remote areas of tropical countries, where solar energy is abundant and fruit spoilage rates are high. The process has been termed Solar Assisted Pervaporation (SAP) and involves the concentration of fruit juices in membrane pouches with solar energy to create shelf-stable fruit juice concentrates or marmalades. The membrane pouches are permeable to water vapour but not liquid water or other nutrients. The hygienic membrane layer of the pouch also prevents the product from contamination during drying because it is impermeable to microorganisms. The process is meant for small-scale use and is especially suitable for rural and remote areas of low-income countries where infrastructure is limited.

This doctoral thesis has focused on evaluating the SAP process under controlled laboratory conditions and under realistic, outdoor conditions in Mozambique. In terms of process feasibility, the findings indicate that it takes 3 to 6 days to produce a marmalade with a soluble solids content of at least 65 degrees Brix when membrane pouches are solar dried in an outdoor, tropical environment. With regards to food safety, it was found with neutron imaging that viscous, fibrous and starchy fruit purées dry inhomogeneously compared to fruit juices. Local regions of high moisture were also observed in the purées, which means there is an increased probability of microbial growth and spoilage in these regions. The mass transport in the purées was also found to be by diffusion. The results of the field study show that by using a solar

dryer, the total drying time can be reduced by 50%. The field study results are in-line with the results obtained under controlled laboratory conditions using a climate chamber, where it was shown that increasing the air velocity had a positive effect on drying flux. A resistance-in-series model was used to model the overall mass transfer resistance and assess how changing internal conditions (i.e. viscosity changes) affect the SAP process. In terms of the microbiological quality, active and passive solar drying were found to significantly reduce the probability of fermentation by yeast during drying. Pasteurisation as a juice pre-treatment was found to significantly reduce the total aerobic count, whereas solar drying setup had a negligible effect on the aerobic count. For all samples tested in Mozambique, mold, lactic acid bacteria and *Enterobacteriaceae* were not a concern. Mold was visible on the exteriors of some pouches yet not detected in the final samples, which indicates that the pouches provided a hygienic barrier during drying. The recommended SAP process is to add sucrose and pasteurise the tangerine juice before adding it to the pouches and then use an active solar dryer to reduce the drying time and the probability of spoilage and fermentation during drying. Pasteurisation and hot filling into sterilised jars is recommended after drying, if the marmalades are to be sold commercially.



Popular Science Summary

What if we could reduce fruit spoilage with breathable pouches and solar energy?

In many countries, enough food is grown to feed the population yet many still go hungry. At the same time, the amount of spoiled food in the world is constantly increasing, with estimates showing that one third of food produced worldwide for human consumption never makes it to our kitchens and instead spoils somewhere along the food chain[1]. In lower income countries, most of the spoilage occurs before the food is harvested or shortly afterwards during processing, such as when the foods are cooled, washed, dried, stored or transported. The amount of spoilage also depends on the type of food. Citrus fruits, for example, have some of the highest spoilage rates globally because they are juicy and ripen very quickly. These characteristics of citrus fruits make them especially problematic for smallholder farmers in lower income countries since the fruits become difficult to handle and difficult to transport to urban markets. If there was a way to preserve citrus fruits close to where they are grown when they are ripe, the amount of spoiled fruit could be reduced and at the same time, the preserved citrus fruit products could provide an additional source of nutrition to the population throughout the year.

One way to preserve citrus fruits and foods in general is by drying them. Drying has been used for thousands of years to remove water from foods, allowing them to be stored without refrigeration for many months or years. The reason that dried foods do not spoil is related to how microorganisms like bacteria, yeast and mold need water to survive. If enough water is removed from a food product, microorganisms can no longer grow and so spoilage is prevented and the food remains safe to consume, even when stored at room temperature. The size and weight of the food is also reduced during drying, which makes it easier to transport and store. Drying is therefore an effective way to preserve foods to prevent them from spoiling and to make transport and storage easier.

Energy is also required to remove water from foods by drying, just like how energy in the form of heated air is required to dry wet clothes after they are washed. In tropical areas, this energy can come from the sun and is referred to as solar energy. Open sun drying is the traditional way to dry foods with solar energy. The food is placed on the ground or on racks and then exposed to the sun for one or more days to dry. With this type of drying, the food is often not protected or sheltered from

[1] FAO. (2011). *Global food losses and food waste – Extent, causes and prevention*. Rome.

the environment, which means that it may become contaminated during drying by rain, dust, bird droppings, pests, insects or microorganisms in the air. To reduce the amount of contamination, a solar dryer can be used. A solar dryer is a type of insulated box that uses solar energy to heat the air surrounding the food and/or increase the speed of the air flowing around the food. The heated, faster flowing air in the dryer allows for water to be removed at a higher rate, and the insulated box provides additional protection from the environment. Even though solar dryers improve the speed and safety of a drying process, there are still some challenges. For example, when there is a lot of cloud cover or during the night, the conditions in the dryer may not be favourable for drying and instead favourable for the growth of microorganisms. Since a solar dryer only protects the food from larger sources of contamination and not from microorganisms in the air, the food can become contaminated and begin to spoil. If the contamination is from yeast in the air, the product may ferment, which may not be desirable. For foods that take multiple days to dry or for areas that have a high risk of fluctuating weather conditions, there is therefore a need for small-scale, solar drying methods that can protect foods from microorganisms in the air during drying.

The research presented in this doctoral thesis addresses this need by investigating a process for preserving fruit juices with breathable membrane pouches and solar energy. The pouches are filled with juice and then placed either in a solar dryer or the open sun to dry. Water can pass through the pouch but other nutrients, like carbohydrates (sugars), vitamins and minerals, remain inside, resulting in a dried product that resembles a juice concentrate or marmalade. If enough water is removed from the juice, the sugar concentration in the final concentrate or marmalade will be high enough to create a self-preservative effect. This means the final product could be stored for many months or years at room temperature without the addition of other preservatives. The membrane also makes the process more hygienic than traditional sun and solar drying since it prevents microorganisms from contaminating the juice, both during the day and night. The process is especially suitable for citrus fruits, which are difficult to preserve with traditional solar drying methods due to their juicy nature. The environmental impact of the process is low since the energy required to evaporate the water comes from the sun. The process can also be carried out on a small-scale close to where the fruits are grown, and it does not require electricity, running water or large factories. It is particularly suitable for rural and remote areas of tropical, low-income countries where fruit resources are underutilized and solar energy is abundant.

The work that was conducted for this project consisted of controlled laboratory experiments and mathematical modelling at Lund University in Sweden as well as fieldwork in a rural area of Mozambique. In Sweden, the focus was on assessing the different parameters that affect the rate of water removal from a pouch (temperature, relative humidity, air velocity and solar irradiance) to predict which parameters would be of importance under realistic drying conditions in Mozambique. An assessment of different fruits was also performed to determine which fruits were most compatible with the membrane pouch. The fruits tested varied from citrus fruits to apples to bananas to an indigenous wild fruit from Mozambique called *Vangueria infausta* (African medlar). With the help of neutron imaging experiments performed at Paul Scherrer Institute in Switzerland, it was possible to obtain images of juices and purées inside black, opaque pouches during drying, and identify wet spots in the fruit purées where microbial growth and spoilage could occur. Since wet spots were not observed in fruit juices dried in pouches in the neutron imaging experiments, the focus of the research was thereafter directed towards the concentration of citrus fruit juices to reduce the food safety risk. Citrus fruits, such as tangerines, are also abundant in Mozambique and have high spoilage rates. The fieldwork that followed was carried out with the aim of producing tangerine marmalades that were safe to consume and had a final sugar content of at least 65 degrees Brix. This sugar content reduces the probability of spoilage, even when the marmalade is stored without refrigeration after opening, and is recommended for marmalades by the Codex Alimentarius Commission[2]. This aim was achieved with the help of two agricultural associations in the district of Inharrime, Mozambique. The best results were obtained when the pouches were dried in a direct active solar dryer (i.e. with direct exposure to the sun and equipped with fans). It was also found that adding sugar to the tangerine juice and pasteurising the juice before drying had a positive effect on the quantity of marmalade produced and on reducing the level of microorganisms, respectively.

An essential part of this research was the development and evaluation of the process in a rural area of Mozambique with the help of smallholder farmers, as well as researchers from University Eduardo Mondlane (UEM) in Mozambique, the Institute for Rural and Regional Research (Ruralis) in Norway and the Division of Energy and Building Design at Lund University in Sweden. By taking a multi-disciplinary approach that involved the farmers, it was possible for them to play an active role in the development of the process and for the researchers to receive important feedback on not only technical aspects, but also social, economic and even logistical aspects of the process. This approach was found to be an effective and critical element of this research and is highly recommended to future researchers who aim to develop and implement new technologies in rural areas of low-income countries. In addition to showing that the process can be used in Mozambique to produce safe citrus marmalades for consumption, we now have a better idea of the actual needs of the local people and the requirements for safe fruit preservation processes in rural areas. In parallel to the experiments, we also taught the local people

[2] Codex Alimentarius. (2009). Codex Standard for Jams, Jellies and Marmalades (CODEX STAN 2962009). In *3.2 Soluble Solids* (pp. 10). Rome: Codex Alimentarius Commission.

about food preservation and food safety and showed them how to make marmalade with traditional methods on-site where the fruits are grown. This had a large impact on the local people and resulted in the creation of small businesses and fruit preservation learning centers in both rural and urban areas of Mozambique.

The breathable pouch solar drying process presented in this thesis challenges the existing view on small-scale solar drying in rural areas. It is one possible solution that aims to make solar drying more hygienic, while helping people make better use of the agricultural resources they already have in an environmentally sustainable way. Even though more research is still required for the process to be suitable and practical for widespread use, the impact from this research is already being felt by the local Mozambican people, and the knowledge gained can be of help to researchers who plan to carry out agricultural research and development projects in the future.

Populärvetenskaplig sammanfattning

Är det möjligt att med hjälp av andningsbara påsar och solenergi minska mängden ej tillvaratagen mogen frukt?

I många länder produceras det egentligen tillräckligt med mat för att mätta hela befolkningen, ändå finns det människor som är hungriga. Samtidigt ökar mängden förskämd mat i världen som man idag uppskattar till en tredjedel av all producerad mat[3]. I låginkomstländer förloras merparten av maten före skörd eller precis efter när maten bearbetas, såsom under kylförvaring, torkning, lagring eller transport. Mängden skämd mat beror också på vilken typ av mat det handlar om. Citrusfrukter, till exempel, går lätt till spillo i stora mängder över hela världen på grund av att dessa frukter innehåller mycket vatten och mognar snabbt och på samma gång. Dessa egenskaper skapar problem för småskaliga bönder i låginkomstländer eftersom det blir besvärligt att hantera frukterna och transportera dem till städer och marknader. En strategi behövs för att konservera citrusfrukter i direkt anslutning till odlingsområdet när de är mogna och på detta sätt kan dessa frukter användas under hela året.

Ett sätt att konservera citrusfrukter och annan mat är att torka den. Torkning har använts i tusentals år för att ta bort vatten från mat så att den kan förvaras utan kylning i flera månader eller år. Förklaringen till detta är att mikroorganismer såsom bakterier, jäst och mögel behöver vatten för att överleva. Om tillräckligt med vatten tas bort från en produkt kan mikroorganismer inte växa längre. Detta betyder att maten blir säker att konsumera och inte går till spillo även vid förvaring i rumstemperatur. Torkning reducerar också storleken och vikten av maten vilket möjliggör att transport och förvaring blir lättare. Av dessa anledningar är torkning ett effektivt sätt att konservera mat.

När man torkar mat behöver man energi för att ta bort vattnet. Detta är precis som när man behöver energi i form av uppvärmd luft för att torka kläder efter att de tvättats. I tropiska områden kan energin komma ifrån solen och kallas då för solenergi. Öppen soltorkning är den traditionella metoden för att torka mat med solenergi där maten placeras på marken och sedan utsätts för solen i en eller flera dagar. Vid öppen soltorkning har maten inte skydd från omgivande miljö vilket innebär att maten kan kontamineras under torkningsprocessen av regn, damm, fågelexkrement, skadedjur, insekter eller mikroorganismer i luften. För att minska

[3] FAO. (2011). *Global food losses and food waste – Extent, causes and prevention*. Rome.

risken för kontaminering kan en soltork användas. Denna apparat består av en isolerad låda av något slag som fångar solenergi för att värma upp luften som passerar över eller cirkulerar runt maten. Genom att öka temperaturen och hastigheten av luften kan en soltork möjliggöra att maten torkas snabbare och samtidigt skyddar maten från omgivande miljö. Trots detta finns det några utmaningar. Till exempel när det finns mycket molntäcken på himlen eller under natten när temperaturen sjunker kan förhållanden i soltorken bli ogynnsamma för torkning och istället främja tillväxten av mikroorganismer. Eftersom en vanlig soltork bara skyddar från större kontamineringskällor och inte från mikroorganismer i luften är det möjligt att maten blir förorenad och går till spillo. Om kontamineringen kommer ifrån jäst i luften är det sannolikt att maten kommer att fermenteras vilket oftast inte är vad man vill ha. Alltså finns det ett behov av småskaliga soltorkningsmetoder som kan skydda mat från mikroorganismer i luften, särskilt när maten ska torkas i områden där processen kan ta flera dagar eller där vädret varierar från timme till timme.

Denna forskning tar upp dessa utmaningar genom att utforska en småskalig konserveringsmetod för fruktsaft med andningsbara membranbelagda påsar och solenergi. Påsar fylls med fruktsaft och placeras sedan i solen eller i en soltork för att torkas. Varje påse har ett membranlager som möjliggör att vatten kan passera ut medan resten (kolhydrater, vitaminer och mineraler) stannar kvar. När vatten kommer ut från påsen, ökar sockerinnehållet vilket också har en självkonserverande effekt. Detta innebär att andra konserveringsmedel inte måste tillsättas. Den slutliga produkten blir antingen fruktsaftkoncentrat eller marmelad, och om tillräckligt mängd vatten kommer ut från påsen kan den torkade produkten förvaras utan kylning i flera månader eller år. Membranlagret är viktigt eftersom det också hindrar bakterier och andra mikroorganismer att komma in i påsen under dagen och natten vilket innebär att processen är mer hygienisk än traditionella soltorkningsprocesser. Processen är lämplig speciellt för citrusfrukter som är utmanande att konservera med traditionella soltorkningsprocesser på grund av det höga vatteninnehållet. Miljöpåverkan är låg då energin som behövs för att avdunsta vattnet är förnyelsebar och kommer ifrån solen. Processen kan utföras på landsbygden i en liten skala nära odlingsområdet och den kräver inte el, fabriker eller stor infrastruktur. Den är även lämplig för avlägsna områden i tropiska låginkomstländer där fruktresurser inte är fullt utnyttjade och där det finns mycket solenergi.

Uppgifterna i detta projekt bestod av labbförsök under kontrollerade förhållanden och matematisk modellering på Lunds universitet i Sverige samt fältarbete på landsbygden i Moçambique. I Sverige undersöktes olika parametrar (temperatur, relativ luftfuktighet, lufthastighet och artificiell solstrålning) för att se hur dessa parametrar påverkar torkningshastigheten. Dessutom testades olika typer av frukter såsom citrusfrukter, äpplen, bananer och en inhemsk frukt från Moçambique som kallas *Vangueria infausta* (African medlar). Med hjälp av en teknik som heter *neutron imaging* blev det också möjligt att visualisera vad som händer inuti en ogenomskinlig svart påse under torkningsprocessen. Neutronexperiment på Paul Scherrer Institute i Schweiz visade att det kan bli fuktiga områden i några delar av produkten efter torkning om man torkar fruktpuréer som innehåller mycket fibrer eller stärkelse. I dessa områden kan bakterier trivas och växa vilket kan förstöra produkten eller orsaka sjukdom. På grund av detta fokuserades forskningen på citrusfrukter under resten av projektet för att minska risken för livsmedelsäkerhetsproblem. Citrusfrukter innehåller inte så mycket fibrer och stärkelse och torkar därför jämnare, med mindre risk för kvarstående fukt. Citrusfrukter är också lätt att odla i delar av Moçambique och går dessutom till spillo i stora mängder. Målet för fältarbetet som utfördes i Moçambique var att producera marmelad som är livsmedelsgodkänd och med sockerinnehållet på minst 65 grader Brix från tangeriner (liknande frukter som clementiner). Med detta sockerinnehåll kan marmeladen förvaras i rumstemperatur efter att förpackningen öppnats. Det är också sockerinnehållet som rekommenderas för marmelad av Codex Alimentarius Commission[4]. Marmeladprojektet genomfördes tillsammans med två jordbruksföreningar i distriktet Inharrime i Moçambique. De bästa resultaten erhölls när påsar torkades i en soltork med direkt solstrålning och påtvingad konvektion, så kallad *direct active solar drying*. Det var också bra att tillsätta socker i fruktsaften och pastörisera fruktmassan innan påsarna fylldes, då ökade mängden marmelad som kunde produceras samtidigt som antalet mikroorganismer i den slutliga produkten minskades.

En viktig del av detta projekt var genomförandet och utvärderingen av torkningsprocessen på landsbygden i Moçambique tillsammans med småskaliga bönder (slutanvändare) med hjälp av forskare från Eduardo Mondlanes universitet (UEM) i Moçambique, Institute for Rural and Regional Research (Ruralis) i Norge och divisionen för Energi och Byggnadsdesign vid Lunds universitet. Med denna tvärvetenskapliga approach kunde vi involvera bönder i utvecklingen samtidigt som vi fick värdefull feedback om tekniska, sociala, ekonomiska och logistiska aspekter på processen. Approachen var effektiv och en väsentlig del av detta projekt och kan rekommenderas till forskare och organisationer som utvecklar och implementerar nya teknologier i lantliga områden i låginkomstländer i framtiden. Förutom att vi har visat att det är möjligt att använda processen i Moçambique för att producera marmelad som är livsmedelgodkänd, har vi nu en bättre bild av vad lokalbefolkningen har för behov och kraven som finns för att konservera frukt på landsbygden på ett säkert sätt. Under samma tid som vi gjorde experimenten lärde vi lokalbefolkningen hur man producerar marmelad med traditionella metoder nära odlingsområdet. Effekten har blivit stor och resulterat i att små företag och lärocentrum har skapats både på landsbygden och i städerna.

[4] Codex Alimentarius. (2009). Codex Standard for Jams, Jellies and Marmalades (CODEX STAN 2962009). In *3.2 Soluble Solids* (pp. 10). Rome: Codex Alimentarius Commission.

Processen med membranpåsar som studerats i denna avhandling visar att det går att använda småskaliga soltorkningsmetoder på landsbygden för att producera hållbar marmelad. Projektet visar att soltorkning går att göra mer hygienisk och processen kan hjälpa folk att utnyttja jordbruksresurser som de redan har i närheten utan att påverka miljön negativt. Även om mer forskning behövs för att processen ska bli lämplig för utbredd användning har effekten redan blivit stor. Kunskapen som förvärvats kan dessutom hjälpa till i framtida jordbruksutvecklingsprojekt.

Resumo de divulgação científica

Redução das perdas pós-colheita das frutas: Uso de bolsas respiráveis e energia solar.

No mundo, apesar de se produzirem alimentos suficientes para as populações, ainda passa-se fome. Cerca de um terço (1/3) dos alimentos produzidos deterioram-se ao longo da cadeia alimentar[5]. Em países de baixa renda, a maior parte da deterioração dos alimentos ocorre antes e depois da colheita e a outra parte durante o processamento, armazenamento e transporte, devido, entre outras causas, à fraca rede de escoamento de produtos, fracas tecnologias de colheita, baixo processamento e conservação.

Os níveis de deterioração variam entre os produtos alimentares produzidos. Nos citrinos, que são facilmente produzidos em alguns países tropicais, os níveis de deterioração são altos porque os frutos amadurecem quase ao mesmo tempo, num curto espaço de tempo, dificultando a colheita, o manuseamento e o transporte para os mercados urbanos. Nos países de baixa renda, esta situação é mais grave para os pequenos agricultores. Para reduzir as perdas pós colheita, uma das alternativas seria a criação de técnicas de processamento e de conservação de frutos próximo dos locais de produção. Os frutos preservados poderiam constituir uma fonte adicional de renda e de nutrição para os pequenos agricultores ao longo do ano.

A forma mais comum de conservação da maioria de frutos, em países em desenvolvimento, é a secagem. A secagem permite a remoção de água dos alimentos, permitindo que estes sejam armazenados sem refrigeração por muitos meses ou anos. A razão pela qual os alimentos secos não se estragam está relacionada ao facto de os microorganismos como bactérias, leveduras e bolores, precisarem de água para poderem se desenvolver e sobreviver. Se a água de um produto alimentício for removida, os microrganismos não tem a capacidade de se desenvolver e assim a deterioração é evitada e o alimento mantém-se seguro para o consumo, mesmo quando armazenado em temperatura ambiente. Por outro lado, o tamanho e o peso dos alimentos são reduzidos durante a secagem, o que facilita o transporte e o armazenamento. Portanto, a secagem é uma forma eficaz de preservar os alimentos de modo a evitar sua deterioração e facilitar o transporte e o armazenamento.

[5] FAO. (2011). *Global food losses and food waste – Extent, causes and prevention*. Rome.

O processo de remoção da água nos alimentos pela secagem, requer energia, o mesmo que acontece quando se seca a roupa lavada. Em áreas tropicais, essa energia pode vir do sol e é conhecida como energia solar. A secagem ao ar livre é a forma tradicional de secar alimentos com energia solar. O produto alimentar é colocado no chão ou em tabuleiros e depois exposto ao sol por um ou mais dias para secar. Com este tipo de secagem, o alimento muitas vezes não é protegido dos agentes nocivos do ambiente, ficando exposto à contaminação por poeira, excrementos de pássaros, pragas, insetos ou microorganismos do ar, e às águas da chuva. Para minimizar essa contaminação é comum o uso de secadores solares. Um secador solar é um tipo de caixa onde se introduzem os produtos alimentares. Quando exposto à luz solar a energia aquece o ar que circunda os alimentos e aumenta a velocidade do ar que flui em torno dos alimentos.

No secador solar, o ar é aquecido com mais rapidez permitindo que a água no produto seja removida a uma taxa mais alta e, ao mesmo tempo, protege o produto dos agentes nocivos do ambiente. Embora os secadores solares melhorem a velocidade e a segurança de um processo de secagem, ainda existem alguns desafios. Por exemplo, durante a noite e quando o céu estiver nublado de dia as condições no secador podem não ser favoráveis à secagem, mas sim favoráveis ao crescimento de microorganismos. Apesar de o secador solar proteger os produtos alimentares de agentes nocivos do ambiente, este não protege contra a contaminação por microrganismos do ar. Se a contaminação for de levedura do ar, o produto pode fermentar, o que não é desejável. Para alimentos que levam vários dias para secar ou nas regiões susceptíveis à flutuações das condições climáticas, há, portanto, uma necessidade de métodos de secagem solar que possam proteger os alimentos dos microrganismos do ar durante s o processo de secagem.

Esta tese de doutoramento apresenta resultados de investigação sobre uma técnica de preservação de sumos de frutas de polpa líquida, tais como tangerinas e laranja, através da utilização combinada de membranas, em forma de bolsas semi-permeáveis, designadas por bolsas respiráveis, e da energia solar. As bolsas respiráveis, quando enchidas com sumo e expostas aos raios solares, permitem a passagem apenas de água em forma de vapor retendo a água em forma líquida e outras substancias químicas tais como carbohidratos (açúcares), vitaminas e minerais no interior, resultando em um produto que se assemelha a um concentrado de sumo ou marmelada. Se for retirada água suficiente do sumo, em forma de vapor, a concentração de açúcar no concentrado final ou marmelada será alta o suficiente para criar um efeito de auto conservação. Isso significa que o produto final pode ser armazenado por muitos meses ou anos à temperatura ambiente sem a adição de outros conservantes. A membrana também torna o processo mais higiênico do que a tradicional secagem solar, uma vez que impede que microrganismos contaminem o sumo, tanto durante o dia quanto à noite. O processo é especialmente adequado para os citrinos, que são difíceis de preservar com os métodos tradicionais de secagem solar, devido à sua natureza suculenta. O impacto ambiental do processo é baixo, já que a energia necessária para evaporar a água provem do sol. O processo também pode ser realizado em pequena escala, próximo do local de produção das frutas, e não requer electricidade, água corrente ou grandes fábricas. É particularmente adequado para áreas rurais e remotas de países tropicais de baixa renda, onde os frutos produzidos são subutilizados e a energia solar é abundante.

A pesquisa baseou-se na realização de vários ensaios que consistiram em i) experimentos laboratoriais em ambientes controlados e modelação matemática, na Universidade de Lund, na Suécia e ii) experimentos em campo em uma área rural de Moçambique, com suporte da Universidade Eduardo Mondlane (UEM). Na Suécia, o foco foi avaliar os diferentes parâmetros que afectam a taxa de remoção de água de uma bolsa (temperatura, humidade relativa, velocidade do ar e radiância solar) para prever os parâmetros que seriam mais importantes sob condições reais de secagem solar em Moçambique. Uma avaliação de diferentes frutas também foi realizada para determinar a compatibilidade dos frutos com a bolsa. Os frutos testados variaram de citrinos, maçãs e bananas a uma fruta silvestre indígena de Moçambique chamada Vangueria infausta (nêspera africana).

Algumas análises foram realizadas no Instituto Paul Scherrer, na Suíça, onde, através de imagens de nêutrons tiradas nas bolsas, foi possível obter, durante a secagem, imagens de sumos e purês dentro de bolsas negras e opacas, e identificar manchas húmidas nos purês de frutas onde o crescimento e a deterioração microbiana poderiam ocorrer. Como os pontos húmidos não foram observados nas imagens de nêutrons de sumos concentrados de frutos nas bolsas, o foco da pesquisa foi posteriormente direcionado para a concentração de sumos de citrinos para a redução do risco de contaminação e deterioração. Os citrinos, como as tangerinas, são abundantes em Moçambique e apresentam altas taxas de deterioração. O trabalho de campo que se seguiu foi realizado com o objetivo de produzir marmeladas de tangerina que tivessem um teor final de açúcar de pelo menos 65 graus Brix, sendo, assim, seguras para consumir. Este teor de açúcar reduz a probabilidade de deterioração, mesmo quando a marmelada é armazenada sem refrigeração após a abertura, e é recomendada para marmeladas pela Comissão do Codex Alimentarius[6].

Os trabalhos de campo foram realizadoss com a ajuda de duas associações agrícolas, na localidade de Chemane, Distrito de Inharrime, Província de Inhambane, Moçambique. Os melhores resultados foram obtidos quando as bolsas foram secas em um secador solar activo directo (ou seja, com exposição directa ao sol e equipado com ventiladores). Verificou-se também que a adição de açúcar ao sumo de tangerina e pasteurização do sumo antes da secagem tiveram, respectivamente, um

[6] Codex Alimentarius. (2009). Codex Standard for Jams, Jellies and Marmalades (CODEX STAN 2962009). In *3.2 Soluble Solids* (pp. 10). Rome: Codex Alimentarius Commission.

efeito positivo sobre a quantidade de marmelada produzida e na redução do nível de microorganismos.

Uma parte considerável desta pesquisa foi o desenvolvimento e avaliação da viabilidade técnica e social do processo de secagem em uma área rural de Moçambique com o envolvimento de pequenos agricultores, que são os usuários finais, bem como dos pesquisadores da Universidade Eduardo Mondlane em Moçambique, do Instituto de Pesquisa Rural e Regional (Ruralis) na Noruega e da Divisão de Energia e Desenho de Edifícios da Universidade de Lund na Suécia. Ao adoptar uma abordagem multidisciplinar que envolveu os usuários finais, foi possível que estes desempenhassem um papel activo no desenvolvimento do processo e que os pesquisadores recebessem feedback importante não apenas sobre aspectos técnicos, mas também sobre aspectos sociais e econômicos, e até de aspectos logísticos do processo. Esta abordagem foi considerada um elemento eficaz e crítico desta pesquisa e é altamente recomendada para futuros pesquisadores que visam desenvolver e implementar novas tecnologias em áreas rurais de países de baixa renda.

Para além de mostrar que o processo pode ser usado em Moçambique para produzir marmelada de frutos de citrinos segura para o consumo, obteve-se uma visão das necessidades reais da população local e os requisitos para os processos de preservação segura de fruta nas áreas rurais. Paralelamente aos experimentos, a população local foi ensinada sobre a preservação de alimentos e segurança alimentar e foi ensinada a preparar a marmelada usando métodos tradicionais, das zonas de produção das frutas. Isto teve um grande impacto na população local e resultou na criação de pequenas empresas e centros de aprendizagem de preservação de fruta nas áreas rurais e urbanas de Moçambique.

O processo de secagem solar por bolsa respirável apresentado nesta tese desafia a visão existente sobre a secagem solar em pequena escala em áreas rurais. É uma solução possível que visa tornar a secagem solar mais higiênica, ao mesmo tempo que ajuda as pessoas a usarem os recursos agrícolas que já possuem de maneira ambientalmente sustentável. Embora ainda seja necessária mais investigação para que o processo seja adequado e prático em Moçambique, o impacto desta investigação já está a ser sentido pela população local moçambicana e o conhecimento adquirido ajudará em futuros projectos de pesquisa e desenvolvimento agrícola em Moçambique.

Translation by co-supervisor Lucas Daniel Tivana, PhD
University Eduardo Mondlane
Maputo, Mozambique

List of Papers

This thesis is based on the following papers which are referred to in the text by their Roman numerals. The papers are appended to the end of the thesis.

I. Phinney, R., Rayner, M., Sjöholm, I., Tivana, L., & Dejmek, P. (2015). Solar Assisted Pervaporation (SAP) for preserving and utilizing fruits in developing countries. Peer-reviewed paper presented at the *3rd Southern African Solar Energy Conference (SASEC Proceedings)*, 11th-13th May 2015, Skukuza, Mpumalanga, South Africa. Available at http://hdl.handle.net/2263/49551

II. Chiau, E., Phinney, R., & Sjöholm, I. Preservation of *Vangueria infausta* (African medlar) in membrane pouches with solar energy: drying characteristics, water activity and texture. *Manuscript*

III. Phinney, R., Defraeye, T., Vontobel, P., Sjöholm, I., & Rayner, M. Neutron radiography as a potential tool for investigating the dehydration of fruit juices and purées in membrane pouches. *Manuscript - Short Communication*

IV. Phinney, R., Sjöholm, I., Östbring, K., & Rayner, M. Method to assess the solar drying performance of a Solar Assisted Pervaporation process for fruit juice preservation. *Submitted*

V. Phinney, R., Tivana, L., Sjöholm, I., Östbring, K., Jeje, I., Guibundana, D., & Rayner, M. Concentration of citrus fruit juices in membrane pouches with solar energy Part 1: How solar drying setup and juice pre-treatment determine the drying flux. *Submitted*

VI. Phinney, R., Tivana, L., Östbring, K., Sjöholm, I., Dhulappanavar, G., Jeje, I., Guibundana, D, & Rayner, M. Concentration of citrus fruit juices in membrane pouches with solar energy Part 2: How solar drying setup and juice pre-treatment determine the microbiological quality. *Submitted*

Paper I is reproduced with permission from the publisher.

Randi Phinney's contributions to the papers

I. Randi Phinney designed the study together with the co-authors, produced the membrane pouches, conducted the experimental work, analysed the results, evaluated the results together with the co-authors and wrote the paper.

II. Randi Phinney designed the Solar Assisted Pervaporation experiments together with the co-authors, produced the membrane pouches with the help of one co-author, conducted the Solar Assisted Pervaporation experimental work at the Department of Energy and Building Design with the help of one co-author, analysed and evaluated the results together with the co-authors and wrote a significant portion of the paper. Randi Phinney did not assist with the *Vangueria infausta* sample preparations, the convective drying experiments or the laboratory analyses to determine the moisture content, water activity and texture of the dried purées.

III. Randi Phinney designed the study together with the co-authors, tested various approaches for producing miniature membrane pouches with input from the co-authors, conducted the experimental work at Paul Scherrer Institute in Switzerland with the help of two co-authors, analysed the results, evaluated the results together with the co-authors and wrote the paper.

IV. Randi Phinney designed the study together with the co-authors, constructed the testing apparatus with the help of one co-author, produced the membrane pouches, conducted the experimental work, analysed the results, evaluated the results together with the co-authors and wrote the paper.

V. Randi Phinney designed the study together with the co-authors, produced the membrane pouches with the help of two co-authors, conducted the experimental work in Mozambique with the help of three co-authors, analysed the results, evaluated the results together with the co-authors and wrote the paper.

VI. Randi Phinney designed the study together with the co-authors, produced the membrane pouches with the help of two co-authors, conducted the experimental work in Mozambique with the help of three co-authors, performed preliminary microbiological analyses with the help of two co-authors, analysed the results, evaluated the results together with the co-authors and wrote the paper.

Related papers not included in the thesis

Otte, P. P., Bernardo, R., Phinney, R., Davidsson, H., & Tivana, L. D. (2018). Facilitating integrated agricultural technology development through participatory research. *The Journal of Agricultural Education and Extension*, *24*, 285-299. https://doi.org/10.1080/1389224X.2018.1461662

Otte, P. P., Tivana, L. D., Phinney, R., Bernardo, R., & Davidsson, H. (2018). The importance of gender roles and relations in rural agricultural technology development: a case study on solar fruit drying in Mozambique. *Gender, Technology and Development*, *22*, 40-58. https://doi.org/10.1080/09718524.2018.1444442

Davidsson, H., Olsson, J., Phinney, R., Bernardo, R., Otte, P., & Tivana, L. (2017). Towards a homogenous drying rate using a solar fruit dryer. Paper presented at the *International Solar Energy Society (ISES) Solar World Congress*, 29th Oct - 2nd Nov 2017, Abu Dhabi, United Arab Emirates. Available at: https://swc2017.pse.de/file/display_attachment/c1b31847712587f7a228e90623892de

Döhlen, V., Bengtsson, G., Phinney, R., & Bernardo, L. R. (2016). Performance Testing of a Solar Thermal Fruit Dryer – A Case Study to Reduce Food Waste in Mozambique. Paper presented at the *11th International Solar Energy Society (ISES) EuroSun International Conference on Solar Energy for Buildings and Industry*, 11th-14th Oct 2016, Palma, Mallorca.

Contributions to conferences and workshops

Phinney, R., Rayner, M., Sjöholm, I., Tivana, L., & Dejmek, P. (2015). Solar Assisted Pervaporation (SAP): Parametric study for optimisation of the technique. Poster presented at the *12th International Congress on Engineering and Food (ICEF12)*, 14th-18th Jun 2015, Quebec City, Canada.

Phinney, R., Sjölin, K., Sjöholm, I., & Rayner, M. (2015). Modelling of heat and mass transfer during the cooking of stuffed and unstuffed turkeys. Poster presented at the *12th International Congress on Engineering and Food (ICEF12)*, 14th-18th Jun 2015, Quebec City, Canada.

Phinney, R., Sjöholm, I., Tivana, L., & Rayner, M. (2015). Solar Assisted Pervaporation (SAP) for Preserving and Utilising Fruits in Developing Countries. Oral presentation at *Lund University Africa Day*, 10th Nov 2015, Lund, Sweden.

Phinney, R., Defraeye, T., Vontobel, P., Dejmek, P., Sjöholm, I., & Rayner, M. (2016). Neutron radiography/tomography for visualising and quantifying the novel fruit pulp concentration process "Solar Assisted Pervaporation". Oral presentation at *Neutrons and Food*, 31st May – 2nd Jun 2016, Lund, Sweden.

Phinney, R., Sjöholm, I., Davidsson, H., Bernardo, L. R., Otte, P., Tivana, L., & Rayner, M. (2017). Membrane Bags and Solar Energy for Preserving Fruit Juices in Rural and Remote Areas of Tropical Countries. Oral presentation at *Lund University Africa Day*, 1st Mar 2017, Lund, Sweden.

Phinney, R., Sjöholm, I., Davidsson, H., Bernardo, L.R., Otte, P., Tivana, L., & Rayner, M. (2018). Membrane Bags and Solar Energy for Preserving Fruit Juices in Tropical Countries. Oral presentation at *Lund University Africa Day*, 16th Apr 2018, Lund, Sweden.

Abbreviations and Symbols

a	refers to a sample from Trial I
a_w	water activity
Δa_i	difference in species activity across a membrane
A	surface area of the pouch (m^2)
A	active solar drying
b	refers to a samples from Trial II
β_o	corresponds to the grand mean effect
β_1	corresponds to a main temperature effect
β_2	corresponds to a main relative humidity effect
β_3	corresponds to a main air velocity effect
β_{12}	corresponds to a two-factor interaction effect (*T* & *RH*)
β_{13}	corresponds to a two-factor interaction effect (*T* & *u*)
β_{23}	corresponds to a two-factor interaction effect (*RH* & *u*)
β_{123}	corresponds to a three-factor interaction effect (*T*, *RH* & *u*)
$\boldsymbol{\beta}$	β vector containing the main and interaction effects
C	main or interaction effects
°Bx	degrees Brix, 1 °Bx represents 1 g sucrose in 100 g solution
d.b.	dry basis
d.m.	dry matter
E	driving force
h	convective heat transfer coefficient from the air to the surface of the open dish or pouch ($W\ m^{-2}\ K^{-1}$)
J_i	overall mass transfer flux
k_m	apparent convective mass transfer coefficient ($m\ s^{-1}$)
L	added lemon juice

LP	added lemon juice and pasteurised
L(t)	height of the pouch as a function of time (m)
L_0	initial height of the pouch (m)
m	mass of juice (kg)
$m''_{diff-memb,1}$	diffusive mass flux of water in the top membrane (kg s^{-1} m^{-2})
$m''_{diff-memb,2}$	diffusive mass flux of water in the bottom membrane (kg s^{-1} m^{-2})
$m''_{diff-juice,1}$	diffusive mass flux of water in the juice to the top (kg s^{-1} m^{-2})
$m''_{diff-juice,2}$	diffusive mass flux of water in the juice to the bottom (kg s^{-1} m^{-2})
m''_{evap}	lumped mass flux for mass transport from the inner side of the membrane to the bulk air or drying flux (kg s^{-1} m^{-2} or kg h^{-1} m^{-2})
$m''_{evap,1}$	mass flux of water from the outside of the pouch (top surface) to the air (kg s^{-1} m^{-2})
$m''_{evap,2}$	mass flux of water from the outside of the pouch (bottom surface) to the air (kg s^{-1} m^{-2})
M_w	molecular weight of water (kg $kmol^{-1}$)
O	open sun drying
OD	open dish
P	pasteurised
Pv	passive solar drying
PSI	Paul Scherrer Institute
Δp or Δp_w	water vapour partial pressure driving force (Pa)
$p_{w,juice}(T_{juice})$	partial pressure of water vapour in the juice (Pa) at the average juice temperature T_{juice}
$p_w(T)$	partial pressure of water vapour (Pa) in a material at temperature T
$p_{w,a}(T_a)$	partial presure of water vapour in the air equal to the saturation partial pressure of water vapour at the air temperature T_a multiplied by the relative humidity (Pa)
$p_{w,sat}(T)$	saturation partial pressure of water vapour (Pa) at temperature T
$p_{w,sat}(T_s)$	saturation partial pressure of water vapour on the inner side of the membrane or at the surface of the open dish (Pa) at temperature T_s

$q''_{cond-juice,1}$	conductive heat transfer flux through the juice from the center to the top inner surface of the pouch (W m^{-2})
$q''_{cond-juice,2}$	conductive heat transfer flux through the juice from the center to the bottom inner surface of the pouch (W m^{-2})
$q''_{cond-memb,1}$	conductive heat transfer flux through the top membrane (W m^{-2})
$q''_{cond-memb,2}$	conductive heat transfer flux through the bottom membrane (W m^{-2})
q''_{conv}	lumped convective heat transfer flux from the bulk air to the inside surface of the membrane (W m^{-2})
$q''_{conv,1}$	convective heat transfer flux from the air to the top outer surface of the membrane (W m^{-2})
$q''_{conv,2}$	convective heat transfer flux from the air to the bottom outer surface of the membrane (W m^{-2})
q''_{evap}	lumped heat flux correspondng to the heat of vaporisation (W m^{-2})
$q''_{evap,1}$	heat flux from the top of the pouch corresponding to the heat of vaporisation for water (W m^{-2})
$q''_{evap,2}$	heat flux from the bottom of the pouch corresponding to the heat of vaporisation for water (W m^{-2})
$q''_{rad,net}$	net radiation transferred from the sun and surroundings to the top surface of the pouch (W m^{-2})
$\rho_{w,sat}(T_s)$	concentration/density of water vapour at the saturated surface (kg m^{-3})
$\rho_{w,a}(T_a)$	concentration or density of the water vapour in the air
R	universal gas constant (J $kmol^{-1}$ K^{-1})
$R_{i,total}$	overall apparent mass transfer resistance for species *i*
$R_{w,total}$	overall apparent mass transfer resistance for water vapour (m s^{-1})
RH or RH_a	relative humidity of the air (%)
RSM	response surface methodology
S	added sucrose
SAP	Solar Assisted Pervaporation
SL	added sucrose and added lemon juice
SP	added sucrose and pasteurised
SLP	added surcose, added lemon juice and pasteurised

t	drying time (s or h)
T	temperature (°C)
T_a	temperature of the air (°C)
$T_{a,K}$	temperature of the air (K)
T_{juice}	average temperature of the juice (°C)
T_s	membrane surface temperature (°C)
$T_{s,K}$	surface temperature (K)
u	air velocity (m s^{-1})
UEM	University Eduardo Mondlane
x_1	number between -1 and +1 that represents the temperature driving force
x_2	number between -1 and +1 that represents the RH driving force
x_3	number between -1 and +1 that represents the air velocity driving force
$\boldsymbol{X}$	vector containing the driving forces in geometric notation (-1 to +1)
$\bar{\boldsymbol{y}}$	drying flux vector (kg m^{-2} h^{-1})

Contents

1 Introduction

Food security is a major problem around the world today despite that enough food is produced to feed the global population. Part of the problem is food spoilage. The FAO estimates that one third of food produced for human consumption spoils before it reaches the final consumers (FAO, 2011). One type of food that quickly spoils after it ripens is fruit. In Mozambique, for example, post-harvest fruit losses range from 25-40% which can be attributed to short ripening seasons, poor transportation systems, insufficient storage conditions (e.g. lack of chilled storage) and inadequate preservation technologies close to where the food is grown (FAO, 2011; Future, 2011). Unharvested fruits are not included in this amount, which means the total amount of spoilage is even more. Fruits with the highest spoilage rates are often juicy fruits (e.g. tangerines, oranges, and pineapples) since they are more susceptible to damage during harvesting and transport compared to other types of fruits (Hassan, Lesmayati, Qomariah, & Hasbianto, 2014).

In many tropical countries, such as Mozambique, fruits also have a high cultural and socio-economic value and play an important role in the diet of the rural population (Magaia, 2015). Fruits are abundantly available in rural areas but a lot of this fruit never makes it to the urban areas. It would be beneficial to establish better ways to preserve the fruits by working with the rural populations since they have a lot of valuable knowledge about fruits that they can contribute. If this were successful, it would enable fruits to be transported from rural areas to urban centers, where a large portion of the population lives.

One way to preserve both juicy and non-juicy fruits is by drying. Drying is one of the oldest known preservation methods in which water is removed from foods to prevent pathogenic and spoilage microorganisms from growing in them. A food usually becomes shelf-stable (i.e. can be stored without refrigeration) if it has a water activity below 0.7 (Fontana, 2007). Traditional fruit drying technologies vary from small-scale open air sun drying to large-scale canning, aseptic processing and osmotic dehydration factories. Sun-dried raisins and sun-dried tomatoes are two examples of fruits that are successfully dried using open sun drying on larger commercial scales.

Safely drying and preserving juicy fruits in rural and remote areas can be difficult with traditional technologies. Even though open air sun drying has been used for thousands of years, it still remains underdeveloped today on smaller-scales. This is due to hygiene and food safety, since microorganisms, insects and other pests can contaminate the surface of the product during drying. The hygienic design of the drying process could be improved with solar dryers, but these hygienic considerations are often lacking in non-commercialised operations. Furthermore, a drying process that takes place over many days and nights and/or occurs in areas with variable weather conditions may result in a contaminated or spoiled product, even if a solar dryer is used. If the hygienic nature of sun and solar drying could be better controlled, an additional challenge with juicy fruits is that they are often too juicy to cut and dry in slices. This means the juice of the fruits needs to be dried in large open trays, which can be difficult to handle. Large-scale methods are often not feasible in rural and remote areas because they usually require large investments, electricity and infrastructure, which are often not available. This means there is a need for a solar drying process that is affordable, hygienic and suitable for juicy fruits.

A process that fulfils these requirements is Solar Assisted Pervaporation (SAP), which is the focus of the research presented in this doctoral thesis. SAP is a process for the concentration and preservation of fruit juices whereby membrane pouches and solar energy are used to dehydrate juices made from fruits that would otherwise spoil. Value-added shelf-stable products in the form of a juice concentrate or marmalade can be produced and either saved for personal consumption or sold at local markets for extra income. One of the main benefits of SAP is that it is more hygienic than traditional open air sun drying and multiple-day solar drying processes, since the membrane pouch protects the product from external contamination during drying.

The aim of this research was to challenge traditional solar drying practices through the development and evaluation of the SAP process in Sweden and in Mozambique. In Sweden, the research consisted of controlled laboratory experiments and mathematical modelling, while in Mozambique, the work included an evaluation of the process in a rural area with the help of local farmers and researchers from University Eduardo Mondlane. The main findings from the research are presented in this thesis and the six appended papers. The thesis focuses on five main technical objectives and additionally provides an analysis of the SAP process as a whole, considering the socio-economic, social, logistical, ethical and environmental aspects that were found to be of importance. It should be noted that fruit purées were tested in the first part of this research in order to assess their compatibility with the membrane pouch. Since the findings indicated that drying purées in membrane pouches is problematic, the latter half of the research focused on the concentration of fruit juices. Hence, the title of the thesis and all theoretical descriptions within the thesis refer only to fruit juices.

This project has been an exciting journey filled with new perspectives. It is the intention with this thesis to share this excitement and provide the reader with an opportunity to reflect on both the technical findings and social findings that have resulted from carrying out this engineering development project in Mozambique.

2 Background

This chapter provides key background information to assist with the understanding of the remainder of the thesis. A summary of the geographical characteristics and demographics of Mozambique is first given, followed by an overview of the post-harvest situation in Mozambique, and a description of the indigenous and exotic fruits selected for this research. The theory behind food preservation and drying and the main principles of solar drying are then briefly described. The process investigated in this research, Solar Assisted Pervaporation, is then introduced, including a description of the heat and mass transfer phenomena occurring in the process and how these phenomena can be mathematically modelled. The use of neutron imaging for the investigation of water distribution and transport in biological materials, such as foods, is briefly reviewed. The final section includes an overview of food microbiology and the microorganisms that are of importance to the Solar Assisted Pervaporation process.

2.1 Mozambique

Mozambique is a country located in Southeast Africa that is bordered by six other countries and the Indian Ocean (Figure 1). The country has ten provinces and a capital city (Maputo) that has also been given provincial status. The fieldwork that was a part of this doctoral research project took place in the province of Inhambane in the district of Inharrime (Figure 2). In this district, there are about 28 000 households (Governo do distrito de Inharrime, 2012). The total population of Mozambique in 2017 was 29.67 million, with the population density in that year estimated to be 37.7 people per square kilometer (The World Bank Group, 2017). About 70% of the population resides in rural areas (The World Bank Group, 2019). Within the agricultural sector, which makes up the largest part of the economy, there are 3.2 million smallholder farmers who are responsible for 95% of agricultural production (FAO, 2019). Mozambique's climate is tropical to subtropical with two main seasons. The rainy season occurs from November to March, with the average monthly temperature during these months around 25-26°C and the average monthly rainfall ranging from 71 mm to 206 mm (The World Bank Group, 2019). During the dry season (April to October), the average monthly temperature is 20-25°C, with the average monthly rainfall ranging from 10 to 75 mm. The country is a low-income county and faces a number of challenges, including poverty, low life expectancy and large differences in education levels (The World Bank Group, 2019).

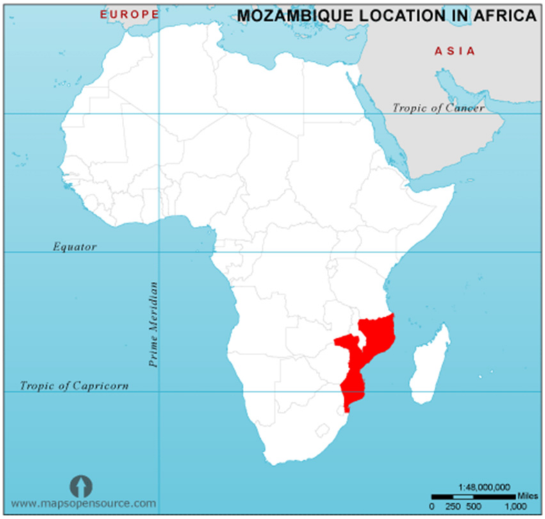


Figure 1 Location of Mozambique on the African continent. The image was obtained from www.mapsopensource.com (n.d.) and is the original image.

Figure 2 The provinces of Mozambique and bordering countries. The location where the fieldwork took place (Inharrime) is indicated by the arrow and green dot. The image was obtained from www.mapsopensource.com (n.d.) and is adapted from the original to show the location of Inharrime.

2.1.1 Overview of the post-harvest situation

Fruit is an agricultural resource in Mozambique that grows in abundance, yet spoilage rates are high (Figure 3). Post-harvest fruit losses in Mozambique are estimated to range from 25-40% (USDA, 2011), with this estimate not accounting for the many wild fruits that grow in the country. Poor post-harvest practices are one reason for the food spoilage in Mozambique and other low-income countries around the world (Affognon, Mutungi, Sanginga, & Borgemeister, 2015; Tivana, 2014). In these countries, it is estimated that more than 40% of the spoilage occurs during post-harvesting and processing due to inadequate knowledge about food preservation methods, such as drying and canning, absent or unsuitable primary processing equipment and/or poor handling and food safety practices (FAO, 2011; USDA, 2011). Some crops, like cassava and peanuts, are solar dried, but fruit preservation by solar drying is less common. If solar-driven post-harvest practices could be improved for fruit preservation, this would help to reduce fruit spoilage and be a step towards lowering food insecurity.

Figure 3 Spoiled tangerines on a farm in the district of Inharrime, Mozambique. © R. Phinney, 2016.

2.1.2 Fruits selected for this research

Figure 4 Tangerines harvested in the district of Inharrime, Mozambique in July 2017. Photograph take by R. Phinney (reproduced from Papers V and VI).

The two Mozambican fruits that were focused on in this research were tangerines (*Citrus tangerina* Yu.Tanaka, *Citrus reticulata* Blanco) and a wild, indigenous fruit called *Vangueria infausta* (African medlar), also known locally as maphilwa. Tangerines (see Figure 4) were chosen because they have some of the highest spoilage rates amongst fruits grown in Mozambique, which is a common worldwide problem for citrus fruits since they are juicy and ripen quickly in large quantities. These attributes make it difficult for farmers to handle the fruits and transport them to distant urban markets (Hassan et al., 2014). Preserving the fruits by solar drying is also a challenge due to their high water content and low insoluble solids content. In the Inharrime district located in the province of Inhambane in Mozambique, it is estimated that 25 000 tons of citrus fruits grow each year (Governo do distrito de Inharrime, 2012). Based on an estimated post-harvest fruit loss of 25-40% in Mozambique (USDA, 2011), up to 10 000 tons of citrus fruits may be lost each year due to spoilage. Citrus fruits are a source of carbohydrates and additionally some vitamins and minerals, such as vitamin C and potassium (Ladanyia, 2008; Y. Liu, Heying, & Tanumihardjo, 2012).

V. infausta is a wild, indigenous fruit that is highly appreciated in Mozambique for its nutritional value (Chiau, 2015). The ripe fruit is soft and has a leathery skin (see Figure 5). Underneath the skin, there are three to five seeds surrounded by soft pulp. The fruits are normally consumed fresh or as a purée that is added to a soft, maize porridge. The fruit is sometimes sun-dried by farmers (Shackleton, Dzerefos, Shackleton, & Mathabela, 2000), but no scientific studies on solar drying have been reported in the literature. *V. infausta* was chosen for this research since it has a high insoluble dietary fibre content (Magaia, Uamusse, Sjöholm, & Skog, 2013). It also spoils in large quantities and so preservation of *V. infausta* by SAP could allow for the fruit to be better utilised by the local people during the year.

Other fruits used during the development and evaluation of the Solar Assisted Pervaporation process included lemons (*Citrus limon* (L.) Osbeck), blood oranges, apples, bananas and mango (*Mangifera indica*). Lemon juice was used in the initial feasibility study to simulate the behaviour of citrus fruit juices with low insoluble solids contents. Mango and apple were chosen for their high insoluble solids contents, whereas banana was chosen because of its high starch content. All of these fruits, apart from apples, grow abundantly in Mozambique.

Figure 5 *Vangueria infausta* fruits available for purchase in the province of Gaza, Mozambique. © R. Phinney, 2015.

2.2 Water activity, food preservation and drying

Drying in relation to food products involves the removal of water from foods in order to preserve them. It is a method that has been used for thousands of years to extend the shelf life of otherwise perishable items (Singh & Heldman, 2014). Foods that have high moisture contents and contain a lot of free water are susceptible to spoilage by either microbial or chemical degradation (Chinachoti & Schmidt, 1991; Scott, 1957). The rates of degradation in both cases are related to the amount of water that is available in the food product for microbial growth or to support chemical reactions. The amount of available water is different from moisture content, where the latter represents the total amount of water in the product. This is why moisture content alone is a poor predictor of the likelihood of spoilage.

The term used to describe the amount of available water in a product is the water activity. It quantifies the amount of water in a product that is not physically or chemically bound to other components and therefore available for use by microorganisms and in chemical reactions (Scott, 1957). Water activity (a_w) is defined as:

$$a_w = \frac{p_w(T)}{p_{w,sat}(T)} = \frac{Equilibrium\ Relative\ Humidity\ (\%)}{100} \qquad (1)$$

where

$p_w(T) =$ partial pressure of water vapour in a material at temperature T

$p_{w,sat}(T) =$ saturation partial pressure of water vapour at the same temperature, T

To give a physical context to the term, an example can be used. If a product with a water activity of 0.7 is placed in a sealed container and is allowed to form an equilibrium with the air inside the container over an extended period of time (e.g. 24 hours), the resulting relative humidity of the air in the container will be 70% and will not change over time as long as the container remains sealed. In the past, water activity was measured using such a method. Today, laboratory equipment based on dew point determination and psychrometrics is commonly available, where one water activity measurement takes about five minutes (METER Group, 2019).

The reason water activity is such a useful parameter within the food industry is that it helps to set targets for various categories of products that require different storage conditions or treatments depending on their respective water activity. Water activity is commonly related to dry basis moisture content with a curve known as a moisture sorption isotherm (T. P. Labuza, 1975). If this relationship is known for a particular food at a particular temperature, then the water activity and shelf life can be predicted based on the measured moisture content of a food. For dried foods, a water activity less than 0.7 usually results in a microbiologically stable product that can be stored without refrigeration (Fontana, 2007). Fruit preserves, such as marmalades, normally have a water activity in the range of 0.75 to 0.85 (J. Farkas, 1997; Schmidt & Fontana, 2007), and can be stored without refrigeration if packaged in a sterile manner. If the water activity is low enough and the soluble solids (i.e. sugar) content high enough in a marmalade, it may also be possible to store the marmalade unrefrigerated after opening. The Codex Standard for Jams, Jellies and Marmalades (Codex Alimentarius, 2009) recommends a soluble solids content of 60 to 65 °Bx for jams, jellies and marmalades, where the upper limit of 65 °Bx would offer the greatest protection against spoilage. By knowing the relationship between moisture content and water activity, or soluble solids content (i.e. °Bx) and water activity, it becomes possible to assess the storage stability of food products.

Drying also provides practical benefits in addition to extending the shelf life of a food. It helps to reduce the mass and volume of an item making storage and transport more efficient. Conventional, industrial drying methods include tray or cabinet drying, tunnel drying, puff drying, fluidized-bed drying, spray drying, freeze drying and drum drying (Singh & Heldman, 2014).

For any drying system, two main factors need to be considered. The first is the mass and energy balances and the second is the drying time (i.e. the time required to achieve a desired final water activity) (Singh & Heldman, 2014). Drying involves simultaneous heat and mass transfer so the mass and energy balances and how they are coupled play an important role in the drying process. The drying time is another important factor that needs to be considered and is often divided into a constant rate period, in which the drying flux (i.e. the amount of water evaporated per unit time per unit surface area with units of kg water s^{-1} m^{-2} or kg water h^{-1} m^{-2}) is constant, and one or more falling rate periods, in which the drying flux decreases with decreasing product moisture content (Figure 6) (Dennis R Heldman & Singh, 1981). During the constant rate period, the product temperature remains constant at a temperature equivalent to the wet bulb temperature of the air (Singh & Heldman, 2014). After a critical moisture content is reached, the falling rate period commences, where the drying flux decreases with time as a function of moisture content. The onset of the falling rate period and the number of different falling rate periods depends on the food matrix being dried and the drying conditions used, and can have implications on the economic feasibility of the process (Singh & Heldman, 2014).

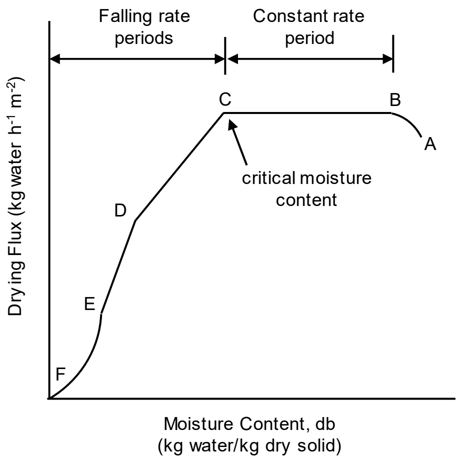


Figure 6 Example of a drying flux curve showing the relationship between drying flux and moisture content (dry basis, db). AB may or may not be present and refers to the initial phase of drying when water removal begins and the product temperature increases. BC represents the constant rate period. CD, DE and EF refer to different falling rate periods. Image drawn by R. Phinney based on Heldman and Singh (1981).

Food preservation and/or shelf-life extension can also be achieved without drying using high temperature processing. Examples of high temperature preservation processes include pasteurisation, canning and aseptic processing. Similar to conventional industrial drying methods, these types of equipment are usually only economic on larger scales and require large investments, infrastructure and electricity. Small-scale preservation methods include fermentation and open sun or solar drying. Open sun and solar drying are related to the focus of this research and will be discussed in more detail in the next section.

2.3 Solar drying principles and applications

Open sun drying has been used all over the world for thousands of years as the traditional method for drying and preserving agricultural products. It is still used today in many countries to dry crops such as fruits, vegetables, grains and tobacco. The crops are distributed on the ground and then turned at regular intervals until enough water has been removed that the products can be stored safely for later use (Sodha & Chandra, 1994).

Open sun drying can be challenging, especially for small-scale operations, since there are many external factors that are difficult to control. Examples include cloud coverage, rain, contamination by insects, animals, microorganisms or dust, and high levels of air pollution (Chua & Chou, 2003; Eswara & Ramakrishnarao, 2013). The drying process itself is also uncontrolled which means that it can be difficult to standardize the final product quality (Brenndorfer et al., 1987). As a result, many products can be under-dried or over-dried. Under-dried products may have a water activity greater than 0.7-0.75, which would then promote spoilage. Over-dried products may have a texture that is unsuitable for consumption (i.e. too hard to chew). These limitations are part of the reason why open sun drying has remained on a small-scale and relatively underdeveloped in many countries (Brenndorfer et al., 1987; López-Malo & Ríos-Casas, 2008).

One option to improve both the hygienic nature and control of open sun drying is to use a solar dryer. A solar dryer is an apparatus that uses harnessed solar energy to increase the temperature and/or increase the velocity of the air flowing around the substance to be dried, such as food. There are three main components of a solar dryer: a solar air collector that is used to heat ambient air, a drying chamber where the products to be dried are located and where moisture removal takes place, and an air handling unit which helps to bring the heated air from the solar collector to the drying chamber (Sodha & Chandra, 1994). Depending on the design, some components may be combined or not needed at all. Many different solar dryer designs exist but the majority can be classified as direct, indirect and mixed mode dryers. A further classification can be made between active and passive dryers, where the airflow in the former is driven by forced convection and the latter by natural convection (Kalogirou, 2014). Schematics of the different types applicable to this research are shown in Figure 7. With a direct active solar dryer, the product is enclosed in a drying chamber with black internal surfaces and a transparent cover, and directly exposed to the sun. Air circulation is driven by forced convection, such as by solar-powered fans. With an indirect passive solar dryer, the product is enclosed in a chamber that is completely protected from solar exposure. A solar air collector is used to heat the ambient air, which then flows into the drying chamber as a result of natural convection (i.e. a lower air density in the solar air collector due to an increased air temperature). Mixed mode passive solar dryers are similar to indirect passive solar dryers except that the walls of the drying chamber are transparent. With mixed mode dryers, the ambient air is pre-heated with a solar air collector and the temperature of the food products in the chamber may be increased via radiation heat transfer (Sodha & Chandra, 1994). Direct mode and mixed mode dryers offer advantages in terms of drying speed since the radiant energy can be absorbed directly by the products rather than transferred first to the air and then to the products (Kalogirou, 2014; Sodha & Chandra, 1994).

There are many advantages to using solar dryers but also many challenges, especially if processing is performed outdoors and if there is direct contact between the product to be dried and the surrounding air. These challenges include:

i) Microbial spoilage may result if the ambient weather conditions are unfavourable for drying and the maximum drying temperature in the solar dryer does not reach above 50°C on a particular day. The air temperature in a solar dryer should be between 50 and 60°C as much as possible during drying to prevent microbial spoilage and deteriorations in product quality (Pott, Neidhart, Mühlbauer, & Carle, 2005).

ii) The airflow conditions inside the dryer are affected by the ambient weather conditions and amount of cloud cover throughout a day. If the airflow is poor, the product may not dry uniformly (Brenndorfer et al., 1987).

iii) A solar drying process is often discontinuous, unless the solar dryer has been equipped with an additional energy source (e.g. fossil fuels or electricity provided from the grid or a solar-charged battery), which could then allow for drying to continue during the night (Eswara & Ramakrishnarao, 2013).

These three challenges may result in spoilage (e.g. fermentation and/or mold growth) during a solar drying process. The probability of spoilage could be reduced if there was a way to prevent the food products from being contaminated by the air when the weather is poor or when drying continues through the night

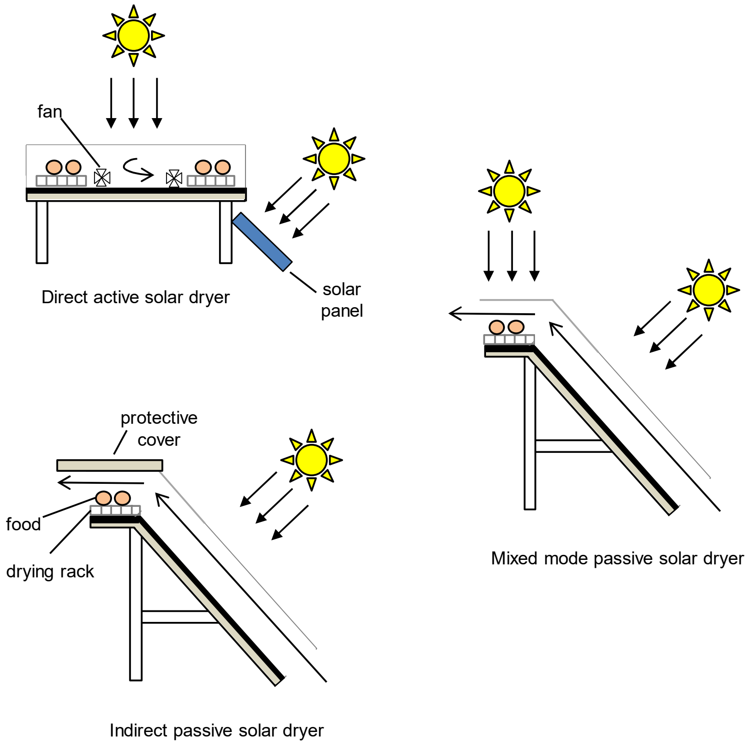


Figure 7 The different types of solar dryers applicable to this research. Images drawn by R. Phinney.

2.4 Solar Assisted Pervaporation for juice concentration

Solar Assisted Pervaporation (SAP) is the term that was given to the small-scale, juice concentration process investigated in this research. Hygienic membrane pouches that are permeable to water vapour are used to dehydrate fruit juices, with the energy required to drive the process provided by solar radiation. The hygienic benefit is attributed to the membrane, which provides a barrier to microorganisms and other pests in the surroundings due to the void spaces in the membrane being too small for microbial penetration. SAP primarily targets juicier fruits with low insoluble solids contents, such as tangerines, oranges and lemons, since these fruits are difficult to preserve by open sun drying (i.e. cannot be sliced and dried easily) and difficult to transport to urban markets, resulting in high spoilage rates compared to other types of fruits (Hassan et al., 2014). An alternative to using the SAP process would be to sun/solar dry fruit juices in large open trays. However, this would increase the probability of contamination and make handling more difficult. In theory, SAP could also be used to concentrate fruit purées made from fruits with high insoluble solids contents (e.g. mango). The benefit of using SAP with these types of fruit would be the hygienic protective barrier to microorganisms. For both juicy and non-juicy fruits, the SAP process addresses the hygienic challenges of traditional solar drying practices mentioned in the previous section, while providing a way to create value-added products from underutilised fruit resources.

2.4.1 Pervaporation theory

The SAP process is technically similar to the membrane separation process pervaporation, whereby a liquid mixture is separated by partial vaporisation using a membrane that is nonporous and permselective (Lipnizki & Trägårdh, 2001; Néel, 1995; Pangarkar & Ray, 2015). Permselective means that separation is achieved by the permeation of a species from one side of the membrane to the other, where the permeability of the dissolved chemical species across the membrane is an important parameter (Lindner, Gyurcsányi, & Buck, 2006). The phenomenon of pervaporation was first documented in 1917 by Kober who observed aqueous vapour permeating through a liquid-filled collodion membrane bag suspended in air (Kober, 1917). Binning et al. (Binning, Lee, Jennings, & Martin, 1961) later completed the first extensive investigation of pervaporation, referring to the phenomenon as liquid permeation. Since then, the process has been industrialised and is often carried out as a continuous process, with a liquid mixture passing transversely along the feed side of the membrane and an applied vacuum or swept inert gas applied to the permeate side to improve the driving force for mass transport (Jonquières et al., 2002; Mulder, 1996). The applications for pervaporation are widespread, and include the recovery of organic compounds from wastewater (Lipnizki & Field, 1999), the removal of ethanol from water or fermentation broth (Frank Lipnizki, Field, & Ten, 1999; Y. Wu, Xiao, Huang, & Zhong, 2005), catalytic reactions (Qing, Wu, Deng, Liu, & Zhang, 2017), desalination (Zwijnenberg, Koops, & Wessling, 2005) and intelligent systems (Farhadi, Pazuki, & Raisi, 2018). In the food industry, applications have been reported for the separation of organic aroma compounds from juices, such as in apple, pineapple, grape and orange juice (Olsson & Trägårdh, 1999; Pereira et al., 2005; Rajagopalan & Cheryan, 1995; Shepherd, Habert, & Borges, 2002).

In pervaporation, the species that is transported across the membrane has an affinity for the membrane. Solution-diffusion theory is normally used to describe the mass transfer through the membrane. The process includes the following three steps (Mulder, 1996; Olsson, Trägårdh, & Lipnizki, 2002):

- Selective sorption into the membrane on the feed side
- Selective diffusion through the membrane
- Desorption into a vapour phase on the permeate side

Since the species is in liquid form on the feed side of the membrane and vapour form on the downstream side, a phase change occurs during the process. The heat of vaporisation must be provided in order for this to occur (Mulder, 1996). The rate at which the separation occurs can be adjusted by controlling the driving force for mass transfer. The driving force is the chemical potential difference of the species (or partial pressure difference of the species if an ideal gas is assumed) between the feed and downstream sides of the membrane. In addition, the solubility and diffusivity of the species in the membrane play a role in the separation. Both parameters are strongly dependent on the composition of the feed stream (e.g. the type(s) of non-permeating species in the feed mixture) because the feed stream is in a liquid rather than gaseous state (Mulder, 1996).

Pervaporation theory applies to SAP since a hydrophilic, nonporous permselective membrane is used to separate water vapour (i.e. the permeating species) from a liquid mixture (i.e. fruit juice) and the driving force for mass transfer is the difference in the partial pressure of water vapour across the membrane. For example, when a fruit juice is dried in a SAP pouch in the open sun, the driving force is the difference in the partial pressure of water vapour in the fruit juice (i.e. water activity) and the partial pressure of water vapour in the surrounding air (i.e. relative humidity). Sweep gas pervaporation principles also apply to SAP if air is forced along the downstream side of the membrane at a controlled air velocity (i.e. by forced convection). If the air is pre-heated in a solar dryer, then the relative humidity of the air will decrease and the mass transfer driving force will further increase.

2.4.2 Applications of pervaporation and membrane distillation

In pervaporation, the type of membrane required depends on the type of species to be removed. Hydrophobic membranes are used when the permeating species to be removed is hydrophobic (e.g. ethanol or organic aroma compounds), whereas hydrophilic membranes are used to remove water vapour and other hydrophiles. This is a result of the nonporous nature of the membrane and the fact that the species must have an affinity for the membrane in order to permeate through it (Mulder, 1996). An example of the use of hydrophilic membranes in pervaporation is with solar driven membrane desalination for the production of desalinated fresh water from seawater and wastewater, either with a tubular membrane configuration (Zwijnenberg et al., 2005) or a black membrane bag (Asadi et al., 2012; Maria, 1968). The solar drying of solid food pieces has also been reported with a black membrane bag (Maria, 1968). More recently, a bi-layered photothermal membrane containing a hydrophilic mixed cellulose ester membrane layer with antibacterial activity has additionally been described for clean water production (Y. Li et al., 2019).

Membrane distillation is another low-energy consuming, non-pressure driven membrane separation process that can be used to separate water vapour from a liquid mixture similar to pervaporation. The main difference between the two processes, in terms of water vapour removal, is that membrane distillation requires a hydrophobic, porous membrane, while pervaporation requires a hydrophilic, nonporous membrane. Furthermore, in membrane distillation, the water vapour molecules are transported through pores (normally 0.1 to 1 μm) based on a thermally-induced vapour pressure difference, while for pervaporation, water vapour molecules adsorb into the membrane, permeate through it and then desorb/evaporate on the downstream side (Wang, Li, Bolto, Hoang, & Xie, 2016). Membrane distillation can also be driven by solar energy since the process is normally performed at a temperature of 50-90°C. However, the disadvantage is that the hydrophobicity of the membrane can decrease with time, which can then result in membrane fouling and wetting (Tijing et al., 2015).

2.4.3 Heat and mass transfer phenomena occurring during SAP

The SAP process is complex as it involves simultaneous heat and mass transfer inside, outside and through a permselective membrane. The different modes of heat and mass transfer that could occur during SAP are shown in Figure 8. For the SAP process, energy entering the system comes from either convective heat transfer from the air to the surface of the pouch and/or net radiation transfer from the sun and surroundings to the pouch surface. This heat is then conducted through the membrane and fruit juice and/or used as the heat of vaporisation to convert the

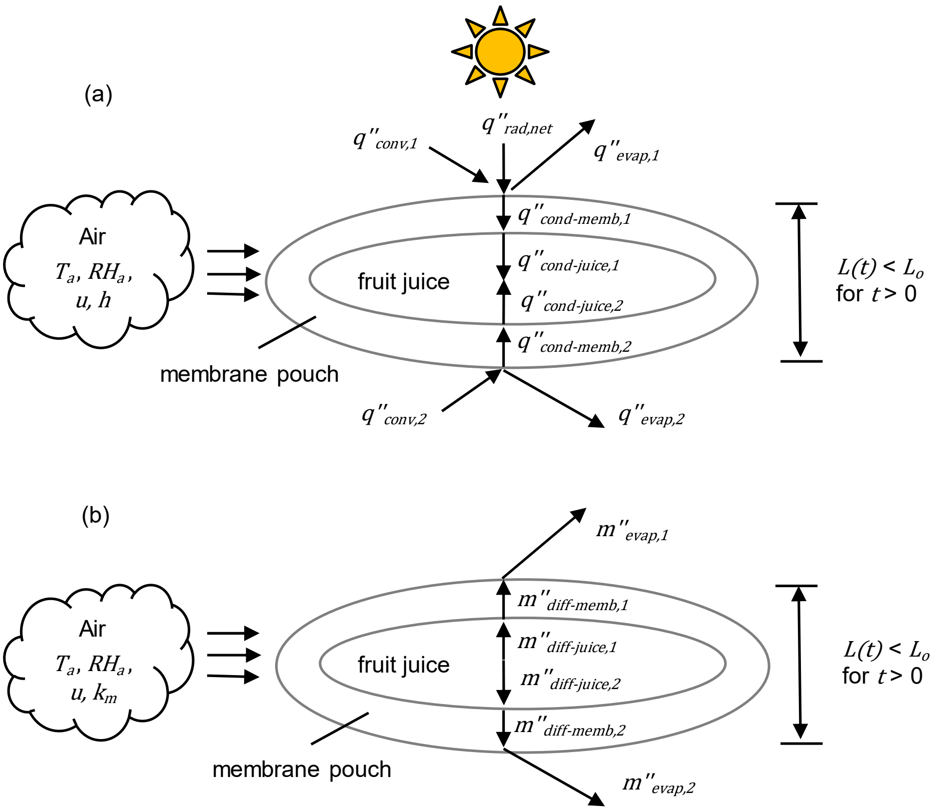


Figure 8 Energy and mass balances illustrating the modes of heat and mass transfer that apply to the SAP process (from Paper IV). The thickness of the membrane is not drawn to scale to be able to visualise the transport phenomena that apply to the membrane. See Abbreviations and Symbols for more details.
Image drawn by R. Phinney.

liquid water to vapour. During the process, water in the fruit juice diffuses from the center to the inner side of the membrane pouch, then permeates through the membrane and enters the surrounding air as water vapour by means of convective mass transfer. The rate limiting step changes throughout the drying process (i.e. external or internal; heat or mass), depending on whether constant rate or falling rate drying takes place. Separate arrows for similar phenomena have been drawn on each side of the pouch (e.g. $m''_{evap,1}$ and $m''_{evap,2}$) to illustrate that the heat and mass transfer fluxes may be different on the top and bottom of the pouch (e.g. if the pouches are exposed to direct solar radiation, the rate of water removal from the top of the pouch may be higher; alternatively, insoluble solids in the juice may settle at the bottom of the pouch resulting in different fluxes on the two sides). The complexity further increases as a function of time since the height of the pouch decreases as water vapour leaves the pouch, the driving force for mass transfer decreases as the fruit juice water activity decreases and the relative humidity in the air changes during the day/night, and the diffusivity of the water molecules diffusing through the fruit juice may decrease with increasing soluble solids content (i.e. degrees Brix) due to a viscosity increase in the juice concentrate.

The overall drying flux for the pouch is the average of the fluxes on the top and bottom (i.e. $m''_{evap,1}$ and $m''_{evap,2}$) and is obtainable by measuring the overall mass change with time. The way in which this overall drying flux is affected by the conditions inside and outside the pouch depends on whether the conditions influence the driving force for mass transfer, the mass transfer resistances, or both. The conditions outside or external to the membrane refer to the conditions in the surrounding air or atmosphere, such as radiant exposure (i.e. radiant energy received per unit surface area), air velocity, relative humidity and temperature. For example, the temperature and relative humidity would affect the driving force for mass transfer since both affect the partial pressure of water vapour in the air. The air velocity and air temperature affect the external resistances to mass transfer since they influence the thickness of the heat/mass transfer boundary layers surrounding the pouch and/or the convective heat/mass transfer coefficients (Incropera, DeWitt, Bergman, & Lavine, 2007). The overall drying flux could also be affected by the internal conditions inside the membrane pouch, such as the soluble solids content and temperature of the juice. These parameters would affect both the driving force for mass transfer (i.e. they both affect the partial pressure of water vapour in the juice) and the internal mass transfer resistance (i.e. diffusivity of water molecules in the juice as influenced by the juice viscosity). Since the viscosity of sucrose solutions increases non-linearly as a function of increasing soluble solids content (Bourne, 2002; Knecht, 1990), and an increase in soluble solids content from 20 to 70 °Bx in sucrose solutions results in a 10-fold decrease in the diffusion coefficient of water at 30°C (Yamamoto, Morihiro, Ariyoshi, & Aktas, 2005), the inverse relationship between diffusivity and viscosity and the effect of an increasing soluble solids content on drying flux cannot be neglected. The overall drying flux is therefore affected by both the external and internal conditions, where these conditions affect the driving force for mass transfer and/or mass transfer resistances in different ways.

Since it can be challenging to model a complex process like SAP by considering all of the heat and mass transfer phenomena taking place, which are functions of time and position, another approach is to apply the principles of conversation of mass to a set of control surfaces on either side of a physical boundary, such as a membrane (Incropera et al., 2007). By doing this, it becomes possible to isolate certain heat and mass transfer phenomena. An example of how this can be done is shown in Figure 9, where the control surface approach is used to isolate the mass transfer through the membrane and from the outer surface of the membrane to the surroundings. Conduction and diffusion occurring in the juice have been disregarded, since a controlled boundary condition exists on the inner side of the membrane. In this figure, it is assumed that the SAP pouch is dried in an indirect solar dryer, and so the radiation term has also been ignored. If the membrane is assumed to be infinitesimally small, the heat conduction through the membrane can be neglected, which means that the temperature on the inner and outer surfaces of the membrane is the same. This temperature is denoted as T_s and is shown on the inner side of the membrane in Figure 9 since m''_{evap} includes both the mass transfer through and outside the membrane. The convective mass transfer coefficient (k_m) is the proportionality coefficient between the mass transfer flux and the driving force for mass transfer (Incropera et al., 2007) and it is related to the drying flux as follows:

$$m''_{evap} = k_m(\rho_{w,sat}(T_s) - \rho_{w,a}(T_a)) \quad (2)$$

where $m''evap$ is the evaporation or drying flux (kg s^{-1} m^{-2}), km is the convective mass transfer coefficient (m s^{-1}), T_s is the surface temperature (°C), T_a is the air temperature (°C), $\rho_{w,sat}(T_s)$ is the concentration or density (kg m^{-3}) of water vapour at the saturated surface at temperature Ts, and $\rho_{w,a}(T_a)$ is the concentration or density (kg m^{-3}) of water vapour in the air at temperature T_a. Equation 2 can also be re-written in terms of partial pressures of water vapour rather than water vapour concentration assuming the water vapour behaves as an ideal gas:

$$m''_{evap} = \frac{k_m M_w}{R}\left(\frac{p_{w,sat}(T_s)}{T_{s,K}} - \frac{p_{w,a}(T_a)}{T_{a,K}}\right) \quad (3)$$

where M_w is the molecular weight of water (18 kg $kmol^{-1}$), R is the universal gas constant (8314 J $kmol^{-1}$ K^{-1}), $p_{w,sat}(T_s)$ is the saturation partial pressure (Pa) of water vapour at the surface at temperature T_s, $p_{w,a}(T_a)$ is the partial pressure (Pa) of water vapour in the air equal to the saturation partial pressure of water vapour at the air

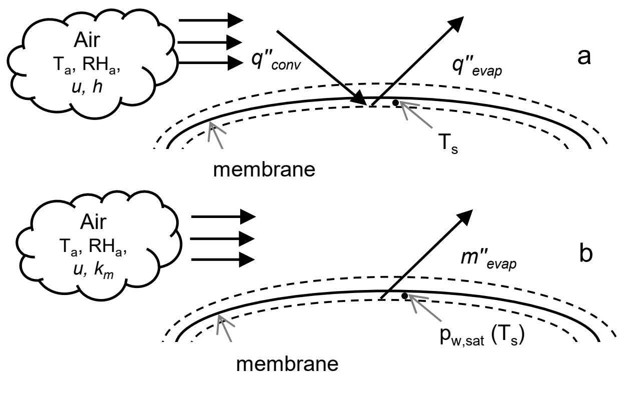


Figure 9 Surface energy and mass balances applied to isolate and investigate the (a) heat and (b) mass transfer inside the membrane and in the external ambient environment (from Paper IV). See Abbreviations and Symbols for more details. Image drawn by R. Phinney.

temperature *(T_a)* multiplied by the relative humidity of the air, $T_{S,K}$ is the surface temperature in Kelvin and $T_{a,K}$ is the air temperature in Kelvin. If the liquid in the pouch is water (i.e. a_w = 1.0), $p_{w,sat}$ refers to the saturated partial pressure of water vapour at temperature T_s. If the liquid is a fruit juice, $p_{w,sat}$ would be the partial pressure of water vapour in the juice (related to the water activity) at temperature T_s. The former case is preferred when assessing the overall mass transfer through the membrane and surrounding air, since the boundary condition would not remain constant with time if a fruit juice was used. Since the model presented in Figure 9 lumps the mass transfer resistances in the membrane and surrounding air into one convective mass transfer coefficient, k_m, it is better to term this coefficient as the *apparent* convective mass transfer coefficient. This terminology will be used in the remainder of the thesis.

2.4.4 Irreversible thermodynamic modelling approach

Irreversible thermodynamics can be used to model transport phenomena by taking a macroscopic approach that does not require any knowledge about the underlying physical mechanisms affecting the transport in the system (Gekas, 1992). This can be beneficial when the transport mechanisms are unknown, when there may be more than one mechanism involved and it is unclear how each affects the flux, or when certain variables (e.g. surface temperature) in a system are unknown. This is in contrast to models based on physical laws, such as the generalized diffusion equation, where the driving forces are based on the kinetic theory of gases and the properties of these gases on a microscopic level (e.g. the partial pressure of gases) (Gekas, 1992).

In irreversible thermodynamic modelling, the system is assumed to be a black box and an equation is written to describe this black box relating the driving forces to one or more fluxes (Gekas, 1992). The coefficients in the equation relating the driving forces to the fluxes have no physical meaning. In the case of the simplified heat and mass transfer model described for the SAP process in the previous section, an equation incorporating three driving forces (i.e. temperature (1), relative humidity (2) and air velocity (3)) and their interaction effects can be written for drying flux as follows:

$$m''_{evap} = C_1E_1 + C_2E_2 + C_3E_3 + C_{12}E_{12} + C_{13}E_{13} + C_{23}E_{23} + C_{123}E_{123} \quad (4)$$

where m''_{evap} is the drying flux (kg m^{-2} s^{-1} or kg m^{-2} h^{-1}); C_1, C_2, and C_3 correspond to the main effects of temperature, relative humidity and air velocity on the drying flux, respectively; C_{12} is the interaction effect between temperature and relative humidity on drying flux; C_{13} is the interaction effect between temperature and air velocity on drying flux; C_{23} is the interaction effect between relative humidity and air velocity on drying flux; and C_{123} is the three-factor interaction effect on the drying flux. The interaction effects are sometimes also called coupling effects. The E variables represent the driving forces. With the way the equation is written, it is difficult to determine the numerical values for E_{12}, E_{13}, E_{23} and E_{123} since they are combinations of the different driving forces. A way to solve this is by using response surface methodology (RSM). This methodology includes a number of statistical and mathematical techniques for determining the main and interaction effects, and incorporates geometric notation to account for the combined driving forces (Myers, Montgomery, & Anderson-Cook, 2016; Tamhane, 2009). This notation also make it possible to solve the model by regression with the analysis of variance method. By using RSM and taking a two-level factorial approach, the equation becomes:

$$m''_{evap} = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 \quad (5)$$

where the driving forces are now represented by x_1, x_2 and x_3, which are numbers between -1 and +1 in the case of a two-level factorial design. For example, if an experiment is designed to find the coefficients for the main and interaction effects and two temperatures are tested, then $x_1 = -1$ for the lower temperature and $x_1 = +1$ for the higher temperature. This "+" and "-" notation is called geometric notation. The β coefficients are related to the C coefficients in equation 4, where the extra variable β_0 in equation 5 represents the grand mean effect and corresponds to the case when all driving forces are "low" (i.e. equal to -1 in geometric notation). This two-level factorial approach has been applied previously to study, for example, apple purée drying in a convective dryer (Bains, Ramaswamy, & Lo, 1989), the spray drying of tomato powder (Al-Asheh, Jumah, Banat, & Hammad, 2003), the separation of fruit juice aroma compounds by pervaporation (Dawiec-Liśniewska, Podstawczyk, & Witek-Krowiak, 2018), as well as aroma recovery from beer by pervaporation (Catarino, Ferreira, & Mendes, 2009).

Taking an irreversible thermodynamic approach that is solved with a two-level factorial regression model and assuming the system is a black box can be beneficial for a number of reasons. The first is the equation for drying flux becomes a function of directly measurable process parameters (i.e. air temperature, relative humidity and velocity in this case). The parameters are directly inputted into the model using geometric notation and no other correlations, heat/mass transfer coefficients or dimensionless numbers are needed to calculate the drying flux. A second benefit is that specific system properties that are difficult to estimate or measure are not required. For example, in the case of the simplified heat and mass transfer model in Figure 9, the surface temperature needs to be known to model the system with physical models. This is because the surface temperature is needed to calculate the partial pressure of water vapour at the surface of the membrane (i.e. at the evaporation front) and determine the driving force for mass transport. This temperature is often estimated to be the wet bulb temperature in transport phenomena textbooks (Incropera et al., 2007), but this assumption may not always be valid. With irreversible thermodynamic modelling, this surface temperature does not need to be known. The third benefit is that the interaction or coupling effects between process parameters are incorporated into the flux model. For these reasons, this type of model is suitable for investigating the overall mass transport of water through the membrane and external to the membrane pouch in a SAP process.

2.4.5 Resistance-in-series modelling approach

Resistance-in-series models have been previously applied to pervaporation processes as another approach to isolating and investigating the conditions influencing mass transfer. The advantages of using this type of model are that i) the model combines process conditions (e.g. module geometry and flow regime) with membrane characteristics, ii) the "effects" that influence the mass transfer (i.e. the resistances) can be assessed individually, and iii) the driving force and resistances can be separated from each other (Lipnizki & Field, 1999; Lipnizki & Trägårdh, 2001). In addition to accounting for the permeation of a species through a membrane, the model allows for realistic processing phenomena to be incorporated into the model, such as interface/support layer effects, sorption/desorption effects, fouling and boundary layer effects (Chen, Shi, Chen, & Chen, 2018; F Lipnizki & Trägårdh, 2001; Mohammadi & Rezaeian, 2009; Qing et al., 2017).

The resistance-in-series model was introduced to pervaporation by Côte and Lipski (Côté & Lipski, 1988) and later extended and applied by many authors to assess both the overall mass transfer resistance (Ziobrowski & Rotkegel, 2017) and the individual resistances (Bennett, 1996; Ghoreyshi, Jahanshahi, & Peyvandi, 2008; M. G. Liu, Dickson, & Cote, 1996; Stürken, Wenzlaff, & Böddeker, 1993). Modelling has been primarily focused on hydrophobic membranes, but some models for water removal with hydrophilic membranes have been reported (Pantelic, Teitelbaum, Bozlar, Kim, & Meggers, 2018; Quinones-Bolanos & Zhou, 2006; Wu, Gao, Zhao, & Feng, 2018).

In the context of pervaporation, the sum of all resistances can be termed the overall apparent mass transfer resistance, $R_{i,total}$ for species i, which relates to the overall mass transfer flux (J_i) and driving force in the following way:

$$J_i = \frac{\Delta a_i}{R_{i,total}} \qquad (6)$$

Here, the driving force is the chemical potential difference of species i between the feed and permeate sides of the membrane, which can also be expressed as the difference in species activity (Δa_i) across the membrane (Lipnizki & Trägårdh, 2001).

For the SAP process, the permeating species is water vapour and so the activity can be replaced by the partial pressure of water vapour, p_w, if ideal gas conditions are assumed:

$$m''_{evap} = \frac{\Delta p_w}{R_{w,total}} = \frac{p_{w,juice}(T_{juice}) - p_{w,a}(T_a)}{R_{w,total}} \qquad (7)$$

where m''_{evap} is the overall drying flux (kg s^{-1} m^{-2}), $R_{w,total}$ is the overall apparent mass transfer resistance for water vapour (m s^{-1}), $p_{w,juice}$ is the partial pressure of water vapour in the juice (Pa) at the average juice temperature, T_{juice} (°C), and $p_{w,a}$ is the partial pressure of water vapour in the air (Pa) at the air temperature, T_a (°C). The units for resistance are m s^{-1} in this case because of the way equation 7 is derived. Different units for resistance are commonly reported in the literature since resistance can be defined in different ways, depending on the system and variables of interest (Gekas, 1992). The partial pressure of water vapour inside the pouch in this equation is the average partial pressure for the entire pouch of juice, rather than the localised partial pressure at the inner surface of the membrane. Depending on the amount of juice in the pouch and the amount of evaporative cooling, the average juice temperature will vary, with the lower limit being the wet bulb temperature and the upper limit the temperature of the surrounding air. If the external conditions remain constant during the SAP process, the overall mass transfer resistance can give an indication of when the internal conditions begin to change (e.g. significant viscosity changes). Equation 7 is therefore useful for assessing changes in the internal conditions during the SAP process without having to know the surface temperature.

2.5 Neutron imaging for investigating drying

Neutron imaging is a non-destructive radiographic technique that can be used to investigate the inner properties or characteristics of a material. The technique is possible due to the ability of neutrons to interact strongly with only a few of the chemical elements, particularly hydrogen (Lehmann, Vontobel, & Kardjilov, 2004). It is similar to x-ray radiography, with the difference being that x-rays interact with the electrons of the electronic shell of an atom, whereas neutrons interact with the nucleus of an atom (Banhart, 2008). Neutrons can also penetrate to greater depths in most metal materials compared to x-rays, as a result of the zero charge that neutrons carry (Hartnig & Manke, 2009). Radiography (2D) and tomography (3D) are both possible with neutron imaging, where the former produces a simple two-dimensional projection of only one view or angle of the sample. With tomography, a three-dimensional image is reconstructed from a series of two-dimensional projections taken during a certain time interval at different rotation angles (Kak, Slaney, & Wang, 2002; Schillinger, Lehmann, & Vontobel, 2000). Neutron beams used for imaging contain neutrons that have wavelengths on the same order of magnitude as the distances between atoms in solids and liquids (Dobrzynski & Blinowski, 1994). The use of neutron imaging in research is currently limited by the need for a reactor or spallation source to produce the neutron beam needed for experimentation (Kardjilov, Manke, Hilger, Strobl, & Banhart, 2011). Hydrogen has a particularly strong ability to attenuate (i.e. absorb and scatter) neutrons, which is why neutron imaging is suitable for visualising and quantifying the distribution and transport of water in biological materials. Previous work with neutron imaging and biological tissues has included quantifying water distribution in roots (Esser, Carminati, Vontobel, Lehmann, & Oswald, 2010; Menon et al., 2007; Moradi et al., 2011; Oswald et al., 2008), water transport in leaves (Horie, 2005; Matsushima, Kawabata, Hino, Geltenbort, & Nicolai, 2005), and the water transport in wood (Mannes, Josic, Lehmann, & Niemz, 2009; Nakanishi & Matsubayashi, 1997; Sedighi-Gilani et al., 2012). The drying behaviour of various food materials has also been studied by neutron radiography (Aregawi et al., 2014; Balaskó, Kőröusi, & Farkas, 2002; Defraeye et al., 2013; Defraeye et al., 2016) and neutron tomography (Aregawi et al., 2013).

2.6 Microbiological quality and safety of dried foods

The microbiological quality and safety of foods is important to consider when developing a food drying or dehydration process. The quality is related to the amount of spoilage microorganisms present in the food, whereas the safety is related to the presence or absence of pathogens and their toxins (Smoot & Pierson, 1997). Sometimes the distinction between spoilage and safety is not straight forward since it is possible that one type of microorganism can cause both safety and spoilage concerns (e.g. if a glass container shatters due to an overpressure of carbon dioxide produced from contaminating yeast) (Blackburn, 2006). In general, the main difference is that spoilage microorganisms cause a food to deteriorate, with the result being noticeable changes in the characteristics of the food (e.g. visual changes, aromas, or off-flavours). In contrast, pathogens do not often deteriorate the food, which also makes it difficult to detect and avoid food contaminated by pathogens. If pathogens are consumed in harmful levels (where the level depends on the microorganism), they can lead to foodborne illness, resulting in symptoms such as stomach pain, diarrhoea, vomiting and, in the worst case, death (Adams & Moss, 2000). Both spoilage microorganisms and pathogens are important factors to control in a food process and therefore need to be considered in process design.

Food preservation strategies, like drying, can be employed to reduce the number of microorganisms present in a food and/or make the environmental conditions in the food unsuitable for microbial growth. This can be achieved by regulating the intrinsic and extrinsic factors that control the microbial growth (Jay, 1996; Montville, 1997). Intrinsic factors are properties of the food material, such as pH, water activity, and the nutrients that the food contains. Extrinsic factors are factors in the surrounding environment, such as temperature, the types of gases in the atmosphere in contact with the food, and the presence of other microorganisms (Boddy & Wimpenny, 1992). For example, removing water from a food by drying will reduce the water activity (intrinsic factor) in the food, which will result in a decreased microbial growth rate. The effect is non-linear, in that the ability to hinder the growth rate becomes stronger as more and more water is removed (i.e. as the water activity approaches 0.7) (Singh & Heldman, 2014). Extrinsic factors, like temperature, can also be adjusted since each microorganism has an optimal temperature range for growth, and also upper and lower temperature limits determining when growth can and cannot occur. Common ranges of intrinsic and extrinsic factors for the different microorganisms relevant to this research are given in Table 1. It is clear from this table that yeast and mold generally grow under more extreme conditions than bacteria. In particular, yeasts and molds tend to grow at lower pH values, which means that they can cause acidic fruits to spoil. This explains why for fruit juice concentrates, yeasts are highly correlated with product quality and often used as an indicator microorganism (Jay, 1996). The intrinsic and extrinsic factors are therefore important parameters to consider when developing a food process, as they can be used to develop strategies to control the growth rate of microorganisms and help identify which types of foods are more susceptible to certain groups of microorganisms.

Another important element to consider when developing a food preservation process is that foods can be heterogeneous on a microscale (Montville, 1997). This means that even if the food appears to be homogeneous on a macroscale, there can be gradients on a microscale level in terms of pH, oxygen, water and other nutrients. The resulting microenvironments that are created as a result of these gradients can serve as ideal environments for microbial growth. For example, if a fruit slice is being dried, there may be local zones with high moisture contents adjacent to zones with low moisture contents. These local high moisture zones may have a water activity high enough to promote microbial growth, even during drying.

During solar drying specifically, there may be large fluctuations in the weather conditions, which could create environments favourable for microbial growth. In a rural setting, the microorganisms can come from a number of sources, such as the processing equipment (e.g. knives, cutting boards, juicing machines), from the people handling the fruits (e.g. from unwashed hands, open sores, coughing) and/or from the natural flora that exists in the environment and air (e.g. natural yeasts and molds in the air, natural flora on the peels of fruits). Since microorganisms are affected both by a change in water activity (intrinsic) and the drying temperature (extrinsic), both factors need to be considered when assessing the probability of spoilage due to weather fluctuations. For example, at the start of the process, the food is first heated to the air temperature in the solar dryer. If it takes a considerable amount of time for the temperature to increase in the range of 20 to 40°C, microbial growth may occur during this initial heating phase since the temperatures are optimal for growth of mesophiles and the water activity is still high (J. Farkas, 1997). During the night, mold growth may also occur in the product if the outer surface is still moist, especially if the relative humidity in the surroundings is high and the temperature is near the optimal growth temperature for mold (Jay, 1996). As drying continues and the water activity decreases, fluctuating temperatures are less of a concern since microbial growth becomes hindered. Therefore, the cyclical and discontinuous nature of solar drying (Figure 10) increases the food safety risk in a solar drying process, especially at the beginning of the drying process. Aiming to achieve temperatures greater than 40°C as much as possible in the process would help to reduce the time spent in the "risk zone".

Therefore, in order to control the growth of microorganisms that can cause a product to spoil, or in the worst case make someone ill, the intrinsic and extrinsic parameters for the microorganisms of interest should be obtained and used to control and limit the microbial growth as much as possible. Other ways to control the growth are through process hygiene, such as by ensuring that the raw materials used in the process are as clean as possible, the processing equipment is sterilised before use and the people handling the raw materials are trained with proper hygienic practices. Regarding solar dryers, the growth rate can be controlled by designing the dryers to achieve temperatures greater than 40°C as fast as possible in the morning hours and for as long as possible throughout the day. All of these measures can help to reduce the probability of creating favourable growth conditions for microorganisms, and thereby increase the probability that safe and tasty foods can be produced.

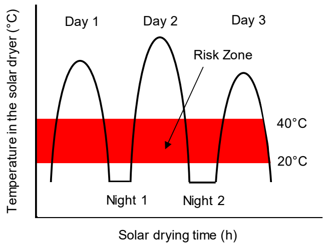


Figure 10 Example of a temperature cycle experienced during solar drying and how this relates to optimal microbial growth. Image drawn by R. Phinney.

Table 1 Intrinsic and extrinsic factors for the microorganisms of interest in this research. The data presented is a compilation of literature values from Jay (1996), Montville (1997) and Fontana (2007).

Type of microorganism	Temperature range for growth (°C)	Minimum water activity for growth at 25°C	pH range where growth is possible	Aerobic or anaerobic growth conditions	Incubation temperature for viable count method (°C)
Most spoilage bacteria (i.e. mesophiles)	20 to 45	0.91	4 to 7.5	Aerobic	30
Most spoilage yeasts	4 to 45	0.88	1.5 to 8.5	Aerobic	25
Most spoilage molds	4 to 30	0.80	0 to 11	Aerobic	25
Lactic acid bacteria	5 to 45	0.93	3.2 to 9.6	Anaerobic	25
Enterobacteriaceae	20 to 45	0.93	4 to 9	Aerobic	37

3 Aim and Objectives

The overall aim of this research was to develop and evaluate a safe and practical fruit juice concentration process that is suitable for rural and remote areas of tropical countries, where solar energy is abundant and fruit spoilage rates are high. The process was termed Solar Assisted Pervaporation (SAP). The development portion of the aim is described in the Methods and Approach section. With regards to the evaluation portion of the aim, the main objectives were to evaluate:

1. The feasibility of the process in terms of drying time, drying flux and fruit compatibility (Paper I and Paper II)
2. The possible effects of internal mass transport on food safety (Paper III)
3. The solar drying performance under controlled laboratory settings (Paper IV)
4. How solar drying setup and choice of juice pre-treatment determine the drying flux under realistic conditions in Mozambique (Paper V)
5. How solar drying setup and choice of juice pre-treatment determine the microbiological quality under realistic conditions in Mozambique (Paper VI)

The above five objectives are discussed in the Main Results and Discussion chapter of the thesis. An evaluation of the overall suitability of the SAP process for tropical countries like Mozambique is presented in Chapter 7.

4 Methods and Approach

4.1 Development of the SAP process

4.1.1 Participatory Rural Appraisal (PRA)

A approach known as Participatory Rural Appraisal (PRA) was used to help identify the needs of the end users (farmers) before introducing the membrane pouch solar drying process to them (Otte, Bernardo, Phinney, Davidsson, & Tivana, 2018; Otte, Tivana, Phinney, Bernardo, & Davidsson, 2018). This approach was taken to increase the probability that the SAP process would be designed to fit the needs and lifestyles of the farmers, rather than the farmers having to adapt their lifestyles to the process. As part of the PRA approach, seven different participatory exercises were conducted between the 7th and 19th of April, 2016, with farmers in the Inharrime district of the province of Inhambane, Mozambique. One aim was to identify key factors to consider during the design and development of the SAP process. Another was to empower the farmers to take an active role in the research and development, which is a characteristic of participatory research (Stewart-Withers, Banks, McGregor, & Meo-Sewabu, 2014). The exercises were completed in groups or on an individual level and consisted of a daily schedule exercise, a SWOT analysis, transect walks (Mahiri, 1998), a difficulty assessment of the entire process, a labour division assessment, a ranking of the technology requirements, and a photo voice exercise. The analyses were focused on technical, socio-economic and cultural factors related to the process, to help identify problems that could arise from introducing the SAP process to the farmers. After identifying the key factors, a prototype pouch was introduced to the farmers to get their feedback on the pouch design and how it should be handled and filled. New prototype pouches were then produced and introduced to the farmers iteratively, where the feedback from the farmers was always integrated into each new pouch design. The aim was to involve the farmers in the project as much as possible and establish a positive and comfortable atmosphere for knowledge and idea sharing.

4.1.2 Membrane material

Two different membrane materials were used in this thesis. In Papers I, II and III, a black, opaque textile with a hydrophilic polyurethane membrane coating was used (8209MF, F.O.V. Fabrics AB, Borås, Sweden). Pouches made from this material are referred to as “supported membrane pouches” in the remainder of the thesis, where "supported" refers to the black textile layer that gave additional support/strength to the pouches. In Papers IV, V and VI, a hydrophilic block polymer membrane film (100 µm thickness) without a textile backing layer (i.e. "unsupported membrane") was used. The polymer (Pebax® MV 1074 SA 01) was purchased from Arkema (France) and blown into a film by LOXY Sweden AB (Sweden). The first reason for using an unsupported membrane in the latter three papers is that the supported membrane material is not food grade, whereas the unsupported membrane material is food grade. It was important to perform the field tests in Mozambique with a food grade material since the aim was to taste some of the finished marmalades. The second reason for using the unsupported material is that the absence of a textile support layer made it possible to perform a two-level factorial analysis on the drying flux without having to consider any resistance effects from a support layer or interface layer. A supported (i.e. composite) membrane introduces complications since there can be interface layer effects, resulting in additional resistances (Gudernatsch, Menzel, & Strathmann, 1991; Frank Lipnizki et al., 2002). It was preferred to first develop and validate the mathematical models without interface layer effects, to ensure that fair comparisons were being made between membrane pouches and between the hydrophilic membrane and open dish. If the SAP process were to be implemented in reality, a supported (black and opaque) food-grade membrane would be preferred to improve the mechanical strength of the pouch and enhance the absorption of solar radiation.

4.1.3 Pouch design and closure mechanism

Different pouch prototypes were developed and tested in the trials/studies included in this thesis. The first prototype was made from the black, supported membrane described in the previous section (Figure 11a). The pouches were produced in-house by sealing all four sides with a Multivac vacuum sealer (model A300/11, Multivac, Sepp Haggenmüller KG, Germany). Testing was then completed with both horizontal and vertical orientations (see Paper I for more details). Subsequent prototype pouches were constructed with the unsupported membrane for use in Paper IV and in Mozambique. All unsupported pouches were produced in-house by sealing three sides of the pouch with a heat sealing machine (SF-400, Zhongmin Machinery, China). The pouch in Figure 11b was the first unsupported prototype tested in Mozambique. The pouches used in Paper IV were miniature versions of this design. The closure mechanism for these pouches consisted of two plastic pipettes. A strip of plastic was removed from one of the pipettes, allowing it to fit snuggly over the second pipette. The pouches in Figure 11d were used in the experiments of Papers V and VI. The pouch in Figure 11c was another prototype tested with the farmers to assess if the two handles would assist with filling. The closure mechanism used with the pouches in Figures 11c and 11d was made of plastic (model # PA 150) and manufactured by WeLoc in Sweden.

(a)

(b)

(c)

(d)

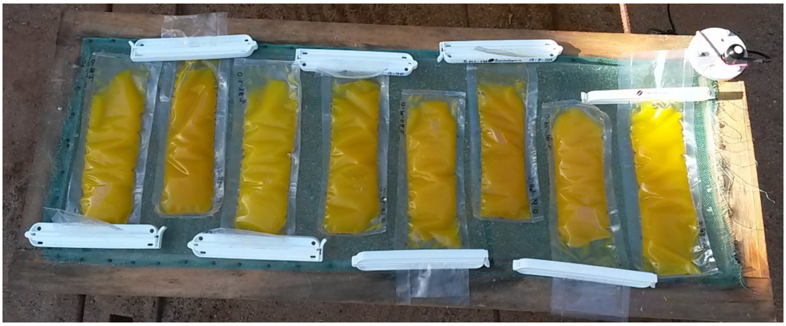


Figure 11 Pouch designs and closure mechanisms tested in this research: (a) supported membrane pouch tested in Papers I and II (and Paper III in miniature form), (b) unsupported membrane pouch with pipette clip (tested in miniature form in Paper IV); (c) unsupported membrane pouch with handles and WeLoc clip; (d) unsupported membrane pouch with WeLoc clip tested in Papers V and VI. The relative dimensions of the imagse correspond to the relative dimensions in realtiy, where the width of the black, unsupported pouches was 7.5 cm. © R. Phinney, 2014, 2016, 2017, 2017.

4.1.4 SAP process from raw to finished product

The entire SAP process, from raw to finished product, includes a number of steps (Figure 12). Before the actual SAP step can take place (marked in yellow), preparatory work is required including the collection and transport of the fruits to the processing area, washing and juicing of the fruits, and filling the pouches. Even though the main focus of this thesis was on the scientific evaluation of the removal of water vapour from membrane pouches by pervaporation, all of the steps were considered in the overall assessment of the process. One of the Participatory Rural Appraisal exercises with the farmers also included a pre-assessment of the entire process before conducting SAP experiments with them. This was to better understand how the farmers perceived the various tasks and also identify the steps that the farmers expected to be the most challenging.

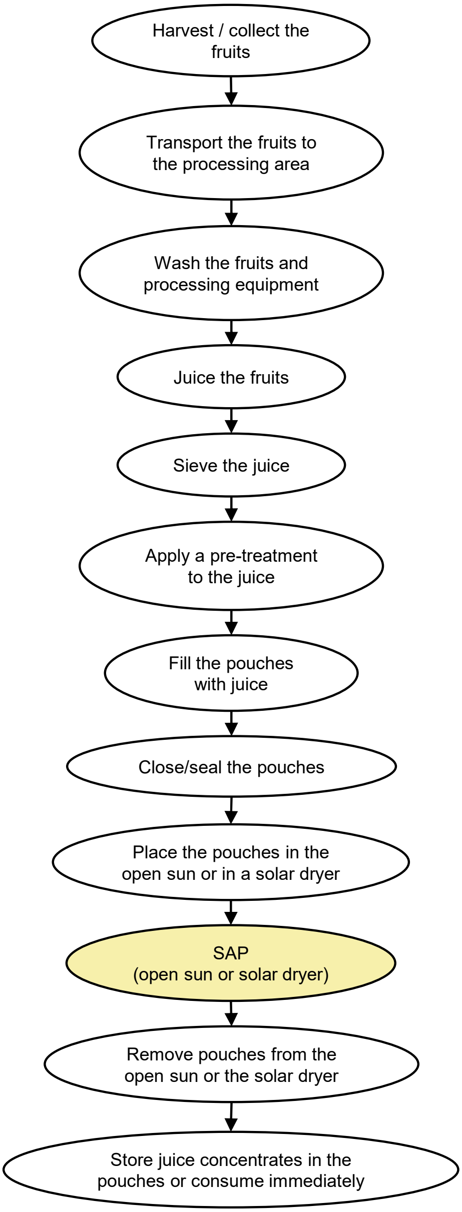


Figure 12 Steps involved in the entire SAP process, from raw to finished product.

4.2 Experimental approach

The experimental approach included five different experimental setups described in the sub-sections below. Each experimental setup represented either open sun drying or a type of solar drying. The raw materials used with each experimental setup varied depending on the aim of the specific study. On a laboratory scale, open sun drying was simulated with the solar simulating lamp and the neutron radiography setup, while indirect passive solar drying was simulated with the convective dryer and the climate-controlled chamber. During the field study in Mozambique, open sun drying, direct active solar drying and mixed mode passive solar drying (also referred to in this thesis as tilted passive solar drying) were tested under realistic drying conditions. The theory behind the solar drying methods is described in section 2.3.

4.2.1 Raw materials used in the experiments

The raw materials that were used in each experimental setup are shown in Table 2. Detailed information about the sources and suppliers of the raw materials can be found in the respective papers.

The type of fruit/raw material chosen for each experiment varied depending on the aim of the experiment. Lemon juice and blood orange juice were used during the initial feasibility experiments as model citrus fruits with a low insoluble solids content to assess compatibility of citrus fruits with the membrane pouches. Mango, apple, banana and *Vangueria infausta* purées were chosen because of their high insoluble solids contents to assess the compatibility of high fibrous fruits with the pouches and investigate potential food safety risks. Milli Q water was used as the test substance in Papers I and IV to achieve a constant boundary condition on the inside of the pouch (i.e. water activity of 1.0). This was important to be able to quantify and model the mass transport of water vapour occurring through the membrane and external to the pouch. Tangerine juice obtained from freshly harvested tangerines was used in Papers V and VI to assess the performance of the pouches under realistic drying conditions in rural Mozambique for producing tangerine marmalade. Sucrose was added before drying in some cases either to increase the weight of the final product (i.e. with marmalade) or investigate the effect of sucrose on the final texture (i.e. with purées). All citrus juices mentioned above were sieved before use to remove the pulp.

Table 2 Raw materials that were used with each experimental setup.

Experimental setup	Raw materials	Paper
Convective dryer	milli Q water, milli Q water + sucrose (20 wt%), lemon juice, lemon juice + sucrose (20 wt% or 25 wt%), mango purée, apple purée	I
	Vangueria infausta purée	II
	blood orange juice + sucrose (20 wt%)	N/A*
Solar simulating lamp	lemon juice + sucrose (20 wt%)	I
	Vangueria infausta purée*, Vangueria infausta* purée + sucrose (using purée:sucrose mass ratios of 1:1, 1:0.5 and 1:0.25)	II
Neutron radiography	apple juice, apple purée, banana purée, apple purée + D_20	III
Climate-controlled cabinet	milli-Q water	IV
Field study in Mozambique	tangerine juice, tangerine juice + sucrose (17 wt%), tangerine juice + lemon juice (10 wt%), tangerine juice + sucrose (17 wt%) + lemon juice (12 wt%)	V, VI

* Blood orange juice with added sucrose (20 wt%) was concentrated in SAP pouches in the convective dryer as part of a fruit compatibility study. The results are presented in section 5.1.5 of the thesis.

4.2.2 Convective dryer (Papers I and II)

A convective dryer (Skjöldebrand, 1980) was used in Papers I and II to simulate an indirect active solar dryer (Figure 13). Supported (black) pouches were used for all experiments. With this drying setup, it was possible to control the temperature and velocity of the air passing over the pouches. During the experiments, the air temperature in the dryer was measured with Type K (0.5 mm) thermocouples connected to a USB TC-08 Pico logger, while a Pico Humidprobe relative humidity probe was used to measure the temperature and relative humidity of the ambient air outside the dryer. The relative humidity in the dryer was then determined with an online psychrometric calculator knowing that the physical place for the measurement (Lund) is 51 meters above sea level (Universal Industrial Gases, 2003). Both parameters were logged with PicoLog data logging software (Pico Technology Limited Release 5.23.0, Cambridgeshire, United Kingdom). Air velocity was monitored with a Testo 416 small vane anemometer (Testo, Alton Hampshire, United Kingdom). Full descriptions of the procedures can be found in the respective papers.

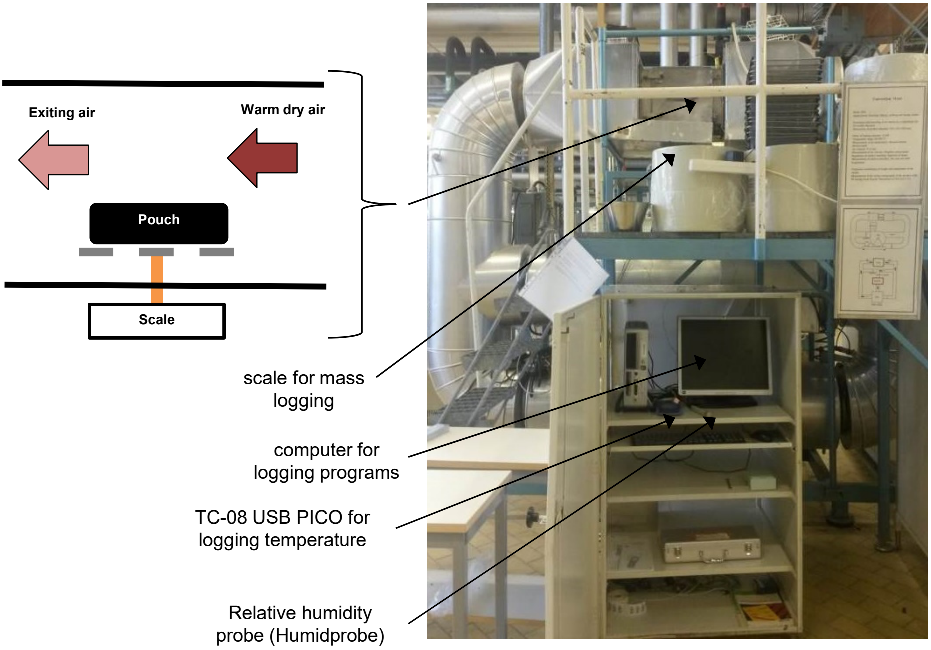


Figure 13 Convective dryer equipped with a scale that was connected to the computer for logging mass data. This apparatus was used in Papers I and II. © R. Phinney, 2017.

4.2.3 Solar simulating lamp (Papers I and II)

A solar simulating lamp was used to simulate open sun drying in Papers I and II (Figure 14). Supported (black) pouches were used in all experiments. The experiments were conducted at the Division of Energy and Building Design, Lund University Sweden. Solar irradiation was simulated with a sulphur plasma lamp (Fusion Lighting, Inc., USA) with a wavelength range of 400 to 900 nm and maximum irradiance of 1 kW/m^2 and was measured with a Hand Pyranometer type 105hp (SolData Instruments, Silkeborg, Denmark). Full experimental details are given in Papers I and II.

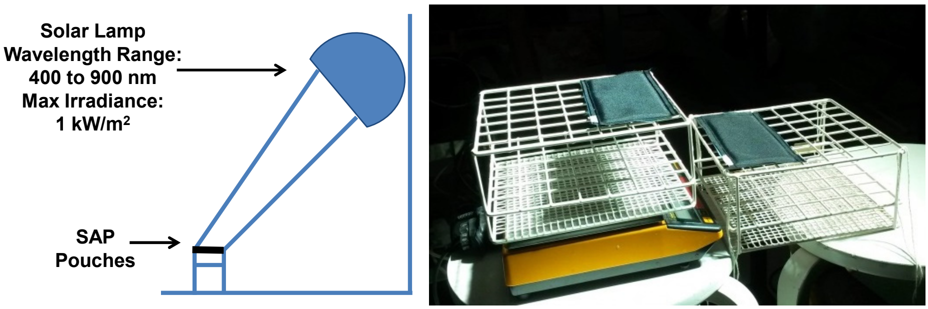


Figure 14 Left: Position of the SAP pouches in relation to the solar simulating lamp. Right: image of the pouches exposed to the simulated radiation provided by the lamp. © R. Phinney, 2014.

4.2.4 Neutron radiography setup (Paper III)

Neutron radiography was used to monitor water removal from supported (black) pouches filled with fruit juices or purées under simulated open sun drying conditions (Figure 15). The experiments were conducted at Paul Scherrer Institute (PSI) in Villigen, Switzerland. The beamline used for the experiments was NEUTRA, which is a thermal neutron radiography station with three possible sample positions and an energy level of about 25 meV (Lehmann, Vontobel, & Wiezel, 2001). The pouches were secured on the sample stage at position 2 (Figure 15) in a vertical orientation using an aluminum frame. A horizontal orientation was not possible with this beamline since the maximum thickness of the samples could not exceed 10 mm. The neutron flux at this position was 9.8 x 10^6 neutrons cm^{-2} s^{-1} mA^{-1} (p-current). One experiment focused on monitoring water distributions in apple juice, apple purée and banana purée during drying. The other focused on characterizing the mass transfer in a purée by D_20 injection. Full details about the experimental procedures are given in Paper III.

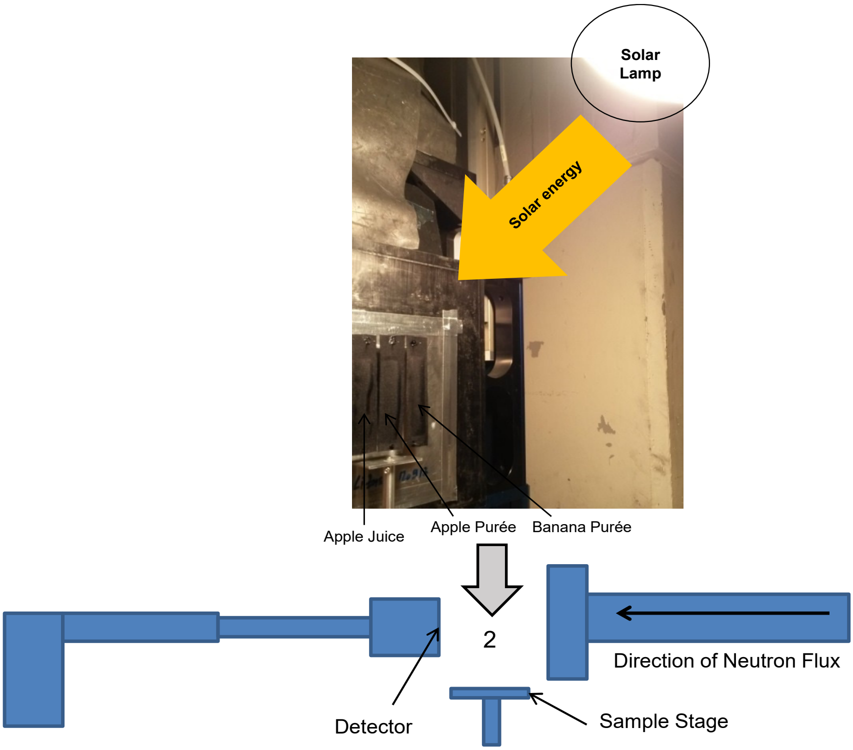


Figure 15 Cross-sectional view of the NEUTRA beamline and where "position 2" is located. Position 2 was the beamline position used for the experiments in this research. A solar lamp was used to heat the SAP pouches and provide the latent heat for evaporation. The pouches were fixed to an aluminum frame in a vertical orientation. The same setup was used for the D2O experiments except only one pouch was used instead of three. This image is reproduced from Paper III.

4.2.5 Climate-controlled cabinet (Paper IV)

A climate-controlled cabinet was used to simulate indirect solar drying under controlled laboratory conditions (Figure 16). The air velocities tested could be achieved in either a passive or active solar dryer. Inside the cabinet, an experimental setup was constructed for measuring and logging the mass loss with time for a pouch or open dish filled with an aqueous liquid and placed in the cabinet to dry. The mass measurements were achieved by equipping the cabinet with an electronic scale (Sartorius Laboratory L 610 Electronic Precision Balance, Sartorius AG, Goettingen, Germany) that was connected to a computer outside the cabinet via an RS-232 cable. This allowed for continuous logging of the mass data and the generation of drying curves that could then be used to calculate the drying fluxes. The main difference between this setup and the convective dryer is that the climate-controlled cabinet allowed for relative humidity control, in addition to temperature and air velocity control. Figure 16 shows two configurations of the setup. The configuration on the right incorporated an insulated cooling system to keep the scale below 40°C (i.e. the maximum working temperature of the scale). This allowed for temperatures higher than 40°C to be tested. Unsupported membrane pouches were used in all experiments. A full description of the setup and procedure is given in Paper IV.

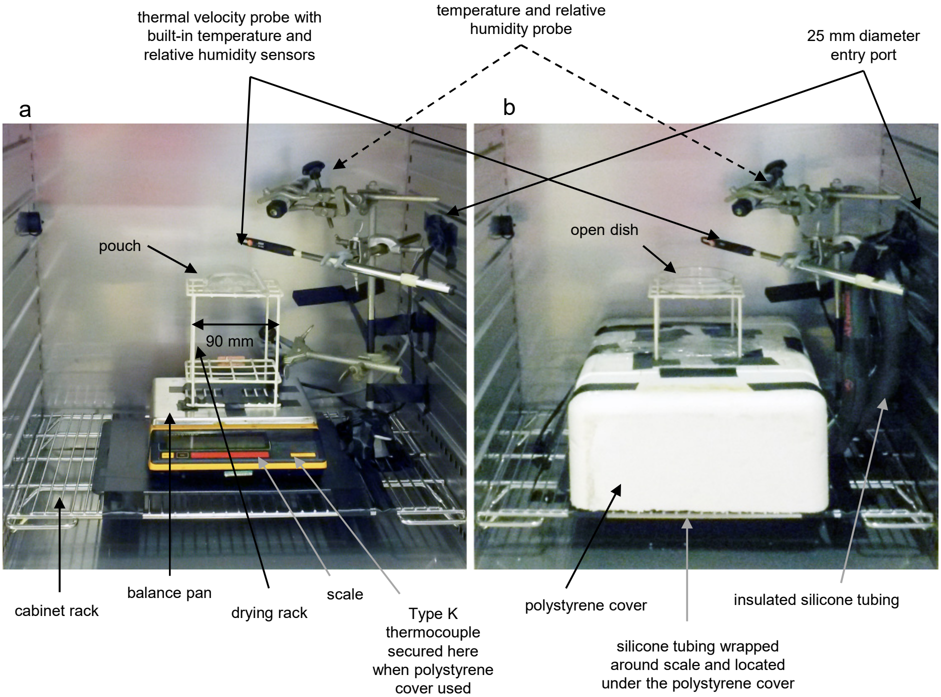


Figure 16 Experimental setup used to simulate an indirect solar dryer with relative humidity control: (a) without cooling system showing the position of the pouch and (b) with cooling system showing the position of the open dish (reproduced from Paper IV).

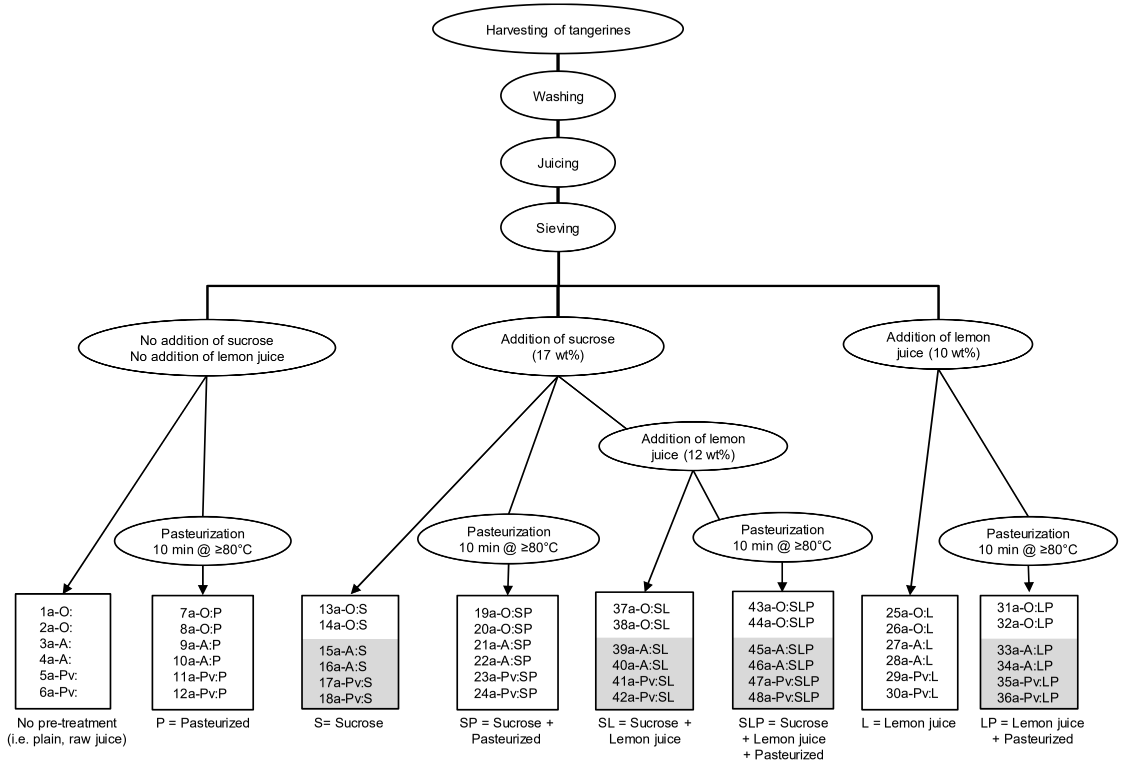


Figure 17 Flow chart illustrating how the juice pre-treatments in the field study were carried out. The symbols in the figure are defined as follows: O = open sun drying, A = active solar drying, Pv = passive solar drying, P = pasteurized, S = sucrose, L = lemon juice, a = sample from Trial I. The same procedure was carried out for Trial II. The codes for Trial II are similar except that “a” is replaced by “b” for all samples (see Papers V and VI). The samples that are shaded grey were prepared on a different day following the same procedure.

4.2.6 Field study in Mozambique (Papers V and VI)

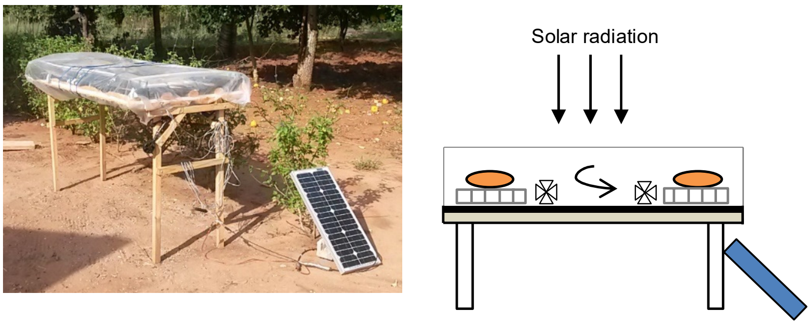
The field study took place in a rural area in the district of Inharrime (latitude 24.4°S, longitude 35.1°E, elevation 29 m) in the province of Inhambane, Mozambique in July 2017, with the help of two local agricultural associations. Two trials were conducted over a period of two weeks, where Trial II was a replication of Trial I. Eight different tangerine juice pre-treatments (Figure 17) and three different solar drying setups (Figure 18) were tested with unsupported membrane pouches (Figure 19) under realistic outdoor processing conditions. The eight juice pre-treatments corresponded to a 2^3 balanced factorial design and were "pasteurised (yes/no)", "added sucrose (yes/no)" and "added lemon juice (yes/no)". The pre-treatments were applied before adding the juices to the membrane pouches. The solar drying setups consisted of two solar dryer designs (i.e. direct active and tilted passive) and a control (i.e. open sun drying). The tilted passive dryer was considered to be a mixed mode passive dryer since the pouches were not protected from solar radiation. The drying of the juices was carried out until a final soluble solids content of at least 65 °Bx was reached, resulting in the production of tangerine marmalades. The twice daily mass measurements were used to estimate when 65 °Bx had been achieved in each sample during the drying process. This soluble solids value was chosen based on the Codex Standard for Jams, Jellies and Marmalades of 60-65 °Bx (Codex Alimentariu, 2009) and the recommendations of not less than 60 °Bx and not less than 65 °Bx given in the United Kingdom and United States of America, respectively (FDA, 2015; "The Jam and Similar Products (England) Regulations 2003," 2003; USDA, 1974).

After the end point had been reached, the samples were immediately analysed for their pH and soluble solids contents. Microbiological analyses were performed at Eurofins Steins Laboratorium A/S (Vejen, Denmark) after the samples had been stored frozen at -20°C for 12 months. The viable count method was used to determine the total aerobic, *Enterobacteriaceae*, lactic acid, yeast and mold counts in each sample. Water activity was also measured after 12 months of storage at -20°C.

An average drying flux was also determined for each sample each day and night, in order to assess the effects of the external and internal conditions on each sample as a function of time. Paper V presents the drying flux results for four of the pre-treatments (i.e. those without added lemon juice). It was not necessary to present the drying flux results for the four lemon juice pre-treatments since the trends were based on soluble solids content, rather than any other specific component in the lemon juice. The average drying flux (kg water m^{-2} h^{-1}) was calculated with the following equation:

$$\text{Average drying flux} = \frac{(m_{t_1} - m_{t_2})}{A \cdot (t_2 - t_1)} \qquad (8)$$

(a) open sun drying



(b) direct active solar drying

(c) tilted passive solar drying

Figure 18 The three solar drying setups tested in the field study. (a) open sun drying, (b) direct active solar drying (c) tilted passive solar drying. The pyranometer was used to log the solar irradiance. The figure is reproduced from Papers V and VI.

where m is the mass of the juice (kg) at a certain time, t (h), 1 and 2 represent two different time points, and A is the surface area of the pouch (m^2). Radiant exposure was also calculated for each day of a trial by integrating the logged irradiance values over a time period of 30 600 seconds (8.5 hours).

Reference marmalades (i.e. commercial, homemade over a stovetop, and produced by SAP) were also included in the study. Full descriptions of these marmalades are given in Paper VI. One of these marmalades that will be given particular attention here was the SAP "reference" marmalade (sample 200). This marmalade was produced in a trial that took place in June 2017 with the same procedure and under similar conditions to Trial I and II in July 2017. The marmalade was given a sucrose + lemon juice + pasteurized (SLP) pre-treatment and was dried in the active solar dryer. After drying, this marmalade was transferred to a stainless steel pot and brought to a boil over an open fire (see Paper VI). The marmalade was then hot filled into a sterilised, re-useable glass mayonnaise jar and stored under ambient conditions for 6 months before being further analysed. This was done to assess the need for an additional heat treatment after drying to produce safe, shelf-stable tangerine marmalades.

Additional details about the field study are given in Papers V and VI.

Figure 19 Unsupported pouches filled with tangerine juices and closed with WeLoc plastic clips. This was the preparation area for juice making and pouch filling.
© R. Phinney, 2017.

4.3 Heat and mass transfer model assumptions

The heat and mass transfer model that was developed for the SAP process to assess the solar drying performance of an unsupported membrane pouch was based on the following assumptions:

- Water vapour is assumed to be an ideal gas. This assumption is valid at lower temperatures (0 – 50°C) and when the pressure is close to atmospheric pressure (Kroos & Potter, 2015). By making this assumption, it is possible to approximate the chemical potential of water vapour by the partial pressure of water vapour.
- All radiation effects are negligible if the pouch is dried inside an indirect solar dryer. The is because the net radiation exchange between the interior surface of the dryer and the bag would be minimal due to the low temperature of the wall surface (Incropera et al., 2007). With direct sun exposure, the radiation from the sun is to be considered but the net radiation exchange with the surroundings can still be disregarded.
- Steady-state conditions apply. This means that the temperature of the liquid in the membrane pouch is assumed to be in equilibrium with the air temperature and that all heat transferred convectively to the surface is used as the heat of vaporisation. For this to be valid, the height of the liquid in the pouch must be large enough so that the effects of evaporative cooling on the temperature of the entire liquid mass are negligible.
- Constant pouch surface temperature and negligible resistance to conductive heat transfer through the membrane. This means that the same temperature can be assumed on the inner and outer surface of the membrane.
- The drying fluxes on the top and bottom membrane surfaces are equal if the pouch is dried inside an indirect solar dryer and the test substance is always homogeneous (i.e. water). If the pouch is exposed to direct solar radiation and/or a fruit juice is dried, it cannot be assumed that the fluxes are equal on both sides of the membrane. However, the overall drying flux encompasses both fluxes and can therefore be used instead.
- Negligible permeation of the other juice components in the hydrophilic membrane. This means no fouling of the membrane is assumed.
- No energy or mass generation or storage.
- Surface energy and mass balances are applicable.

4.4 Statistical methods

For experiments that required tests of significance, two-sample unequal variance (Welch-Satterthwaite) *t-tests* were used to determine if there were statistically significant differences between samples means at a significance level of p ≤ 0.05 (two-tail). This test is recommended by Zimmerman (2004) for all types of data sets, especially those with unequal samples sizes, since equal sample variances do not guarantee equal population variances. Throughout the thesis and appended papers, data has also been presented as averages ± standard deviations whenever possible.

In Paper IV, a two-level factorial experimental design was applied to determine a statistical regression model for drying flux as a function of temperature, relative humidity, air velocity and the interaction effects between these parameters. The 2^3 design was balanced and completely randomized with p = 3 factors and n = 2 observations per treatment combination. Each factor was assigned two levels, *low*(-) and *high*(+), resulting in eight different treatment combinations (see Paper IV for more details). The hypothesis was that the factors (i.e. temperature (a), relative humidity (b) and air velocity (c)) and the samples means (i.e. drying fluxes) were related by certain *effects* according to the following equation (Tamhane, 2009):

$$\overline{\boldsymbol{y}} = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + e \quad (9)$$

$$\text{where} \quad e \sim N(0, \sigma^2/n),$$

$$x_1 = \begin{cases} -1 \text{ if } a \text{ is low,} \\ +1 \text{ if } a \text{ is high,} \end{cases}$$

$$x_2 = \begin{cases} -1 \text{ if } b \text{ is low,} \\ +1 \text{ if } b \text{ is high,} \end{cases}$$

$$x_3 = \begin{cases} -1 \text{ if } c \text{ is low,} \\ +1 \text{ if } c \text{ is high,} \end{cases}$$

$$\boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_{12} \\ \beta_{13} \\ \beta_{23} \\ \beta_{123} \end{bmatrix} \quad \text{and} \quad \overline{\boldsymbol{y}} = \begin{bmatrix} \overline{y_{(1)}} \\ \overline{y_a} \\ \overline{y_b} \\ \overline{y_c} \\ \overline{y_{ab}} \\ \overline{y_{ac}} \\ \overline{y_{bc}} \\ \overline{y_{abc}} \end{bmatrix}$$

Each value in the $\boldsymbol{\beta}$ vector has a corresponding effect in Table 3. If $\boldsymbol{\beta}$ and $\overline{\boldsymbol{y}}$ are vectors of dimension [8 x 1] and $\boldsymbol{X'X} = 8\boldsymbol{I}$ is an orthogonal model matrix where $\boldsymbol{I}$ is an 8 x 8 identity matrix, the model can be re-written in matrix notation as follows:

$$\boldsymbol{\beta} = (\boldsymbol{X'X})^{-1}\boldsymbol{X'}\overline{\boldsymbol{y}} \quad (10)$$

If the $\boldsymbol{\beta}$ vector is solved for, the resulting values can be used to determine the effects in Table 3. MATLAB R2015a (v 8.5.0.197613) was used to solve for the $\boldsymbol{\beta}$ vector in Paper IV. A test statistic was also calculated based on the mean square error of each effect and the mean square error of all of the treatments to determine if the effect was significant or not (see Paper IV for a detailed description of the procedure).

Table 3 Effects and formulas corresponding to the regression model in equation 9 (adapted from Tamhane (2009)).

Effect	Formula	Description
I	β_o	Grand mean effect
A	$2\beta_1$	Main effect (*T*)
B	$2\beta_2$	Main effect (*RH*)
C	$2\beta_3$	Main effect (*u*)
AB	$2\beta_{12}$	Two-factor interaction effect (*T* & *RH*)
AC	$2\beta_{13}$	Two-factor interaction effect (*T* & *u*)
BC	$2\beta_{23}$	Two-factor interaction effect (*RH* & *u*)
ABC	$2\beta_{123}$	Three-factor interaction effect (*T*, *RH* & *u*)

T = temperature (°C), *RH* = relative humidity (%), *u* = air velocity (m s^{-1})

4.5 Ethical considerations

Ethical considerations were taken into account when conducting fieldwork with two farmers' associations in the province of Inhambane, Mozambique in April 2015, April-May 2016 and June-July 2017. During the first phase of the fieldwork in April 2015 and 2016, when the activities were primarily based on the Participatory Rural Appraisal approach, all participants remained anonymous when the data was later reported to a third party outside the working group and all members of the farmers' associations were also given the option not to participate in the studies. The manner in which questions were asked was also taken into consideration to avoid leading questions and obtaining biased data. Starting in May 2016, technical experiments with the membrane pouches were also conducted with the associations. All testing with fruit juices and other foods was taken very seriously by the researchers and so extra effort was made to ensure the juice preparation area was as hygienic as possible. The farmers were also informed of the risks in participating in such a study (e.g. foodborne illness may result if hands are not washed properly, a participant may harm themselves with knives or the juicing machines, the activities may be time consuming which may reduce the farmers' agricultural productivity on the day that the activities take place), and were given the option not to participate. In June-July 2017, a longer and more complex set of field experiments was conducted with the associations, where the same measures were taken as in May 2016 to ensure that all participants were properly informed and to ensure the experimental area was as safe and hygienic as possible. In addition, safety measures related to the use of two manual juicing machines had to be considered, where each participant received proper training in the use of the machines before being allowed to participate in the experiments. Permission was also obtained from the participants before publishing any photographs or videos that included them.

5 Main Results and Discussion

5.1 Drying time, drying flux and fruit compatibility (Papers I and II)

The drying flux and drying time are important aspects to consider when developing a safe and practical food preservation process. The main results from an initial screening analysis looking at how dry solids content, temperature, relative humidity and simulated solar irradiance affect the drying flux and drying time for a supported SAP pouch are presented in this section. Additional details about the experiments performed during this screening phase can be found in Papers I and II.

5.1.1 Effect of dry solids content on drying time

The effect of dry solids content on drying time was not the same depending on the type of fruit. The drying time in the convective dryer was approximately the same for lemon juice, Milli Q water plus sucrose and lemon juice plus sucrose (Figure 20), assuming that the final moisture content was 0.25 kg water/kg dry solids for all three samples. This moisture content corresponds to a final water activity of 0.7 for orange juice (Iglesias & Chirife, 1982). The similar drying times can be explained by considering how less water needs to be removed if the initial dry basis moisture content is lower. However, for *Vangueria infausta* dried in SAP pouches under simulated open sun drying conditions, the purées with added sucrose at a ratio of 1:1 (purée:sucrose) required a longer drying time to reach a stable moisture content compared to samples with added sucrose in ratios of 1:0.5 and 1:0.25 (Figure 21). Less water also needed to be removed from the 1:1 samples to reach a shelf-stable water activity, yet the drying time was 1.5 times longer. Comparing the highest and lowest dry basis moisture contents for the lemon juice and *V. infausta* samples in Figures 20 and 21, respectively, the 10.6 °Bx lemon juice sample had an initial dry basis moisture content 4 times greater than the lemon juice plus sucrose (27.1 °Bx) sample, while the 1:0.25 *V. infausta*, sample had an initial dry basis moisture content about 2 times greater than the 1:1 sample. Despite the larger ratio between initial moisture contents for the lemon juice samples, the total drying time was approximately the same. Since *V. infausta* has a higher insoluble solids content than lemon juice, this suggests that insoluble solids content plays a strong role in determining drying time when sucrose is added.

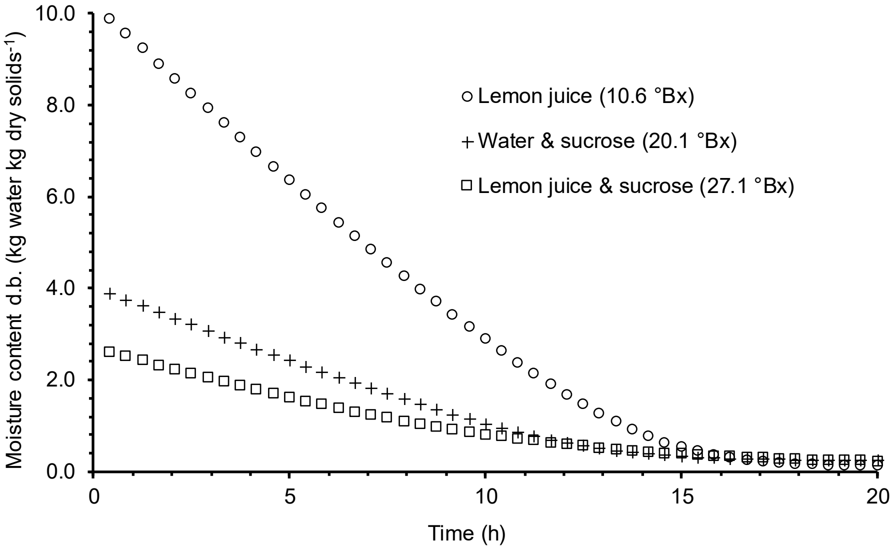


Figure 20 Drying curves for model solutions dried in supported SAP pouches in a convective dryer simulating an indirect solar dryer with the following conditions: 40.9 ± 0.1°C, 13.9 ± 1.5% relative humidity, 1.8 ± 0.2 m/s air velocity (adapted from Paper I).

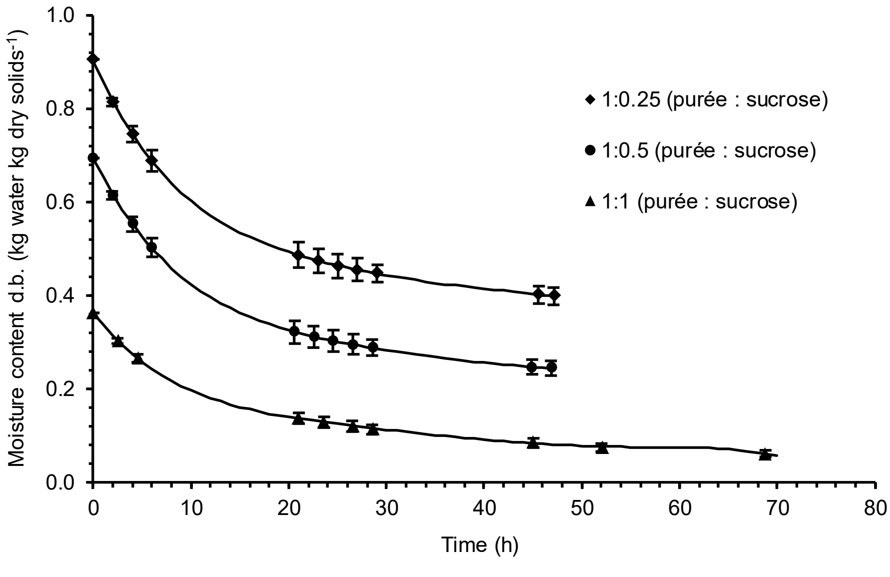


Figure 21 Drying curves for *Vangueria infausta* purées with added sucrose dried in supported SAP pouches (simulated open sun drying) with the following conditions: 520 ± 90 W/m^2 simulated irradiance, 1.4 ± 0.2 m/s ambient air velocity, 19-25°C ambient temperature and 26-40% relative humidity. The purée to sucrose mass ratios used were 1:1, 1:0.5 and 1:0.25 (adapted from Paper II).

The drying time to achieve a final moisture content of 0.25 kg water/kg dry solids was approximately 15 hours for the lemon juice samples without any interruption to the process. In an outdoor setting, this would result in a total processing time of about two days, if an indirect solar dryer could provide heated air at an average temperature of 41°C and average relative humidity of 14% for 8 hours per day. In contrast, the *V. infausta* samples were dried with interruptions, with the experiment designed for 8 hours of simulated direct sunlight exposure and 16 hours of night time conditions with continued forced convection. This resulted in drying times of 45-46 hours for the 1:0.25 and 1:0.5 samples, and 69-70 hours for the 1:1 sample (i.e. 2 days for the former and 3 days for the latter). These drying times are also reasonable for open sun drying.

5.1.2 Effect of increasing dry matter content on drying flux

Drying flux and change in dry matter content as a function of time are shown in Figure 22 for a lemon juice model solution (10.6°Bx) dried in a supported SAP pouch in a convective dryer at 51.6°C, 7.5% relative humidity and with 1.8 m/s air velocity. The graph shows how the drying flux and dry matter content are related to each other throughout the drying process. Due to the dilute nature of the lemon juice, the drying flux remains within a range of 0.33 to .040 kg h^{-1} m^{-2} for about 7 hours (i.e. approximately constant rate drying), until a certain critical dry matter content is reached causing the drying flux to decrease rapidly and the dry matter content to increase rapidly. It is not clear from Figure 22 what the exact cause is of the rapid decrease in drying flux. It can be explained by a sudden decrease in the water activity of the fruit juice, which would affect the driving force for mass transfer, and/or an increase in the viscosity of the juice due to the increase in the dry matter content. An understanding of which of the two mechanisms is responsible for the decrease in drying flux would be beneficial to be able to optimise the process.

To expand on this assessment, a comparison was also made between *Vangueira infausta* purée and lemon juice (both without added sucrose) dried in supported membrane pouches. Drying flux curves for the two fruits are presented in Figure 23. The lemon juice had a much higher initial moisture content, resulting in constant rate drying until the moisture content reached approximately 3 kg kg^{-1} d.m. After this, falling rate drying occurred as the dry matter content continued to increase. Since *Vangueira infausta* had a lower initial moisture content, a constant rate period was not observed. Instead, drying began in the falling rate period. From 2 kg kg^{-1} d.m. until the end of drying, both fruits had similar drying flux curves. However, for the same moisture content, the lemon juice flux was slightly higher, which can be explained by the high amount of insoluble dietary fibre in *V. infausta*.

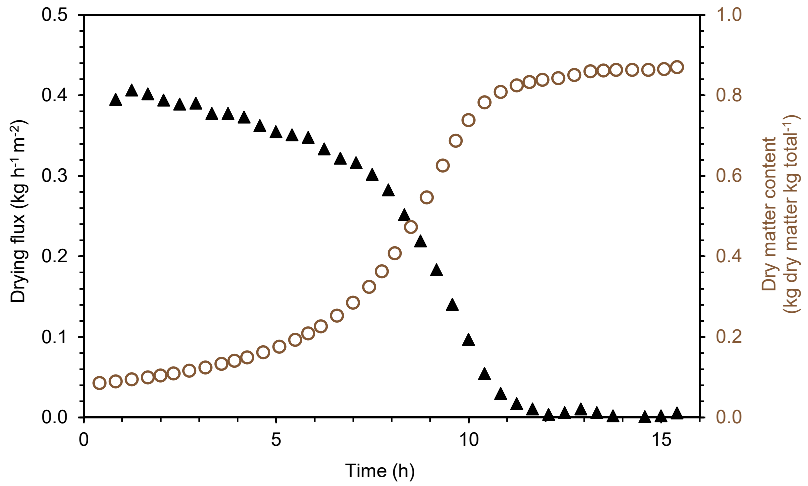


Figure 22 Drying flux and change in dry matter content as a function of time for lemon juice (10.6 °Bx) dried in a convective dryer (to simulate an indirect solar dryer) with a supported SAP pouch exposed to the following conditions:51.6 ± 0.1°C, 7.5 ± 0.5% RH, 1.8 ± 0.2 m/s air velocity.

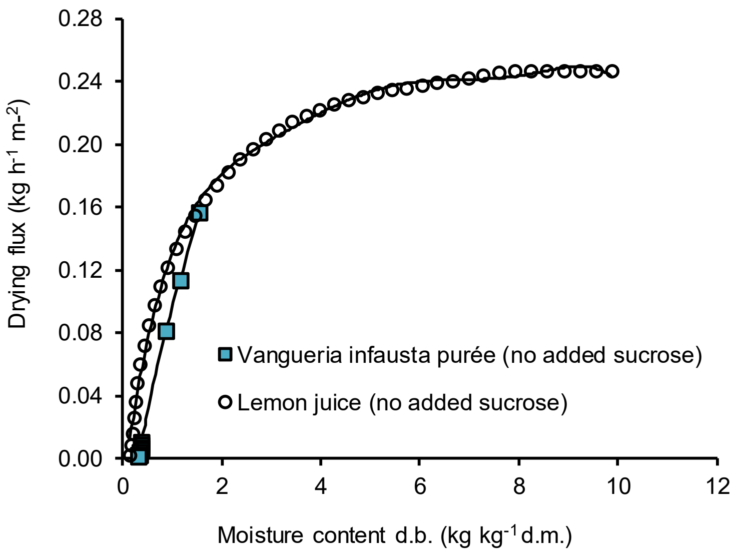


Figure 23 Drying flux curves for *Vangueria infausta* and lemon juice (both without added sucrose) dried in supported SAP pouches. *V. infausta* was dried with a solar simulating lamp (520 ± 90 W/m^2, 1.4 ± 0.2 m/s air velocity, 20°C and 31%RH). Lemon juice was dried in a convective dryer simulating indirect solar drying (40.9 ± 0.1°C, 13.9 ± 1.5%RH, 1.8 ± 0.2 m/s air velocity). The initial moisture content of the *V. infausta* purée was 1.55 kg water kg^{-1} d.m. The initial solule solids content of the lemon juice was 10.6 °Bx.

5.1.3 Effect of solar irradiance on drying flux

Drying flux was found to be a linear function of irradiance for supported SAP pouches filled with lemon juice plus sucrose solutions (27.1°Bx) positioned under the solar lamp in such a way that only the top of the pouch was exposed to the solar radiation (Figure 24). In all of the experiments, a fan providing forced convection was applied, as it was thought that this would reduce the boundary layer effects on the topside and underside of the pouch. Considering the net amount of radiation that would be possible for a pouch to absorb in Mozambique (i.e. maximum global radiation at midday in June in Mozambique is approximately 600 W/m^2 (Nijegorodov, Devan, Simao, & Mabbs, 2003), the irradiance values studied were in a reasonable range for daily average values.

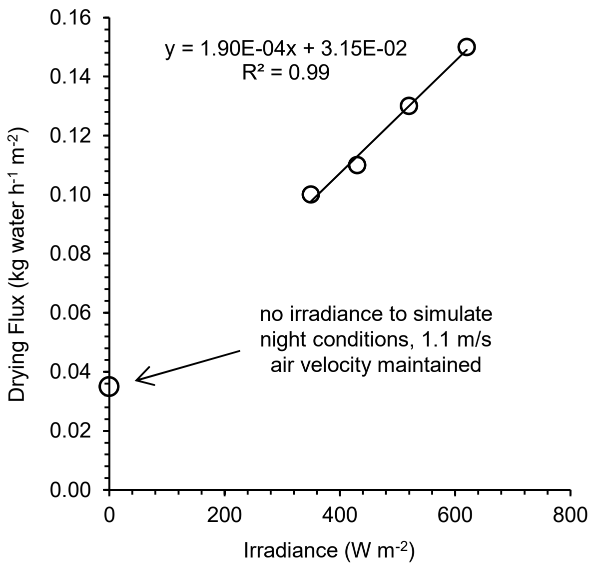


Figure 24 Drying flux as a function of irradiance for lemon juice + sucrose (27.1°Bx) solutions with ambient surrounding conditions (20.7 ± 0.1°C and 51.1 ± 1.3% RH) and 1.1 ± 0.2 m/s airflow (reproduced from Paper I).

5.1.4 Limitations of open air sun drying

Solar radiation can have a positive effect on the drying flux as was observed in Figure 24. However, it is possible that the presence of ambient forced convective airflow (i.e. a prevailing wind) reduces this positive effect. In Figure 25, the drying flux for sample C (solar + convection) was less than that for sample D (solar + no convection). The pouch surface temperature was also measured for these two cases and the result was a surface temperature of 40°C without forced convective airflow and 25°C with forced convective airflow. This can be explained by the air being able to convect energy away from the heated surface if the air temperature is less than the surface temperature of the pouch. This means less energy is available for the heat of vaporisation, which results in a reduction in the drying flux. These results suggest that convective ambient temperature airflow combined with direct sunlight exposure may decrease the drying flux, prolong the drying time and increase the risk of spoilage during the drying process. This motivates the use of a direct active solar dryer to pre-heat the air that passes over the pouches and reduce the temperature difference between the air and the pouch. This would enable more of the solar energy to be used for evaporation rather than being lost as waste heat.

Another option would be to use an indirect solar dryer, which is the situation that was simulated for samples A and B in Figure 25. If the temperatures and relative humidities indicated could be achieved on average during a day of solar drying, then the drying flux values shown could also be achievable as the average drying flux for one day. This example shows that indirect active solar drying (i.e. with forced convection) is a better option than open sun drying in the ambient temperature air.

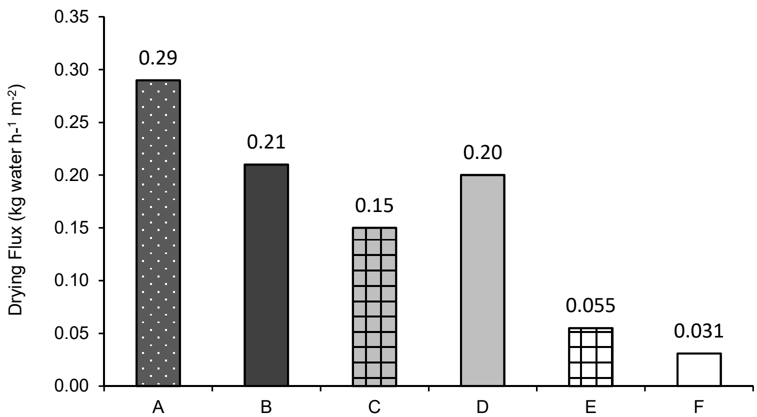


Figure 25 Comparison of drying fluxes in the constant rate drying period period for lemon juice plus sucrose solutions (27.1°Bx) dried with different drying treatments. A: no solar + convection (51.6°C, 7.5%RH, 1.8 m/s), B: no solar + convection (40.9°C, 13.9%RH, 1.8 m/s), C: solar (620 W/m^2) + convection (20.7°C, 51.1%RH, 1.1 m/s), D: solar (620 W/m^2) + no convection (20.7°C, 51.1%RH, 0 m/s), E: no solar + convection (20.7°C, 51.1%RH, 1.1 m/s), F: no solar + no convection (20.7°C, 51.1%RH, 0 m/s).

5.1.5 Fruit compatibility

A preliminary fruit compatibility assessment showed that many types of fruits are compatible with SAP pouches (Figure 26). This assessment was based on the ability of a supported SAP pouch to produce fruit concentrates or dried fruit leathers with measured water activities less than 0.7, while maintaining acceptable sensorial properties of the product (e.g. taste, aroma and texture).

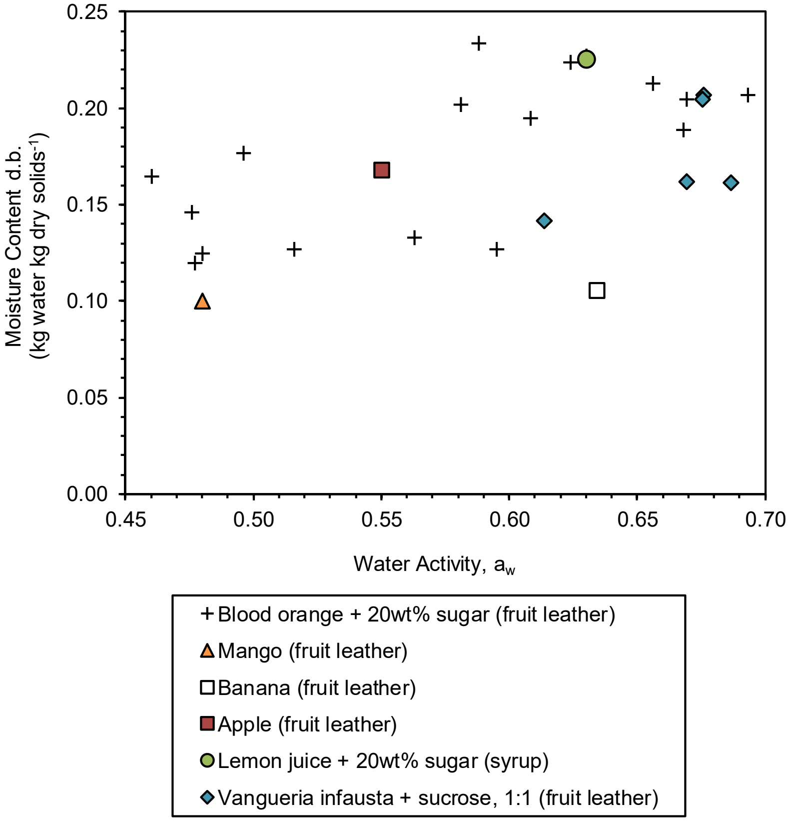


Figure 26 Moisture content (dry basis) and water activity for different fruits dried with supported SAP pouches showing the various products that are possible to produce. In the legend, an indication of the texture and form of the final product is given (i.e. fruit leather or syrup). The data for mango, apple and lemon juice is from Paper I and the data for *V. infausta* is from Paper II.

5.2 The effects of internal mass transport on food safety (Paper III)

The food safety aspects of the SAP process are one of the main challenges of this research. Even if the membrane pouch provides a barrier to external contamination, there is still a risk of spoilage during drying depending on the drying rate and drying uniformity. Since it is not possible to measure the water activity in every region of a fruit concentrate or leather, this means there can be high moisture content zones in the concentrate/leather that promote microbial growth. This section describes key results obtained from neutron radiography experiments that were used to investigate the distribution of water inside an opaque pouch during drying to address this potential problem of high moisture content zones. A supported SAP pouch was used to investigate these possible effects of internal mass transfer on food safety. The main results are presented here (see Paper III for more details).

5.2.1 Inhomogeneous drying with complex food matrices

Inhomogeneous drying was visually observed for certain drying conditions when drying banana and apple purées in supported SAP pouches (Figure 27 and 28). The banana purée formed a crust during drying, which may be related to the high starch content in banana compared to other fruits. This crust was undesirable as it prevented the remaining water in the center of the purée from leaving the system. For the apple purée, uneven drying was observed during the process, as is evident by the thick and thin layers of partially dried product that were spread over the inner side of the membrane (see Figure 28a, note: the pouch has been turned inside out in this image). In another experiment with apple using the same drying conditions, the product was dried for 16.4 hours to try to ensure that all parts of the final product were below a water activity of 0.7 (Paper I). The final dried apple product from this experiment is shown in Figure 28b. The darker and lighter shaded regions on the dried apple slab indicate that the final product was not completely homogeneous. These results indicate that the drying of complex matrices with SAP pouches is not straightforward and that there is a risk of non-homogeneous drying.

5.2.2 Visualising and quantifying inhomogeneous drying

The experiments described in the previous section were conducted with black, opaque pouches (i.e. the supported membrane). This made it difficult to observe how the water was distributed inside the pouches during drying without opening the pouches. For this reasons, neutron radiography was used to obtain a visual image of the mass transfer phenomena taking place inside SAP pouches during a simulated open sun drying process.

Figure 27 Banana purée dried with a supported SAP pouch in a convective dryer, to simulate an indirect solar dryer without relative humidity control. The drying conditions were 51.4°C ± 0.1°C, 10.6%RH ± 2.3%RH, and 1.8 m/s ± 0.2 m/s.

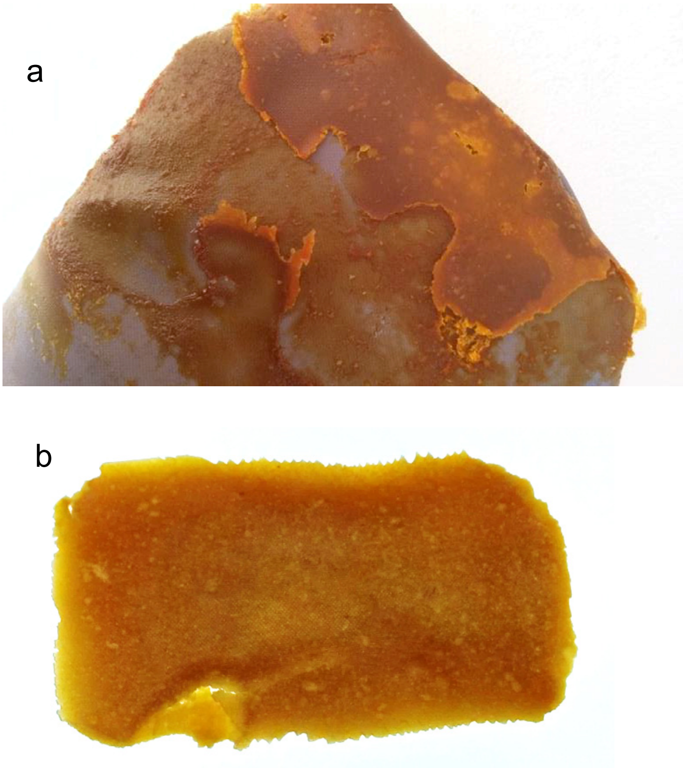


Figure 28 Apple purée dried with a supported SAP pouch in a convective dryer to simulate an indirect solar dryer without relative humidity control. The dried form of the purée is more like a fruit "leather". a: Sample removed after 10 hours of drying. b:Sample removed after 16.4 hours of drying. The drying conditions were 52.0°C ± 0.2°C, 10.6%RH ± 1.5%RH, and 1.8 m/s ± 0.2 m/s for both a and b.

In the first experiment, three pouches were tested in a vertical orientation. One pouch was filled with banana purée, one with apple purée and one with apple juice. (see Paper III for more details). This experiment allowed for the water distribution and changing water concentration to be monitored with time in each type of food matrix, as water was removed from the pouches. The results of the experiment are shown in Figure 29. In this figure, the dark grey colour indicates where the water is located in the samples and the intensity of the darkness indicates the concentration of water at a specific location along its thickness.

The three food matrices exhibited different behaviours over the course of the 8 hour drying period. Due to the vertical orientation of the pouches, the effect of gravity could not be avoided in the experiments. The apple juice, being the least viscous of the three substances, collected at the bottom of the pouch as more and more water evaporated. The banana purée lost the least amount of water of the three substances, where the water loss primarily occurred on the right side of the pouch. The apple purée exhibited behavior similar to the banana purée, except that more water evaporated after 8 hours from the apple purée. In the apple purée and banana purée images at 8 hours, there are also localised dark spots of varying sizes, which provides evidence that uneven drying occurred. These local regions of high moisture may have developed from localised concentrations of fibers that were able to bind water more effectively, from the presence of air in the system or from an interaction between the hydrophilic entities of the carbohydrate molecules and the hydrophilic membrane. Further research is needed to identify the actual mechanism(s) and their relative contributions to the inhomogeneity.

In the second experiment, D_2O (i.e. deuterium oxide or heavy water) was injected into a pouch filled with apple purée to observe whether convective or diffusive mass transfer was taking place internally. It was found that the D_2O concentration near the injection point decreased with drying time, and the D_2O mass appeared to spread out slowly and evenly towards the top and bottom of the pouch (Figure 30). By plotting the gray value at each pixel along a vertical line at different time steps, it was possible to observe a peak at time zero at the same height where the D_2O was injected. As drying proceeded, the center of the peak remained at the same height while the magnitude of the peak slowly decreased until it was no longer visible. This result suggests that for a viscous fruit purée, the mass transport inside the pouch is likely dominated by diffusion and not thermally-driven convection. This could help explain why uneven drying is more likely to occur in a fruit purée compared to a juice since the lower viscosity of the juice may be an enabler for thermally-driven convective mass transfer in the juice.

The main finding from the neutron radiography assessment was that there is an additional food safety risk involved when drying fruit purées in SAP pouches compared to drying fruit juices. Since citrus fruits, such as tangerines, grow and spoil in large quantities in Mozambique and they have very little fibre on the order of less than 1wt% (Li, Andrews, & Pehrsson, 2002), they are suitable candidates to be concentrated in SAP pouches. For this reason, citrus fruits became the focus of the latter half of the doctoral project.

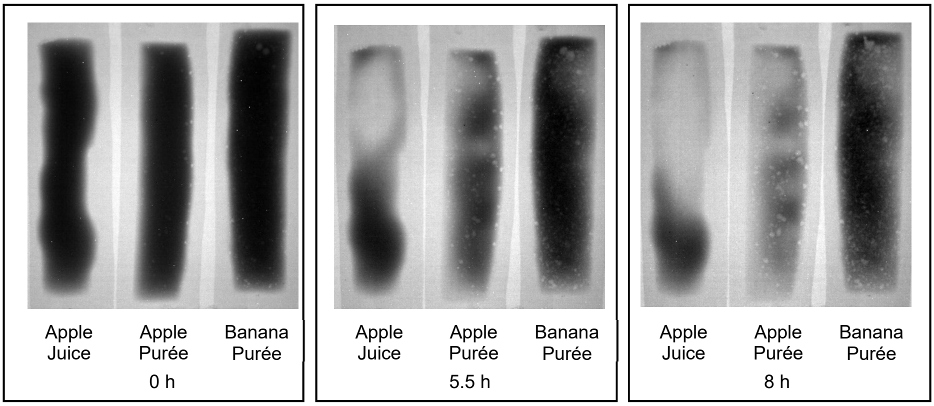


Figure 29 Neutron radiography images for the drying of vertical pouches with three different food matrics: apple juice, apple purée and banana purée. Each pouch had active surface area dimensions of 15 mm x 72 mm x 2 since there are two sides for drying. The dark colour represents the concentration of water molecules diffusion (reproduced from Paper III).

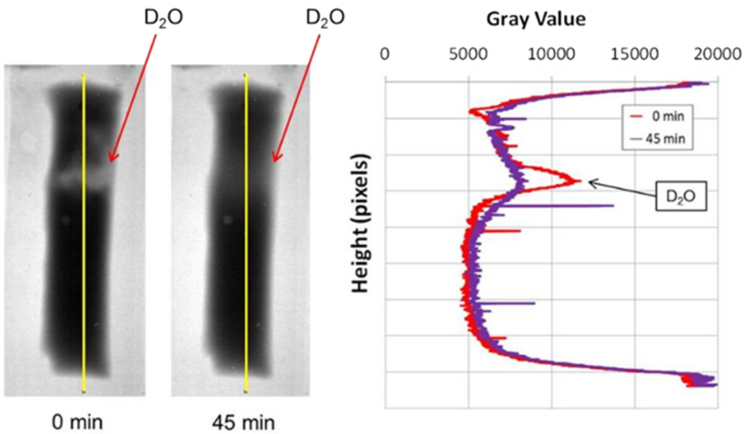


Figure 30 Neutron radiography images for a vertical pouch filled with apple purée (active surface area dimensions 15 mm x 75 mm x 2 since there are two sides for drying) that was injected with D_2O. The gray values along the yellow line were plotted at different time points to see how the D_2O peak changed. There was no translation of the peak but only dissipation which indicates the transport was likely due to diffusion (reproduced from Paper III).

5.3 Solar drying performance under controlled laboratory settings (Paper IV)

In section 5.1, it was shown that a solar dryer has the potential to improve the SAP process in terms of drying flux. The results presented below have been obtained using a climate-controlled cabinet simulating an indirect solar dryer with relative humidity control. This was both to verify that an indirect solar dryer has the potential to improve the process, and to identify the criteria that are critical for the design of an indirect solar dryer adapted for SAP pouches. Unsupported SAP pouches were used to ensure that only the effect of the membrane resistance was being measured rather than the effect of the combined resistances of the membrane and support material. Full details can be found in Paper IV.

5.3.1 Drying performance of a SAP pouch compared to an open dish

The SAP pouch flux was approximately 80% of the open dish flux for temperatures in the range 20.2°C to 39.6°C, irrespective of the air velocity or relative humidity (Figure 31). Since the ratio of pouch flux to open dish flux remained constant up to 39.6°C, this means that the open dish and pouch fluxes were also increasing by approximately the same proportion in the temperature range 20.2°C to 39.6°C. At 49.3°C and 53.9°C, the pouch flux no longer increased by the same proportion as the open dish flux, with the relative performance of the pouch decreasing to approximately 66%. This shows that at higher temperatures, the evaporation from the pouch is limited by the resistance of the membrane, rather than the convective heat transfer to the surface of the pouch. This also means that within the operational limits tested (i.e. 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity), the ratio between the mass transfer resistances (i.e. pouch to open dish) remains constant at 0.8 (pouch : open dish) until 40°C. Above 40°C, this ratio decreases in relation to the membrane resistance.

5.3.2 Coupling effects and driving forces

Drying flux was found to increase with increasing temperature for a constant relative humidity (Figure 32a and 32b). It might seem that the drying flux should be constant for a constant driving force, which in this case is represented by relative humidity, but the issue is that relative humidity expresses the absolute humidity or moisture content of air as a value that is relative to a different saturation value at each temperature. This means 17.4% relative humidity at 29.8°C is not the same as 17.4% relative humidity at 39.6°C. This can be further illustrated in Figure 33, where the partial pressure driving forces (Δp) for the two relative humidities investigated in this study are plotted as functions of temperature. Two important observations can be made from this figure. The first is that the Δp driving force is linearly related to temperature for a constant relative humidity. The values and slopes are the same no matter which kind of container is used since the partial pressure driving force is purely related to the partial pressures of water vapour at the wetted surface and in the air and their respective temperatures. The second observation is that the slopes of the two trendlines in Figure 33 for the two different relative humidities are different and diverging as temperature increases. The same effect can be seen in Figure 32b for the open dish and pouch data where, for example, the slopes of the 17.4%RH and 38.2%RH trendlines for the open dish with water dried at 0.39 m/s are different and diverging. A similar trend is observed for the pouch. Without looking at Figure 33, the conclusion would be that there must be a synergistic coupling effect between temperature and relative humidity. However, by considering Figure 33, it becomes apparent that the divergence observed in Figure 32 is not entirely a coupling effect between temperature and relative humidity, but a combined effect of the Δp being different at each temperature plus a potential coupling effect.

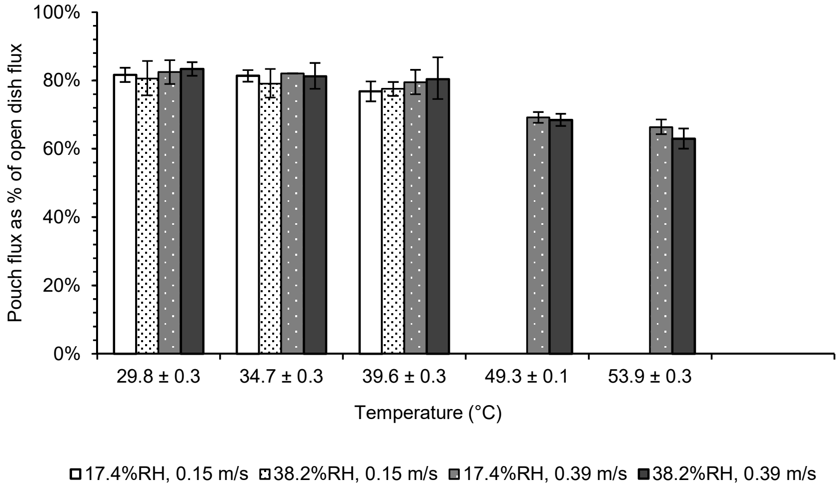


Figure 31 Pouch flux as a percentage (%) of its corresponding open dish flux with the same temperature, relative humidity and air velocity. The standard deviations for the relative humidities and air velocities were: 17.4% ± 2.0%, 38.2% ± 2.0%, 0.15 ± 0.09 m/s and 0.39 ± 0.12 m/s (reproduced from Paper IV).

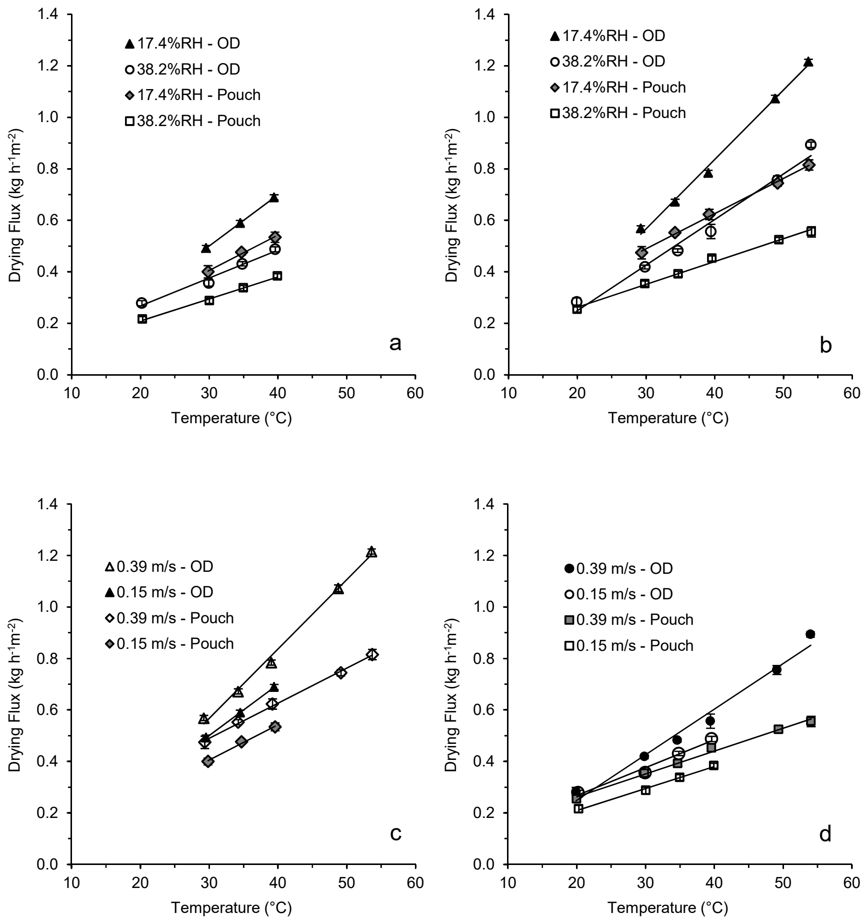


Figure 32 Drying flux as a function of temperature for the open dish (OD) and pouch for constant relative humidities (a and b) and constant air velocities (c and d). a: 0.15 ± 0.09 m/s, b: 0.39 ± 0.12 m/s, c: 17.4 ± 2.0%RH, d: 38.2 ± 2.0%RH (reproduced from Paper IV).

The purpose of conducting this analysis with Δp as a function of temperature is to show that one needs to be cautious about making conclusions about coupling effects strictly from graphs and the slopes of linear regression equations if one or more of the variables is actually a function of another variable. With the case of temperature and air velocity, there are no other variables that influence the temperature and air velocity. However, because relative humidity is a relative value, it is more appropriate to compare driving forces with Δp.

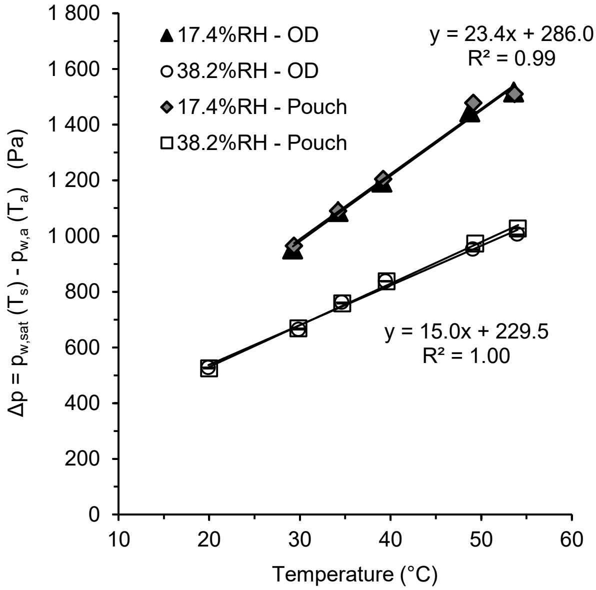


Figure 33 Δp (i.e. difference in water vapour partial pressure between the inner surface of the membrane and the bulk air) as a function of temperature for two relative humidities.

5.3.3 Two-level factorial analysis for deriving a regression equation

A two-level factorial analysis was used to obtain a regression equation for the pouch drying flux as a function of temperature, relative humidity, air velocity and their interaction/coupling effects. The statistical analysis revealed that the grand mean effect, the three main effects, and the interaction effect between temperature and relative humidity were significant within the operational limits tested. By incorporating only these significant effects into equation 9, a new equation for drying flux can be written as follows:

$$m''_{evap} = 0.44 + 0.059x_1 - 0.069x_2 + 0.036x_3 - 0.011x_1x_2 \quad (10)$$

where:

$$x_1 = \begin{cases} -1 \text{ if temperature } (T) \text{ is } 29.8°\text{C} \\ +1 \text{ if temperature } (T) \text{ is } 39.6°\text{C} \end{cases}$$

$$x_2 = \begin{cases} -1 \text{ if relative humidity } (RH) \text{ is } 17.4\% \\ +1 \text{ if relative humidity } (RH) \text{ is } 38.2\% \end{cases}$$

$$x_3 = \begin{cases} -1 \text{ if air velocity } (u) \text{ is } 0.15 \text{ m/s} \\ +1 \text{ if air velocity } (u) \text{ is } 0.39 \text{ m/s} \end{cases}$$

The coefficient of determination (R^2) for the model was 0.997, thus the fit is good. To confirm this, drying flux values were predicted with equation 10 then compared to the experimental values (Table 4). The errors in the predictions are less than 2.2%. Equation 10 can also be used to predict drying flux for other values of temperature, relative humidity and air velocity that fall within the upper and lower ranges given above. In this case, the corresponding x value (i.e. $-1 < x < +1$) is determined by linear interpolation. Extrapolating should be done with caution.

Insights about how the external conditions affect the SAP process can also be obtained from the coefficients of the main and interaction effects. The positive coefficient for temperature indicates that drying flux and temperature were positively correlated, while the negative coefficient for relative humidity indicates that drying flux and relative humidity were negatively correlated. This is the expected result since higher temperatures and lower relative humidities reduce the partial pressure of water vapour in the surrounding air and therefore increase the driving force for mass transfer. The coefficient for air velocity was positive, which means that drying flux increased as a function of increasing air velocity within the velocity range tested. This indicates that the heat and/or mass transfer boundary layers surrounding the pouch are significant at velocities up to 0.39 m/s and that by increasing the air velocity, the thickness of the boundary layer(s) can be reduced. This result supports the use of a solar dryer with natural or forced convective airflow when carrying out the SAP process under realistic conditions. Since the three main effects and interaction effect are also on the same order of magnitude, this shows that the coupling/interaction effect between temperature and relative humidity cannot be neglected. However, according to section 5.3.2, the difference between relative humidity and Δp needs to be considered when interpreting the interaction coefficient.

Table 4 Comparison of the experimental pouch drying fluxes with the pouch drying fluxes predicted using the regression model in equation 10.

Temperature (°C)	Relative Humidity (%)	Air Velocity ($m\ s^{-1}$)	Experimental pouch drying flux ($kg\ h^{-1}\ m^{-2}$)	Predicted pouch drying flux ($kg\ h^{-1}\ m^{-2}$)	% difference between the experimental and predicted fluxes
29.8	17.4	0.15	0.40	0.40	0.3%
39.6	17.4	0.15	0.53	0.54	1.7%
29.8	38.2	0.15	0.29	0.28	2.2%
29.8	17.4	0.39	0.47	0.47	0.3%
39.6	38.2	0.15	0.38	0.38	0.3%
39.6	17.4	0.39	0.62	0.61	1.4%
29.8	38.2	0.39	0.35	0.36	1.8%
39.6	38.2	0.39	0.45	0.45	0.3%

5.4 Field study in Mozambique (Papers V and VI)

In this section, a summary is presented of the main findings obtained during the field study in Mozambique. This includes an assessment of how the juice pre-treatment and solar drying setup influenced the drying flux as well as the microbiological quality of the final marmalades. All experiments performed during the field study in Mozambique were conducted with unsupported membrane pouches.

5.4.1 Effect of solar drying setup and juice pre-treatment on drying flux

The average drying flux generally decreased each day for all solar drying setups and pre-treatments tested (Figures 34 and 35). This was due to a change in the internal conditions inside the pouches as a function of time (i.e. an increase in the soluble solids content with time). As water was removed from the pouches by pervaporation, the soluble solids contents of the juices increased, resulting in a decreasing partial pressure of water vapour and decreasing water activity in the juices with time. This means that the driving force for mass transfer was continuously decreasing with time, irrespective of the external conditions surrounding the pouches. This trend of a decreasing drying flux with time may have also been due to an increase in viscosity of the juices/marmalades. It is known for sucrose solutions that viscosity increases non-linearly as a function of increasing soluble solids content (Bourne, 2002; Knecht, 1990), and that a change in soluble solids content from 20 to 70 °Bx can cause a 10-fold reduction in the diffusion coefficient of water at 30°C (Yamamoto et al., 2005). This means that a viscosity increase may have influenced the transport of the water molecules diffusing from the center of the pouch to the inner surface of the membrane, and that the effect of an increasing soluble solids content on the viscosity and mass transfer cannot be neglected. Therefore, the general trend of a decreasing average drying flux with time was related to the changing internal conditions inside the pouches, which affected the driving force for mass transfer and/or the diffusivity of water molecules in the juices/marmalades.

There were a few exceptions to this trend of a decreasing drying flux with time. For open sun drying, the drying fluxes in Trial II were higher on day three than day two. This can be explained by the poor weather conditions (i.e. unfavourable external conditions for mass transfer) on day two, since the radiant exposure and temperature were considerably lower and the relative humidity considerably higher on day two compared to day three. In Trial I, the drying fluxes for the open sun samples were also lower than expected on day three compared to day four as a result of poor weather conditions on day three. Similar results were obtained for open sun non-pasteurised samples with and without added sucrose (see Paper V). These results show that poor weather conditions have a strong influence on open sun drying.

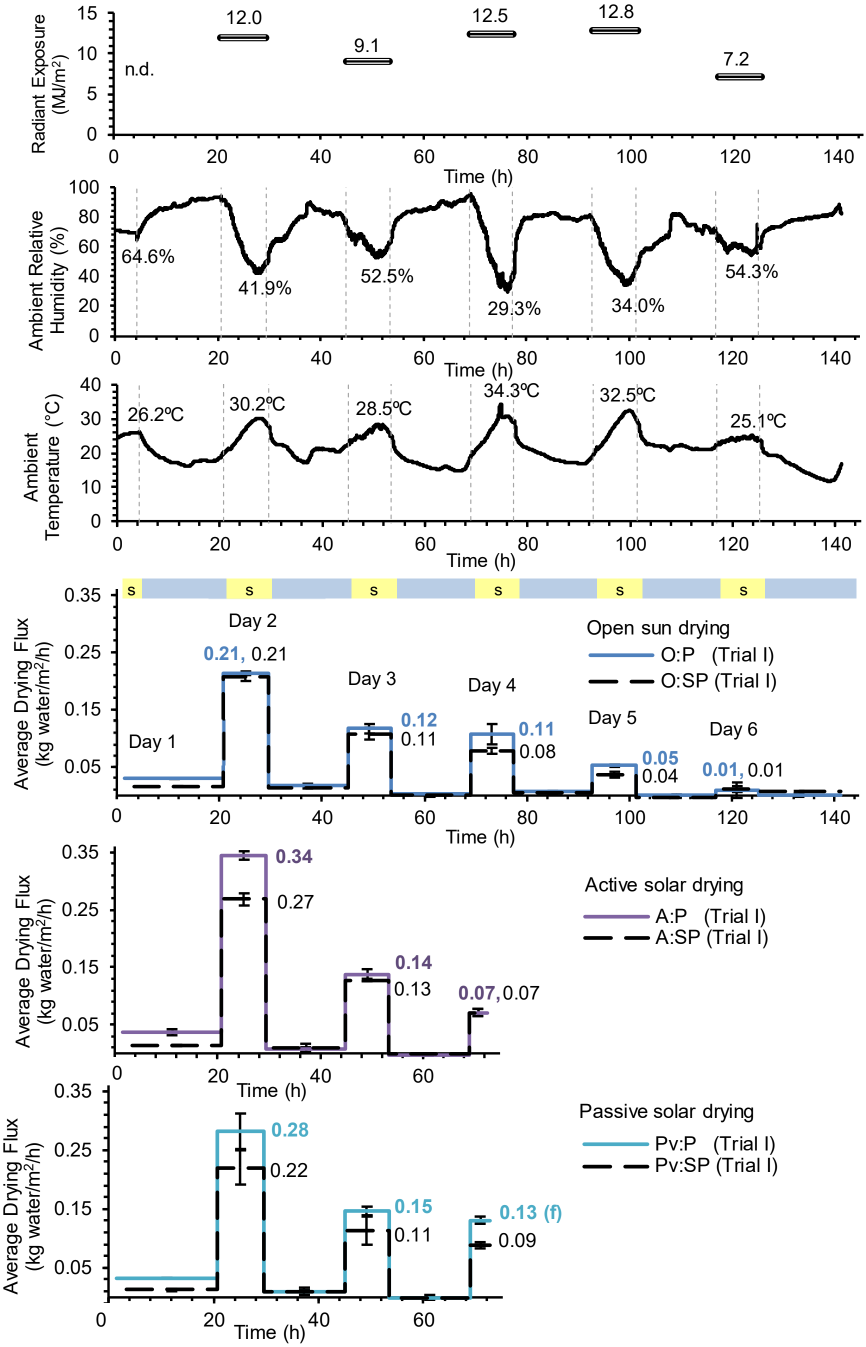


Figure 34 Trial I average drying flux results and ambient conditions (reproduced from Paper V). On day one, all samples were exposed to the sun for half a day and so an average drying flux has been calculated from the start of day one to the start of day two. n.d. = no data, s = sun (i.e. when the pouches were exposed to the sun), O = open sun drying, A = active solar drying, Pv = passive solar drying, P = pasteurised, SP = sucrose and pasteurised, (f) = fermentation observed visibly and/or by a fermented-like smell. This figure is adapted from Paper V.

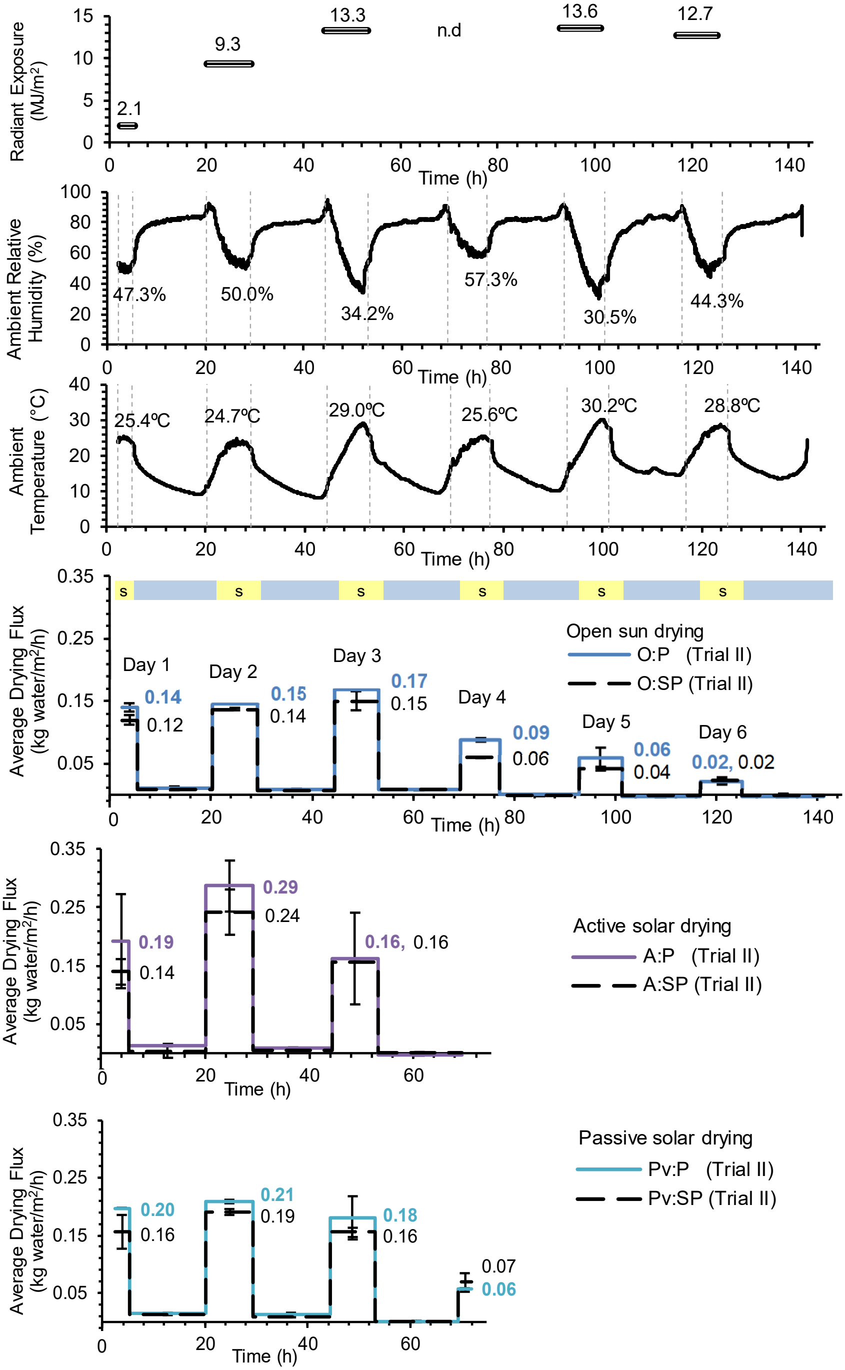


Figure 35 Trial II average drying flux results and ambient conditions (reproduced from Paper V). n.d. = no data, s = sun (i.e. when the pouches were exposed to the sun), O = open sun drying, A = active solar drying, Pv = passive solar drying, P = pasteurised, SP = sucrose and pasteurised. This figure is adapted from Paper V.

The highest drying fluxes were achieved with the active solar drying setup (Figures 34 and 35). This can be explained by higher temperatures and lower relative humidities inside the active dryer compared to the ambient environment, and additionally by the presence of forced convection. On day three of Trial II, the maximum temperature and minimum relative humidity achieved in the active solar dryer were 57.7°C and 11.7%RH, respectively. In the ambient environment, the maximum temperature and minimum relative humidity were 29.0°C and 34.2%RH, respectively (Figure 36). The lower relative humidity inside the active dryer during each 8.5 hour period of sun exposure would have allowed for a greater driving force for mass transfer in the active dryer than in the open sun as a result of a lower partial pressure of water vapour in the air of the dryer. This helps explain why the drying fluxes were higher in the active dryer compared to the open sun.

The presence of forced convection in the active dryer is another reason why the drying fluxes were higher in the active dryer than the open sun, and additionally why the fluxes were higher in the active dryer compared to the passive dryer. The active and passive dryers were found to have similar temperatures and relative humidities at certain time points in Trial II (Figure 36). This means that the partial pressure of water vapour in the air of each dryer was approximately the same at these time points. It also means that it was possible for the driving force for mass transfer to be approximately the same in each dryer at certain time points (i.e. assuming that the soluble solids contents of the samples in the dryers were also equal). However, the average drying fluxes were always higher in the active dryer on day two of each trial when the soluble solids contents were still approximately equal. The higher and more stable air velocities achieved in the active dryer with forced convection (i.e. 3.8 to 4.4 m/s) compared to the passive dryer with natural convection (0.5 to 1.5 m/s as reported by (Chaignon & Davidsson, 2017; Samuelsson & Deslandes, 2017) likely contributed to a decrease in the boundary layer thicknesses and/or an increase in the convective heat/mass transfer coefficients in the air surrounding the pouches in the active dryer, resulting in higher drying fluxes in the active dryer (see Paper V for more details). This result agrees with the results obtained in Paper IV where the air velocity under controlled laboratory conditions was found to have an influence on the boundary layer thickness. The presence of forced convection in the active dryer could also explain why the passive dryer was found to be more sensitive to poor weather conditions. On day two of Trial II, the radiant exposure, ambient relative humidity and ambient temperature were unfavourable for drying and as a result, the drying fluxes in both dryers were reduced. Comparing day two of Trial I to day two of Trial II, the average drying flux of the active pasteurised samples (A:P) was reduced by 15%, whereas in the passive dryer, the average drying flux of the passive pasteurised samples (Pv:P) was reduced by 25%. Similar trends were observed for sucrose + pasteurised samples in Figures 34 and 35 where the drying fluxes were reduced by 11% and 14% for A:SP and Pv:SP, respectively, and for non-pasteurised

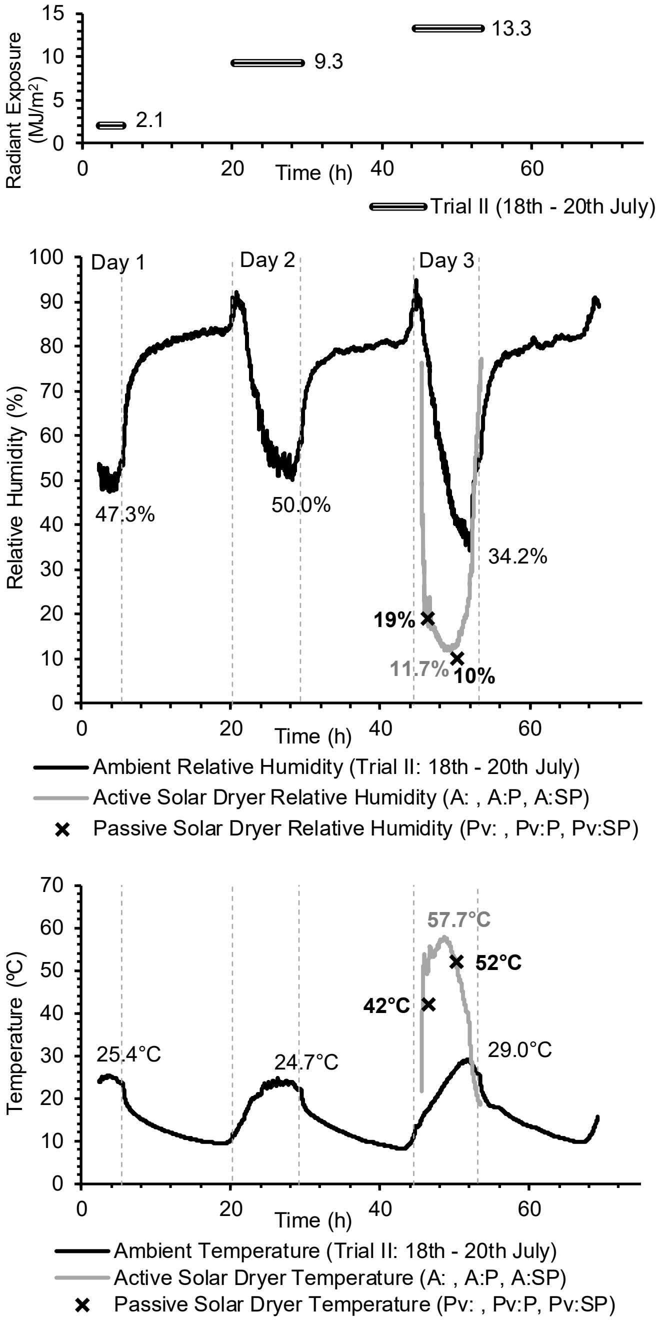


Figure 36 External conditions logged in the ambient environment and inside the active and passive solar dryers during the first part of Trial II (18[th]-20[th] July). This figure is reproduced from Paper V.

samples without added sucrose, where the drying fluxes were reduced by 24% and 29% for A: and Pv: , respectively (see Paper V for more details). The larger percentage reductions in drying flux in the passive dryer could be due to the lower radiant exposure in Trial II having a stronger effect on the air velocities and airflow patterns produced by natural convection in the passive dryer compared to those produced by forced convection in the active dryer. This is in agreement with previous findings which showed that the air velocity in the passive dryer was strongly affected by the amount of radiant exposure (Chaignon & Davidsson, 2017; Samuelsson & Deslandes, 2017). These results suggest that forced convection was responsible for the higher drying fluxes in the active dryer, and that the active dryer was less sensitive to poor weather conditions than the passive solar dryer.

The total drying time for open sun drying was approximately two times longer than for active and passive solar drying (i.e. 6 days versus 3 days – see Figures 34 and 35) as a result of the higher drying fluxes in the solar dryers. Halving the drying time means that the quantity of marmalade produced per unit time is doubled and the probability of spoilage during drying is reduced. Since the total drying time was approximately the same for the active and passive samples, this shows that the drying fluxes and drying conditions (i.e. temperatures, relative humidities and air velocities) in the passive dryer were just as suitable as those in the active dryer for producing tangerine marmalade within 3 days. However, the active dryer may be the more reliable option since the passive dryer appears to be more sensitive to weather fluctuations, as discussed previously. This result shows the importance of using a solar dryer with the SAP process to reduce the drying time, increase the productivity and reduce the probability of spoilage.

Sucrose addition as a juice pre-treatment had negligible effect on the total drying time (Figures 34 and 35). This was partly because less water needed to be removed from the pouches with added sucrose to reach a final soluble solids content of 65 °Bx, and partly because the drying fluxes were similar in some cases between samples with and without added sucrose. The former explains why all samples could be dried in the active and passive solar dryers within 3 days even though there were observed differences in the drying fluxes between samples with and without added sucrose on certain days (e.g. day two of Trial I). These differences in drying flux were likely due to the internal conditions controlling the mass transfer as a result of the external conditions in the solar dryers being favourable for drying (i.e. higher temperatures and lower relative humidities than in the ambient environment). With open sun drying, there were very few differences in the drying fluxes between samples with and without sucrose, which means that the external conditions in the ambient environment were controlling the mass transfer rather than the soluble solids contents inside the pouches. Since adding sucrose to the juice before drying had little effect on the total drying time, this means it can be used as a pre-treatment to increase the quantity of marmalade produced per membrane pouch without negatively affecting the drying behaviour or extending the processing time.

The drying fluxes achieved with the three different solar drying setups are also in line with the fluxes achieved under controlled laboratory conditions in Papers I and IV. In Paper I, open sun drying was simulated. The drying flux values obtained in these experiments (i.e. 0.10 to 0.16 kg water h^{-1} m^{-2}) were within the same range as those obtained with open sun drying in the field study. The lower values obtained in Paper I may be related to how a supported membrane was used in Paper I, which would have introduced additional membrane resistances. In Paper IV, unsupported pouches filled with water were tested and the drying flux ranged from 0.22 kg water h^{-1} m^{-2} when the temperature, relative humidity and air velocity were 20.2°C, 38.2%RH and 0.15 m/s, respectively up to 0.81 kg water h^{-1} m^{-2} when the temperature, relative humidity and air velocity were 53.9°C, 17.4%RH and 0.39 m/s, respectively. The flux values obtained in the field study agree well with those obtained in the climate-controlled chamber considering that i) the field study fluxes are average drying fluxes after 8.5 hours of sun/solar drying with fluctuating weather conditions, ii) the pouches were filled with juices in the field study rather than water, and iii) the climate-controlled chamber simulated indirect solar drying without direct solar exposure. This shows that the laboratory experiments provided useful insight into the ranges of drying fluxes that were possible to achieve in the Mozambique. It also verifies that that the drying flux values obtained in the field study were reasonable and on the correct order of magnitude.

5.4.2 Effect of solar drying setup and juice pre-treatment on the microbiological quality

The following sections discuss the most important findings related to the microbiological quality of the marmalades produced with SAP pouches. Microbial counts obtained for reference citrus marmalades are first given, followed by the aerobic, yeast, mold, lactic acid and *Enterobacteriaceae* counts for the SAP marmalades. A summary related to the relationship between water activity and soluble solids content is then presented, where the commercial relevance is discussed.

5.4.2.1 Reference citrus marmalades

The reference citrus marmalades tested had microbial (viable) counts < 1.0 Log CFU/g in almost all cases (Table 5). These values are in agreement with previously published results for industrial marmalades and jams produced by thermal treatments (Center for Food Safety, 2014; Saddozai et al., 2014, Sravani et al, 2017). The samples with counts greater than 1.0 Log CFU/g (i.e. samples 104 and 400) were still safe to consume considering the microbial limits for ready-to eat foods (i.e. foods cooked and sold immediately for consumption). Ready-to-eat foods are classified as satisfactory when the total aerobic count is < 3 Log CFU/g, marginal when between 3 and 5 Log CFU/g and unsatisfactory when > 5 Log CFU/g (Center for Food Safety, 2014; FSANZ, 2018). The pH values of all reference samples were all less than 4.6, indicating *Clostridium botulinum* was not of concern, although sample 104 was close to the limit. The SAP reference marmalade also had excellent microbiological quality, showing that the sterile hot filling method used in the rural area of Mozambique to package the marmalade after water removal by SAP was effective. These results for the reference citrus marmalades indicate that all microbial counts (i.e. total aerobic, yeast, lactic acid bacteria, mold and *Enterobacteriaceae*) for marmalades produced for long-term, shelf-stable storage and commercial purposes should be < 1.0 Log CFU/g.

Table 5 Measured microbial (viable) counts and pH values for commercial, SAP reference and homemade citrus marmalades.

Nr.	Description	Total aerobic count (Log CFU/g)	Yeast (Log CFU/g)	Lactic acid bacteria (Log CFU/g)	Mold (Log CFU/g)	*Enterobacteriaceae* (Log CFU/g)	pH
101	Commercial (Sweden)	1.0	< 1.0	< 1.0	< 1.0	< 1.0	3.21
102	Commercial (Sweden)	< 1.0	< 1.0	< 1.0	1.0	< 1.0	3.10
103	Commercial (Sweden)	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	3.20
104	Commercial (Portugal)	2.2	1.0	< 1.0	< 1.0	< 1.0	4.32
105	Commercial (France)	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	3.10
200	SAP reference (Mozambique)	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	3.50
300	Homemade (Mozambique)	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	3.13
400	Homemade (Mozambique)	1.5	< 1.0	< 1.0	< 1.0	< 1.0	3.11

5.4.2.2 Total aerobic count

Solar drying setup had only a minimal effect on the total aerobic counts in SAP marmalades, whereas juice pre-treatment had a noticeable effect (Figure 37). Pasteurisation as a juice pre-treatment had a beneficial effect in all cases, where the pasteurised samples had lower total aerobic counts than the corresponding non-pasteurised samples (e.g. no pre-treatment versus pasteurised, sucrose versus sucrose + pasteurised, etc.). This was observed for all solar drying setups (see Paper VI for more details and for the statistical analyses). The addition of sucrose and/or lemon juice without pasteurisation had no significant beneficial effect on the total aerobic count, with an increase in the total aerobic count occurring in some cases. This was expected for the sucrose pre-treatment since commercial brown sugar was used to increase the sucrose content, and this sugar may have contained impurities, microorganisms and/or microbial spores (Wojtczak, Biernasiak, & Papiewska, 2012). With lemon juice, it was expected that the total aerobic count would be reduced due to a decrease in pH. This was not the case, which suggests that the aerobic microorganisms present were not sensitive to acidic conditions. Since the pH of the tangerine juice ranged from 3.36 to 3.83, lemon juice would not be needed to prevent the growth of *Clostridium botulinum*. Therefore, in terms of the total

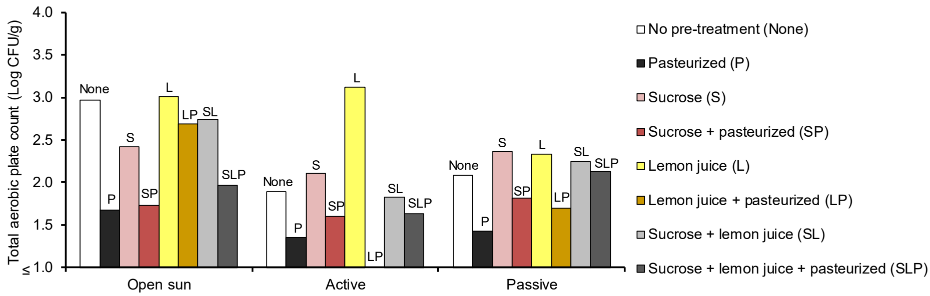


Figure 37 Total aerobic plate countes for tangerine marmalades produced with eight different pre-treatments and three different solar drying setups. Each bar represents the average total aerobic count for all replicates across both trials (reproduced from Paper VI).

aerobic count, there is no benefit in adding lemon juice. Instead, the probability of contamination seems to increase (e.g. from the lemon peels during juicing or from the hands of the person juicing the lemons). However, adding sucrose is beneficial from a productivity/economic point of view since less water needs to be removed and a greater quantity of marmalade can be produced per pouch. The recommended juice pre-treatment is to add sucrose and then pasteurise the juice before adding it to the pouches to maximise the quantity of marmalade produced and minimise the total aerobic count.

For all solar drying setups and juice pre-treatments, the total aerobic counts were generally low and within a range that is considered satisfactory for ready-to-eat foods (i.e. < 3 Log CFU/g) (Center for Food Safety, 2014; FSANZ, 2018). The only exceptions were Open-None (3.0 Log CFU/g), Open-Lemon juice (3.0 Log CFU/g) and Active-Lemon juice (3.1 Log CFU/g) (see Figure 37 and Paper VI), which are still considered marginally acceptable. These marmalades would be safe enough for consumption based on the total aerobic count, if they were consumed immediately from their pouches after drying. For the SAP marmalades to be shelf-stable, the total aerobic count would need to be < 1.0 Log CFU/g, which means that an additional heating and sterile filling step would be needed after drying, similar to that used for the SAP reference marmalade (see Table 5 and section 4.2.6)

5.4.2.3 Yeast count

Solar drying setup influenced the viable yeast counts in SAP marmalades in Trial I but not in Trial II (Figure 38). In Trial I, six out of eight juice pre-treatments had viable yeast counts > 2 Log CFU/g, while the active and passive samples were all ≤ 1.0 Log CFU/g. However, in Trial II, all yeast counts were generally low for all solar drying setups and juice pre-treatments, with no statistically significant differences between yeast count values (see Paper VI). The different trends observed in Trials I and II may be explained by process hygiene. The trials took place outdoors in a rural area where the hygienic conditions varied each day (e.g. due to fluctuations in the microbial quality of the air or the level of contamination on the tangerine peels). This unavoidable variation in the hygienic conditions combined with fluctuating weather conditions may have resulted in different growth rates for the yeast cells in the open samples in Trial I versus Trial II. Even though the active and passive samples were exposed to the same process hygiene variability and weather fluctuations, the yeast counts remained low in both trials. This may be explained by the higher temperatures achieved in the solar dryers compared to the ambient surroundings (Paper V). The temperatures achieved in the solar dryers may have hindered yeast growth and/or killed yeast cells, while the temperature in the ambient surroundings may have promoted yeast growth. The drying fluxes achieved in the solar dryers were also higher than those achieved in the open sun and less affected by fluctuating weather conditions, which resulted in a reduction in drying time from 6 days in the open sun to 3 days in the solar dryers (Paper V). Therefore, higher temperatures and drying fluxes in the solar dryers combined with reduced drying times, may explain why the open sun samples in Trial I contained substantial amounts of viable yeast cells, whereas the active and passive samples did not. These results suggest that the probability of yeast growth due to process hygiene and weather fluctuations increases with open sun drying, and that by using an active or passive solar dryer, the probability of the presence of viable yeast cells in the final marmalade can be reduced.

Fermentation was also detected visibly and/or by a fermented-like smell in some samples during drying (see Tables 3 and 4 in Paper VI for more details). An example of a fermenting pouch is shown in Figure 39. For open sun drying, this observed fermentation correlated well with the measured viable yeast counts. The same correlation could not be made for active and passive samples that were observed to ferment, since the viable yeast counts for these samples were low. Since the viable plate count method only measures living yeast cells in the final marmalade, this means that fermentation could have occurred in some of the active and passive samples during the drying process when temperatures were favourable for yeast growth (e.g. during the night or on days with substantial cloud cover – see Figure 10). The same yeast cells could have then been killed later in the drying process on days when the radiant exposure and air temperatures in the dryers were high. Since temperatures in the active and passive dryer were found to exceed 55°C at some points in the drying process (Paper V) and spoilage yeast cells are normally killed at temperatures above 55°C within about 5 to 10 minutes (Deak, 2004), it is likely that the yeast cells that caused the fermentation in the active and passive samples were killed by the end of the drying process. In Trial II, the low yeast counts in the open samples that were observed to ferment may have been a result of lower growth rates in the open samples in Trial II compared to Trial I, due to variability in the weather conditions between trials. This explains why viable yeast cell counts were low in some samples even though fermentation was observed.

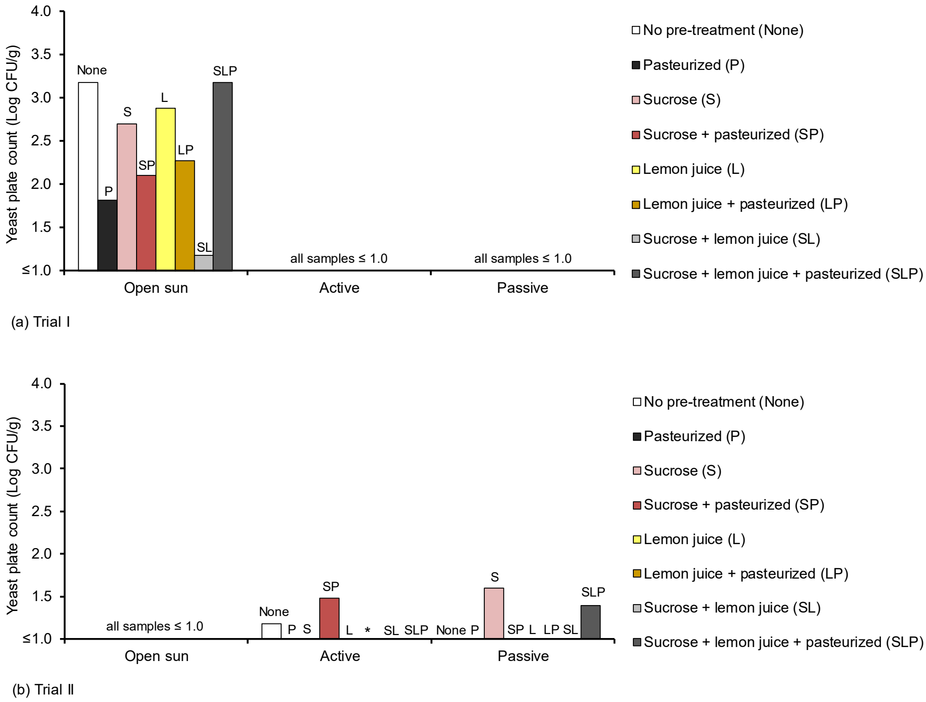


Figure 38 Yeast plate counts for tangerine marmalades produced with eight different pre-treatments and three different solar drying setups: (a) Trial I (b) Trial II. Each bar represents the average yeast count of all replicates in a particular trial. *No data was available for "Lemon juice + pasteurized (LP)" for the active solar dryer in Trial II (reproduced from Paper VI).

Figure 39 Side view of a fermenting pouch (Trial I, open sun (O) with no pre-treatment) (reproduced from Paper VI).

Fermentation was also observed visibly and/or by a fermented-like smell in many samples with added lemon juice (see Tables 3 and 4 in Paper VI for more details). In Trial I, the four open samples with added lemon juice were observed to ferment, where three out of four of these samples had yeast plate counts > 2 Log CFU/g. In this trial, the active and passive samples with added lemon juice (L) were also observed to ferment. These results suggest that lowering the pH had no inhibitory effect on yeast growth and fermentation in the juice samples. The optimal pH range for yeast growth is normally 4 to 6.5 (Deak & Beuchat, 1996; Tauro, Kapoor, & Yadav, 2004), but with some yeast strains, growth can occur at pH values as low as 2.5 (Fröhlich-Wyder, 2003; Mauersberger, Ohkuma, Schunck, & Takagi, 1996). The yeast strains present in the rural area where the trials took place were likely the latter type since they were tolerant to acidic conditions. Similar to with total aerobic count, the addition of lemon juice appears to have no beneficial effect on the microbial quality of the final marmalade as it seems to increase rather than decrease the probability of fermentation and yeast growth.

5.4.2.4 Lactic acid bacteria, Enterobacteriaceae and mold

No significant differences were found between pre-treatments or solar drying setups for the lactic acid bacteria, mold and *Enterobacteriaceae* viable counts (see Table 6 and Paper VI). All counts were also on the same order of magnitude as the reference samples (i.e. < 1.0 Log CFU/g).

Mold growth was visibly observed on the outside of some open sun sample pouches in Trial I (see Table 6 and Figure 40). Despite this observed mold growth, the viable mold counts were low inside the pouches in the final marmalades. This means that the membrane pouches provided a hygienic barrier to mold and prevented contamination during drying. Mold growth was not observed on the outside of pouches dried in the active and passive solar dryers, which may be attributed to the higher air temperatures achieved in the solar dryers (Paper V). Even though the pouches were found to prevent contamination by mold in the Trial I open samples, it would be recommended to use a solar dryer instead of open sun drying. This is because the presence of mold on the outside of a pouch introduces a health risk to the person handling the pouch, and the final marmalade could become contaminated when it is transferred to another package or consumed directly. Therefore, the recommendation is to use a solar dryer to avoid mold growth on the outside of the pouches and reduce the health and food safety risks during handling and consumption.

The fermentation and mold growth observed during the trials would have been difficult to discover if the pouches had only been tested under controlled laboratory conditions. This shows why it is important to test new technologies in the environment where they intend to be used, since it is difficult to both predict and simulate the process hygiene variability and fluctuating weather conditions that exist in reality.

Table 6 Mold plate counts for tangerine marmalades produced with eight different pre-treatments and three different solar drying setups. The values shown are the mean values of all replicates in Trials I and II for a given pre-treatment and solar drying setup. There were no statistically significant differences between mean values

		Mold plate count (Log CFU/g)		
Pre-treatment	Code	Open (O)	Active (A)	Passive (Pv)
None (i.e. raw, plain juice)		(m-TI) < 1.0 (n=4)	1.1 (n=4)	< 1.0 (n=4)
Pasteurized	P	(m-TI) < 1.0 (n=4)	1.1 (n=4)	< 1.0 (n=4)
Sucrose	S	< 1.0 (n=4)	1.1 (n=4)	1.2 (n=4)
Sucrose + Pasteurized	SP	1.2 (n=3)	< 1.0 (n=4)	< 1.0 (n=4)
Lemon juice	L	(m-TI) 1.1 (n=3)	< 1.0 (n=4)	< 1.0 (n=4)
Lemon juice + Pasteurized	LP	(m*-TI) < 1.0 (n=4)	1.0 (n=2)	1.1 (n=4)
Sucrose + Lemon juice	SL	1.2 (n=4)	1.5 (n=4)	1.2 (n=4)
Sucrose + Lemon juice + Pasteurized	SLP	< 1.0 (n=4)	< 1.0 (n=4)	1.1 (n=4)

(m-TI) indicates that mold was detected on the outside of both pouches in Trial I.
(m*-TI) indicates that mold was detected on the outside of one pouch in Trial I.

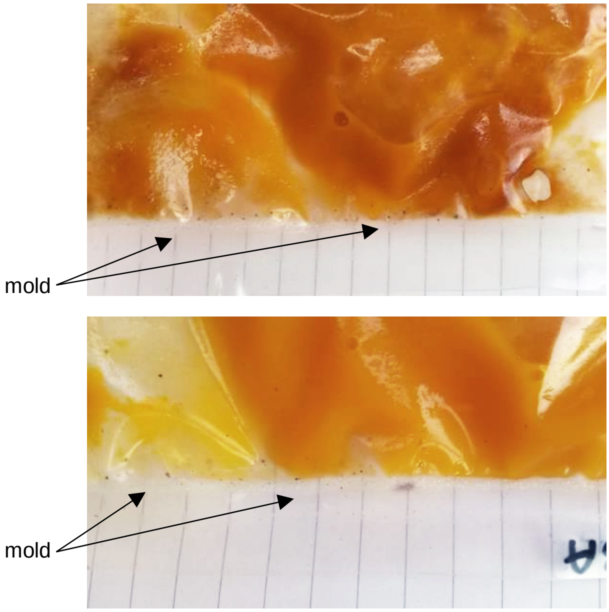
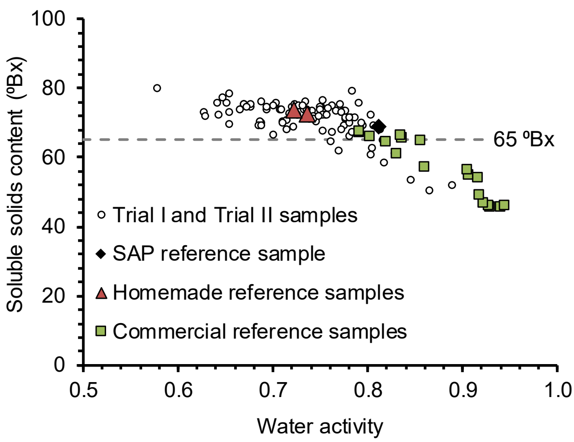


Figure 40 Observed mold on the outside of two pouches dried in the open sun.

5.4.3 Relationship between water activity and soluble solids content

The SAP marmalades produced in Trials I and II had water activities less than 0.85 and soluble solids contents of at least 65 °Bx, with only a few exceptions (Figure 41). The exceptions (i.e. the eight Trial I and Trial II data points below the dashed line in Figure 41) were samples mainly dried in the passive solar dryer that were observed to ferment visibly or by a fermented-like smell (see Paper VI for more details). Since mono- and disaccharides are required for yeast fermentation (Kimball, 1991), the sugars in the juices may have been consumed by yeast cells, resulting in final soluble solids contents less than 65 °Bx in some marmalades. On day 3 of Trial I, the weather conditions were poor (Paper V), which may have promoted optimal temperatures for yeast growth. Since most samples with low soluble solids contents were dried in the passive dryer, and the passive dryer was shown to be more sensitive to fluctuating weather conditions than the active dryer, it is possible that the temperatures in the passive solar dryer were optimal for fermentation at certain points in the drying process. The recommendation would be to use a direct active solar dryer is possible to reduce the probability of fermentation and increase the probability of producing a high quality, shelf-stable marmalade with a soluble solids content of at least 65 °Bx.

Many of the commercial reference samples (10 out of 18) had soluble solids contents less than 65 °Bx and water activities greater than 0.85 (Figure 41). The majority of these samples were produced in Sweden or for the Swedish market (see Table A1 in the Appendix of Paper VI). Despite that the Codex Standard for Jams, Jellies and Marmalades states that a soluble solids content of 60-65 °Bx or more is required for citrus marmalades (Codex Alimentarius, 2009), and that the United States of America and the United Kingdom recommend a minimum of 65 °Bx and 60 °Bx, respectively (FDA, 2015; "The Jam and Similar Products (England) Regulations", 2003; USDA, 1974), the Swedish regulations have no such requirement and instead state that there must be 200 g of citrus fruit in the finished product (Livsmedelsverket, 2003). Since refrigeration is available in Sweden, it is possible to sell these types of low-sugar marmalades since they can be stored cool after opening. In Mozambique, refrigerated storage is often not available, which is why a soluble solids content of at least 65 °Bx is recommended. Since some of the SAP marmalades in Figure 41 that have a soluble solids content of 65 °Bx or more also have a water activity close to or less than 0.7, the probability that these marmalades would spoil when stored unrefrigerated after opening would be reduced.



Figur 41 Soluble solids content versus water activity for all tangerine marmalade samples produced in Trials I and II, and additionally all reference marmalade samples (i.e. homemade, SAP and commercial). The soluble solids content data is from Paper V. Water activity values are given in the Appendix of Paper VI.

5.5 Preliminary assessment on how the internal conditions control the mass transport using a resistance-in-series approach

The results of the field study confirmed that the internal conditions affect the drying flux in two ways. There can be an effect on the driving force for mass transfer (i.e. partial pressure of water vapour inside the pouch) and/or an effect on the diffusion coefficient of water in the juice due to an increasing soluble solids content with time, as water is removed during drying. It is beneficial to know which of the two phenomena have a greater influence on the drying flux at different parts of the drying process, as this information can be used to modify the processing conditions. A preliminary assessment was completed with data for a lemon juice plus sucrose solution that was dried in a supported membrane pouch in a convective dryer (i.e. simulating an indirect solar dryer). A resistance-in-series approach was taken to demonstrate how a relationship between water activity and overall apparent mass transfer resistance can be used to investigate the internal mass transport phenomena.

The results of the preliminary assessment are shown in Figure 42. The overall apparent mass transfer resistance was calculated according to equation 7, where the driving force for mass transport was based on the difference in partial pressure of water vapour inside and outside of the pouch. In Figures 42a and 42b, two curves are presented as part of a sensitivity analysis to show how the resistance is affected by the assumed temperature of the juice. In the upper curve, the average partial pressure of water vapour in the juice is based on the wet bulb temperature. In the lower curve, the dryer air temperature is used to determine the average partial pressure of water vapour in the juice. The curves are similar except that the curve based on the wet bulb temperature is vertically translated. The same trend is observed in both cases whereby the resistance gradually increases with decreasing water activity until a certain water activity is reached. At this point, the resistance increases substantially, which can be attributed to a rapid increase in viscosity. This trend is reasonable considering that viscosity increases non-linearly with respect to soluble solids content (Bourne, 2002; Knecht, 1990). This shows that by using the overall apparent resistance, it is possible to identify the water activity at which the viscosity begins to control the mass transfer.

One limitation to this approach is related to how the water activity is determined. The water activities shown in Figures 42a and 42b were determined by using experimentally obtained moisture contents and two different isotherms: (a) for mandarin orange juice with added sucrose (initially 20.0 °Bx), where water activity measurements were performed at 20°C (Ferawati, 2016) and (b) for grapefruit juice with pulp, where the water activity measurements were performed at 45°C (Wolf, Spieβ, & Jung, 1973).

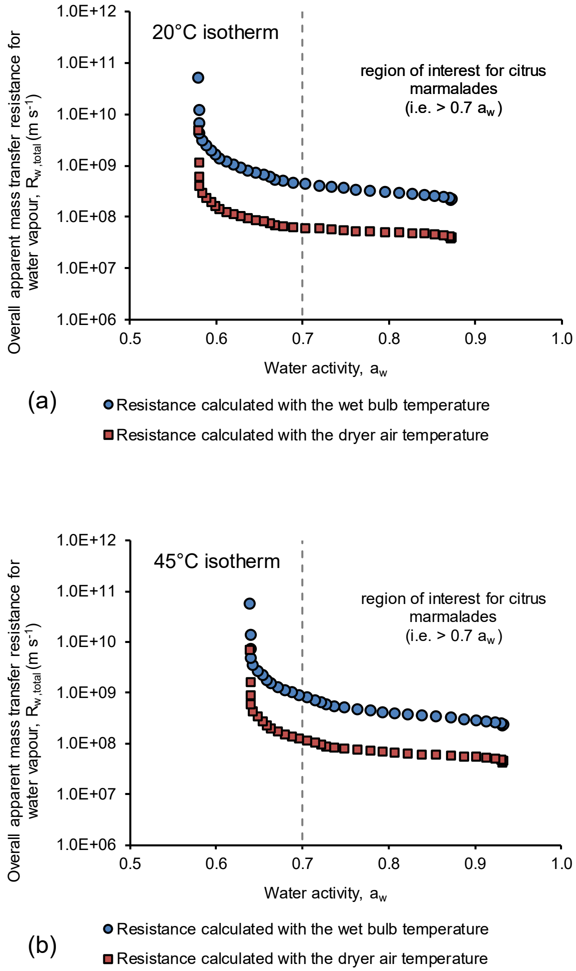


Figure 42 Assessment of how the internal conditions control the mass transport when SAP is used to concentrate a lemon juice plus sucrose solution (27.1 °Bx – see Figure 20 for details about the drying conditions). (a) The driving force was calculated with an isotherm for mandarin orange juice plus sucrose (initially at 20.0 °Bx), where the water activity measurements were conducted at 20°C. (b) The driving force was calculated with an isotherm for grapefruit juice with pulp where the water activity measurements were conducted at 45°C

An isotherm for lemon juice with added sucrose at 40°C would have been preferred since this was the drying temperature. However, the two isotherms chosen are representative of the sorption behaviour of citrus fruits at 20 and 45°C and are therefore suitable for the analysis.

From Figures 42a and 42b, the effect of isotherm temperature on the estimated water activity is significant. The curves in 42b are horizontally translated to the right since the water activity is higher at higher temperatures for the same moisture content (dry basis). In Figure 42b, the point when the resistance begins to increase substantially also becomes closer to the 0.7 boundary for the region of interest for citrus marmalades. If the situation in Figure 42a is more representative of the actual situation, then the rapid increase in viscosity will likely not play a role since the marmalade will be finished before the viscosity increase occurs. If the situation in Figure 42b is more representative of the actual situation, then the rapid increase in viscosity may occur near the end of the SAP process when the marmalade is close to being finished (i.e. when the soluble solids content has reached 65 °Bx). This could result in considerably slower drying and/or uneven drying in the final phase of the SAP process, both of which are undesirable. If the latter were true, the processing conditions could be adjusted to reduce the negative effects of higher viscosities. For example, if the temperature of the solar dryer could be increased, this would reduce the viscosity and could promote more uniform drying and/or a re-distribution of water inside the marmalade. Besides temperature, the other external conditions (i.e. relative humidity and air velocity) would not play a crucial role since the process would at this point be dominated by the internal mass transfer resistances rather than the external resistances. This sensitivity analysis shows that the choice of isotherm is a critical parameter when using this type of resistance model. This is because the isotherm influences the predicted water activity, which in turn affects the prediction of when the effects of viscosity play an important role in the drying process. An incorrect prediction could result in the incorrect choice of processing conditions near the end point of drying.

This preliminary assessment shows that an overall apparent resistance model has the potential to be used to separate the driving force from the internal resistances during the SAP process. However, there are limitations to this modelling approach, with one of the main limitations being that an isotherm at the processing temperature must be available for the substance that is to be concentrated. Without this information, it is difficult to make accurate predictions about the relationship between viscosity and water activity. Some isotherm data is available in the literature for foods, but often only at lower temperatures (e.g. 20°C). It could be possible to predict isotherms at other temperatures based on the existing isotherms at lower temperatures, but this is only possible if the heat of sorption is known (Labuza, Kaanane, & Chen, 1985). Another limitation is that the average temperature of the juice is unknown. However, from this preliminary assessment, the effect of the juice temperature on the relationship between water activity and resistance was minimal. The juice temperature affected the absolute value of the overall apparent resistance, but not the trend, which means that the juice temperature assumption is not as critical as the temperature assumption made for the isotherm. Overall, this resistance modelling approach has potential for the study of the internal mass transport phenomena occurring inside a SAP pouch, where the main limitation currently is obtaining an accurate isotherm for the juice to be concentrated.

6 The Recommended SAP Process

A recommended SAP process is presented in this chapter (Figures 43 and 44). The process expands on the process presented in Figure 12, and is based on the technical evaluation discussed in Chapter 5 as well as practical knowledge obtained in the field. The main attributes of the recommended process are:

- Juicing is performed with two manual juicing machines. The machines improve the efficiency of the juice making process compared to squeezing the fruits by hand. In the future, the manual machines could be replaced by a more ergonomic semi-automated or automated setup. One design has already been explored at the University of Guelph in Guelph, Canada, where a direct current motor was used to power the setup (Kang, 2017).
- The juice pre-treatment includes the addition of sucrose plus a pasteurisation step. Thereafter, the pasteurised juice is hot filled into membrane pouches. This maximises the quantity of marmalade produced and lowers the probability of spoilage by aerobic bacteria and/or yeast.
- A direct active solar dryer is the preferred solar drying setup, as it increases the probability of producing high quality marmalades with a soluble solids content greater than 65 °Bx, even when weather conditions are poor. When an active dryer is used instead of open sun drying, the drying time is reduced by 50% and the probability of fermentation is also reduced.
- Re-useable glass mayonnaise jars and lids are used to package the marmalade for long-term storage. These jars/lids are sterilised in boiling water for 30 minutes before the marmalade is packaged.
- The marmalade is heated treated after solar drying by transferring it to a pot and then heating the pot over an open fire until the marmalade begins to boil. The heat-treated marmalade is then hot filled into sterilised jars for long-term, shelf-stable storage. Firewood is the current fuel source. An alternative fuel source or more efficient stove could be used in the future.

By following the recommended SAP process, it is possible to produce shelf-stable citrus marmalades that have a microbiological quality that is comparable to the microbiological quality of commercial marmalades (i.e. all counts < 1.0 Log CFU/g).

Figure 43 The first part of the recommended SAP process from harvest to Solar Assisted Pervaporation. Larger membrane pouches could be used in the future. All photographs taken by R. Phinney © 2017

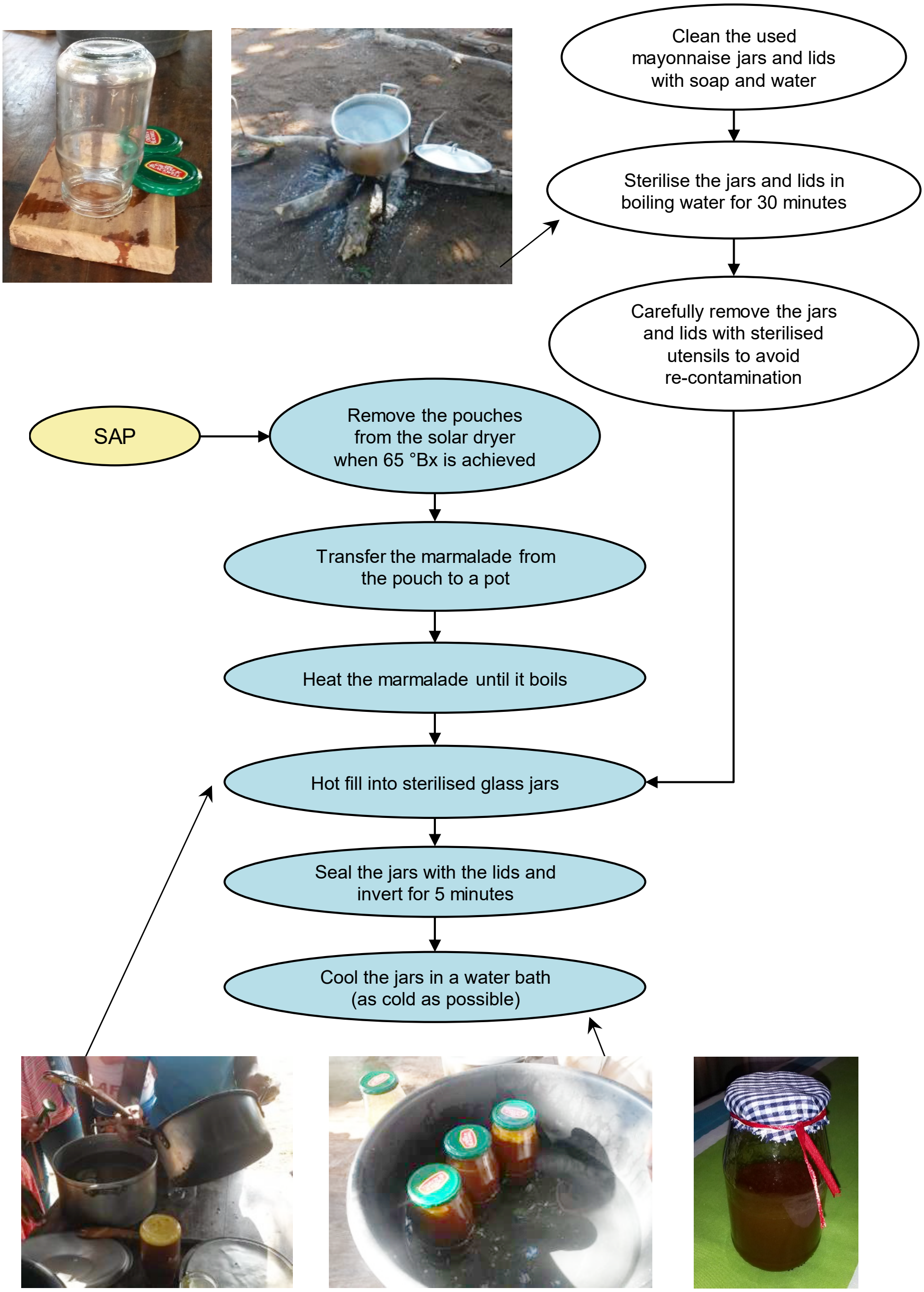


Figure 44 The second part of the recommended SAP process from Solar Assisted Pervaporation to sterile filling. All photographs taken by R. Phinney © 2017

7 Overall Suitability of the Solar Assisted Pervaporation Process

The previous chapter discussed the recommended SAP process based on technical results obtained both under controlled laboratory experiments and in the field. Since the aim is to implement the process in rural areas of Mozambique, it is also important to consider other societal aspects that could affect the suitability of the process in these areas. This chapter discusses the suitability of the membrane pouch and entire process for use in Mozambique, as well the most relevant social, economic and environmental aspects to consider.

7.1 Membrane pouch

The membrane pouch will need to be food grade, UV-stable and biodegradable to be implemented in Mozambique and other tropical countries. Two water vapour permeable materials were tested in this research as potential candidates for the membrane pouch and assessed in terms of these three properties. The supported (black) textile with the polyurethane membrane coating performed well from a drying flux perspective and the black colour improved the ability of the pouch to absorb solar irradiation. However, this material is not yet food grade and therefore not suitable for producing dried fruit products for human consumption. The unsupported membrane pouch performed well in terms of drying flux. Pouches made from this material were also used to produce tangerine marmalades during the field study in Mozambique and the marmalades were shown to be safe for human consumption. The unsupported pouch material is considered food grade and so it would be suitable for producing products for human consumption. However, it is not completely UV-stable (i.e. it breaks down with time when exposed to ultraviolet light). UV stability problems were observed during the field study in Mozambique, with the highest rates of membrane degradation occurring in the direct active and tilted passive (mixed mode) solar dryers (Figure 45). This suggests that the degradation reaction rate is accelerated at higher temperatures. To solve this problem, an indirect solar dryer could be used instead of a direct solar dryer or mixed mode solar dryer, or a transparent plastic or glass cover could be added to a direct

Figure 45 Unsupported membrane pouches that suffered from UV degradation in the direct active and tilted passive solar dryers. © R. Phinney, 2017.

or mixed mode solar dryer to filter out UV wavelengths and prevent them from reaching the pouches. Even though this would solve the UV stability problem, there is a risk that farmers would still use the pouches with direct sun exposure, either by open sun drying or by using a direct or mixed mode solar dryer not equipped with UV filtering glass/plastic. Since it cannot be guaranteed that the pouches will be used in combination with UV filtering solar dryers, it is not recommended to implement the membrane pouch solar drying process until a suitable food grade and UV-stable material can be found.

The biodegradable nature of the material is also a necessity if the environmental impact is to remain low. The two materials tested in this study are not biodegradable and instead made of plastic, which is not a good long-term solution. Many countries in Africa have established bans on plastic in recent years (Amlani, 2018)), as a result of an increasing amount of waste/garbage from plastic in landfills and other parts of the countries. Some countries around the world have facilities for converting plastic and other waste into useable energy for heating homes and producing electricity (Yee, 2018). If such a facility were available in Mozambique, it could be possible to use a UV-stable version of the current unsupported pouch material, since the pouches could be converted into useable energy after use. Since this is not the case at the present time, the pouch material must instead be biodegradable to avoid polluting Mozambique and other countries with unnecessary amounts of plastic.

From an ergonomic and handling perspective, the membrane pouch prototypes were accepted by the farmers. One prototype tested in June 2017 had two handles that enabled easier filling of the pouches (see section 4.1.3 Figure 11c), especially when the juices were pasteurised and added to the pouches at a temperature of 70°C. The WeLoc plastic clips were strong and robust and a pouch could be suspended upside down without breaking open. One drawback of the design was that two people were required for the filling procedure. One person was required to hold the handles while the other filled the pouch with juice. Improving the filling process by using a stand or semi-automated filling machine would be beneficial if the membrane pouch solar drying process is to be implemented in the future. A design for a semi-automated filling and sealing machine has already been tested at the University of Guelph in Guelph, Canada (Taylor, 2017). The machine is operated with a direct current motor, which could be used in combination with a solar panel in a rural area. The handleability and ergonomic characteristics of the pouch are of importance to the farmers and therefore semi-automated filling methods could be beneficial.

7.2 Process from raw fruit to shelf-stable product

The process from raw fruit to finished shelf-stable product includes several steps (see Chapter 6). This research has shown that all parts of the process can be performed in a rural area of Mozambique like the one shown in Figure 46. Compared to producing marmalade by a traditional boiling method over an open fire, one benefit of the SAP process is that a person does not need to monitor a pot of juice boiling over a fire for many hours. Another benefit is that larger quantities of marmalade can be produced in a more efficient way (e.g. 100 membrane pouches can be put in a solar dryer, whereas it would be difficult to have many pots of juice boiling over many fires at the same time). A third benefit is that the amount of firewood required is reduced. This is because in the recommended SAP process, firewood is only used to generate sensible heat for the initial pasteurisation before pouch filling and the final pasteurisation before packaging. When evaporating water from the juice over a fire using the traditional method, firewood is also required to generate the latent heat needed for evaporation. This means from time and productivity perspectives, the SAP process has clear benefits over the traditional open fire method for producing marmalade.

Figure 46 Example of a rural location where food processing takes place in the district of Inharrime, Mozambique. © R. Phinney, 2015.

Based on the Participatory Rural Appraisal approach that was carried out, other steps of the SAP process were found to be of concern. For example, before the SAP process was tested with the farmers, both men and women ranked the transport of tangerines as the step anticipated to be the most difficult based on their previous harvesting experiences (Otte, Tivana, et al., 2018). This was surprising to the researchers since it was assumed that the steps in the process that introduced new technologies to the farmers (i.e. the juicing machines or the membrane pouches) would be anticipated as the most difficult or intimidating. Further discussions with the farmers made it clear that the collection and transport of crops is very difficult in rural areas since there are often no machines available to make the processes more automated. This means that all fruits would need to be picked by hand and then carried in containers or transported in wheelbarrows or trailers. It may be possible to use an animal to pull the trailer, but if not, the workers would need to pull or push the trailer themselves. The soft and juicy nature of citrus fruits also makes them more susceptible to damage during transport. Transport has been reported previously as one of the major challenges in rural areas of sub-Saharan Africa (Murray, Gebremedhin, Brychkova, & Spillane, 2016), which means that the transport problem faced by the farmers in the Inharrime district is not just a localised problem. Since this research did not focus on the collection and transport of the fruits, it is recommended to focus on optimising these steps in the future, whether or not the membrane pouches are used downstream in the process.

An aspect that was overlooked during the research was the availability of clean, hot water that is required during processing. During the field study in Mozambique, clean, hot water was obtained by boiling harvested rainwater over a fire. Since a maximum of 32 pouches were tested in one experiment and the quantities of marmalade produced were not so large, it was possible to obtain a suitable amount of clean, hot water with this method. However, if this process were to be scaled up, another solution would be needed. One idea would be to incorporate a solar water heater into the solar dryer design. This combi-unit would reduce the space requirement on-site and it is possible that the same solar collector (i.e. black absorber) could be used to heat the water and then later dry the pouches. Another alternative would be to design a separate solar water heater that could be secured, for example, to a rooftop (S. Kalogirou, 1997). Depending on the water temperatures achieved, there could be safety risks involved, and so proper safety measures would need to be taken when designing the apparatus to ensure the farmers would not be harmed. Regardless of whether or not the membrane pouches are implemented, a solar water heater to produce clean, hot water for processing would make an important contribution to the hygiene and safety of food processing in rural areas.

An additional challenge that remains is the packaging of the marmalade. The microbiological results (Paper VI) showed that the marmalades were safe to consume if eaten directly from the pouches, but for a longer shelf-life, the marmalades would need to be re-heated and hot filled into sterilised jars. In the field study, the marmalades were transferred from the pouches to pots and re-heated over a fire before being hot filled into sterilised re-useable mayonnaise jars. This method proved to produce marmalades with a commercial microbiological quality, but was not so practical. To improve the process, a type of stainless steel pot with a spout could be used. This pot could be placed on a fire and filled with marmalade from above. After boiling, the marmalade could then be added to each jar via the spout. Safety precautions would still need to be taken when handling the hot jars but the overall safety risk would be reduced compared to the method used in the field study.

The ideas discussed in this section are meant to illustrate that even though research can focus on one element of a process, it is still important to consider the entire process from the raw to the finished product. By taking both social science and technical approaches during the fieldwork, it was possible to uncover challenges that were not considered previously and not directly related to the use/handleability of the membrane pouch. These reflections emphasise the importance of considering different methodologies when developing new technologies, and also the importance of involving farmers and incorporating their perceptions so that new technologies align with the underlying social and cultural practices of the community. This approach may help researchers identify the most significant needs and challenges so that these aspects can be incorporated into the technology development.

7.3 Logistical and commercial considerations

The supply chain logistics are suspected to be a challenging element of the SAP process. Four main challenges have been identified. The first is related to how the pouches will be transported to the rural areas where they are to be used. Reliable logistical transport is not always available in Mozambique and so there is a risk that deliveries will be delayed. If the pouches cannot be delivered on time, the fruits will not be utilised at the optimal time, resulting in a loss of profit and wasted fruit resources. There is also a risk that the farmers may be overcharged for the pouches if a middle player tries to bargain the price. Another challenge is related to the production of the pouches. If the pouches are produced abroad, there will be logistical challenges getting the pouches through customs. If they are produced in Mozambique, logistics related to the pouch production will need to be considered (e.g. the import of the membrane material in pellet or film form, where to acquire the packaging materials required for transporting large quantities of pouches to rural areas, where to obtain the manufacturing equipment and consumable materials required for manufacturing such as cleaning products or lubricants, etc.). A third challenge is how to package the finished marmalades. Re-useable glass mayonnaise jars were used during the field study in Mozambique and found to be a suitable option for longer-term, shelf-stable storage. However, the consumers who purchase the marmalades may not accept these re-useable jars. If new glass jars and lids are required, this may introduce complications since it could be challenging for the farmers to obtain the jars both for logistical and financial reasons. A fourth challenge is the transport of the packaged marmalades to the point of sale. It is possible that the marmalades could be sold on the side of the highway, but it is likely that the quantities sold could be greatly increased if the marmalades were sold in nearby markets or tourist shops. These four challenges would need to be addressed before implementing the SAP process to increase the probability of long-term success.

The commercial potential of the process also still needs to be determined. The farmers were enthusiastic about the marmalades that were produced (i.e. the taste and texture were well liked), and so it seems there is a market for the product. However, before production can be carried out on a larger scale (e.g. 100 pouches drying simultaneously) several questions need to be answered, such as:

- Where will the marmalade be sold? (e.g. Inharrime is located close to the ocean and many beach resorts where South African tourists frequently visit. Could the marmalade be sold at these resorts?)
- Which consumer group is the target market?
- What should the selling price be? If there is a middle player, will the farmers still make a profit?

- What is the total capital cost investment required?
- In terms of operating costs: How much will each pouch cost? What is the cost of new glass jars? What are the costs involved in maintaining the solar dryers?

These aspects are important to consider but a detailed analysis is out of the scope of this research. In relative terms, the operating costs and capital investment cost would be much lower compared to larger factories due to the minimal infrastructure required. Before implementing the SAP process in Mozambique or other tropical countries, it would be beneficial to conduct a thorough analysis of the market in order to develop a sound business case that includes answers to the above questions.

7.4 Socio-economic aspects

This research aims to reduce poverty and improve the quality of life of people in low-income countries through the promotion of economic growth, by giving farmers the opportunity to add value to agricultural resources that normally go to waste. As a result, more nourishment would be available to farmers, their families and the local population throughout the year, and farmers would be provided with a way to earn extra income by selling their dried products at local markets or through other distributors. The extra income earned would remain at the farmer level, which would help avoid the potential negative effects of corruption at the government level (Spector, Schloss, Green, Hart, & Ferrell, 2005). Since it is known there is a link between gender equality and poverty reduction (Lokshin & Mroz, 2003), this suggests that poverty reduction through economic growth could also lead to improvements in gender equality. The hypothesis is that a positive effect on the economy would increase the opportunities for girls and boys and men and women. If families have more wealth, there is a greater chance that all children will have the opportunity to be educated, rather than just the boys (Lokshin & Mroz, 2003). Therefore by improving economic conditions for farmers and keeping as much income as possible at the farmer level, it may be possible to improve gender equality while also reducing the level of poverty.

One aspect to consider related to this is the amount of time that farmers would have each day for solar drying to generate products to sell. It was found when conducting the Participatory Rural Appraisal exercises that the farmers have very little extra time each day to spend on other activities (Otte, Bernardo, et al., 2018). From the daily schedule exercise carried out with the farmers, women were found to be particularly pressed for time compared to men. During times of intense farming, some women have to wake up at 3 a.m. in the morning just to have enough time to complete all of their daily tasks, extending their working day to more than 12 hours. The farmers also expressed that they are only interested in a new form of technology if it will result in economic gain (Otte, Tivana, et al., 2018). This means that in order for the SAP process to be suitable for these farmers, the economic gain needs to be high enough to justify removing other tasks from their schedules. Income is already earned by these farmers through the production and sale of crops like cassava, and so the SAP process needs to be designed in a way that maximises the economic gain from utilising excess fruit without negatively impacting the farmers' already well-established businesses.

7.5 Social and ethical aspects

This research has the potential to affect gender equality and gender roles and relations in a number of ways. The first is by women empowerment. It is estimated that up to 90% of employed women in Mozambique work in the agricultural sector (U. S. Government, 2012). It is also known that many female farmers in low-income countries are often disadvantaged because they have less access to technology due to cultural or financial restrictions (U. S. Government, 2012; Lokshin & Mroz, 2003). An important part of this research has been to promote the SAP process to both men and women in the agricultural sector to increase the likelihood that women will have the same level of access as men to the technology in the future. This proved to be challenging since the Participatory Rural Appraisal exercises showed that there is often a clear division of roles for specific tasks (Otte, Tivana, et al., 2018). For example, in an exercise where participants were asked individually to assign different groups (i.e. men, women or children) to different steps in the SAP process, almost all men and women said that the washing of the tangerines was to be done by women and the juicing of the tangerines was to be done by men. This assessment was done before the experiments were performed based on the farmers' assumptions about what each step wold entail. It was mentioned to the farmers that the juicing would involve a machine (i.e. technology), which could be one reason that men were assigned this task by 10 out of 10 women and 6 out of 7 men (Otte, Tivana, et al., 2018). Cultural attitudes may partly explain this, as it has been reported previously in Mozambique that cultural attitudes often encourage technology access to men rather than women (Sida, 2007). Another observation was that women often assigned children to some of the steps. This shows that there is also a risk that children will be asked to help out with the process, which could mean that they would not have enough time to go to school. This is also something important to consider for the future.

In addition, it was discovered that the introduction of the SAP process offers opportunities to change gender roles and relations within the agricultural associations. Some of the steps in the process, such as filling the pouches with juice and putting the pouches in a solar dryer, were not clearly gender divided according to the women. For these two steps, half of the women said that women would be responsible for the task, while the other half said that men would be responsible.

Because these tasks were not clearly gender divided, it may be possible to use these tasks as a starting point to improve women's access to technology. These results suggest that when developing new technologies, there will likely exist gender norms that influence the division of roles, and at the same time, opportunities for creating new attitudes and defining new roles to give women more access to technology. By focusing on the opportunities, it may be possible to affect gender equality and gender roles and relations with the SAP process.

Theft and vandalism were found to be concerns of the farmers. On one of the first experimental days after the pouches had been prepared and placed in the solar dryers, the farmers became worried about leaving the solar dryers unsupervised. They talked about theft and vandalism being common occurrences, especially with solar panels and other electrical equipment. This is a common problem and concern in many African countries (Akinboro, Adejumobi, & Makinde, 2012). One of the farmers proposed a solution and began camouflaging one of the solar dryers with coconut tree branches. The farmers then placed this solar dryer as close as possible to the trees so that it would blend into the environment. This concern of theft and vandalism had not been considered by the researchers until this point. Instead, the thought was that the farmers would save time by allowing the pouches to dry while they performed other work elsewhere. Theft and vandalism during the night would be even more of a concern. This means it might be difficult to have a solar dryer running with fans powered by solar charged batteries throughout the night. A clever solution to address the challenges of theft and vandalism in this rural area of Mozambique is still required and should be considered in the future if a solar drying apparatus is to be left unsupervised.

Jealousy was another aspect that was discovered to be of importance. The two agricultural associations that were involved in the development and evaluation of this research were located approximately 4 km from each other. It was discovered early during the Participatory Rural Appraisal phase of the research that one association became jealous of the other if only one association was invited to participate in a certain exercise, and vice versa. Leaving equipment, gifts or other tokens of appreciation was also difficult since it had to be done as equally as possible to avoid jealous feelings emerging. Similar observations have been made previously, such as in Ghana where one human cause of bushfires was jealousy, as a result of some farmers becoming envious of others who obtained better crop yields (Yahaya & Amoah, 2013). The agricultural associations in Inharrime seemed like two separate families, and so it is completely reasonable that each wanted the best opportunities for its own members. This jealousy aspect is of importance and should be considered when planning and carrying out development projects.

One of the greatest impacts that emerged from this research came from the transfer of traditional knowledge about food preservation practices to the farmers.

During the fieldwork, it was realised that traditional fruit preservation methods, such as the solar drying of sliced fruit or the making of marmalade by boiling over a fire, were not commonly practiced in these areas. Since a variety of foods are available all year round in Inharrime due to the excellent soil quality and warm climate, preserved food is not needed in these areas for survival in the same way that it is needed in other areas or countries (i.e. areas with poor soil or colder climates). In the past, there was a demand for the development of food preservation methods in many parts of the world, especially in colder climates where one way to preserve food was by freezing with natural ice in the surroundings, developed as early as 1000 B.C. (D. R. Heldman & Nesvadba, 2003). Other reasons for the demand for food preservation included the expansion of cities during the end of the 1800s and the need for food produced on one continent to be safely transported to another (D. F. Farkas, 2003). None of these demands would have applied to the Inharrime district in Mozambique in the past, which may explain why knowledge about food preservation and food safety was lacking. After realising this, effort was made to teach as many people as possible in the area how to make tangerine marmalade with traditional methods (i.e. by boiling a pot of tangerine juice with added sugar over a fire for many hours). This included the development of a sterile filling method where re-useable mayonnaise jars and lids were submerged in boiling water for 20 minutes before being removed and filled with marmalade (also at approximately 100°C). These demonstrations were carried out in parallel to the membrane pouch experiments, which also proved to be pedagogic since the farmers could see and experience first-hand the differences between the two marmalade-making processes. The farmers became very enthusiastic about making marmalade and began producing many jars for home consumption (Figure 47). The same type of demonstration/workshop was then later conducted in the capital city Maputo with a women's group. After the demonstration, this group became very motivated to start a small jam and marmalade making business. Since July 2017, they have continued to grow their business, making hundreds of jars of jam/marmalade with various fruits (Figure 48). In Inharrime, there has been talk about creating a small business, but as a start, a learning center has been established at one of the farms of an association member, where this engaged member now encourages others to come and learn how to make tangerine marmalade and how to solar dry other types of fruits. This result shows that sometimes the greatest impact comes from the simplest solutions and that we should not by-pass teaching people about traditional practices even when a newer technology may seem like the better solution. The membrane pouches are not yet ready for widespread use, but this does not mean that the Mozambican people should wait for the pouches to be ready before starting to preserve their fruits. The traditional method being used is not the most sustainable since it requires firewood or charcoal, but compared to larger factories, the carbon footprint is still low. It only took a few hours to show these people how to make marmalade, yet the impact has been extensive. It is therefore highly recommended that researchers think about what kind of (traditional) knowledge they can pass on to participants in a field study, to ensure that some of this knowledge can be used immediately, especially if parts of the new technology being tested still require further development.

Figure 47 Left photograph: An engaged association member who is now encouraging others to come to his farm to learn how to make marmalade and solar dry fruits. Right photograph: Young women who are part of one of the agricultural associations in the district of Inharrime and who took part in the marmalade-making activities. In both photographs, tangerine marmalade is in the glass jars. © R. Phinney, 2017.

Figure 48 :
Top photograph: women's group in Maputo, Mozambique that started a small marmalade-making business called "Comida Solar" (Solar Food).
Left photograph: jars of mango jam made by the Comida Solar group with a traditional boiling method. Charcoal was used as the fuel source.
© G. Monjane, 2018 (top), 2019 (left).

The last social and ethical aspect that will be discussed is one of the most important lessons learned from the fieldwork. It relates to the notion of introducing something and taking it away again as part of the participatory research conducted. Participatory research can be an effective way to bring farmers and researchers together with the aim of integrating indigenous values and beliefs and building a communication channel between different parties to increase the probability that the technology will be better suited and adapted to the needs and lifestyle of the end users (Hoffmann, Probst, & Christinck, 2007; Kindon, Pain, & Kesby, 2009). However, during the field study, some of the technologies introduced to the farmers were completely new to them, and because of their excitement for these technologies, it felt unfair to take them away again after the field experiments were completed. The membrane pouch is one example, but the juicing machines are another (see Figure 43 in Chapter 6). It was made clear to the participants in the study that this was a research project and that we would not be leaving any of the equipment with them after the study was over. This was actually to avoid jealousy between associations as discussed previously. Even though this was discussed beforehand, the farmers became very excited about the juicing machines and became inspired by the new products they could create. In this rural area, the juicing of fruits had only been done previously by hand (i.e. cutting the fruits in half and squeezing them by hand without any kind of equipment) and so it is completely understandable that they would be fascinated by a new way to make juice. Once they were aware of the machines, it did not feel ethical to take them away again. It would be similar to giving someone a smart phone to test, having them see that it makes their life more efficient and easier, and then taking it away again. With the membrane pouches, we had a limited supply and the farmers knew this and accepted it. However, the juicing machines are commercial products available for purchase in many countries. The only obstacle preventing the farmers from acquiring such equipment is money and logistics (i.e. delivery of the machines to Mozambique and then further to the rural areas). Furthermore, after teaching the farmers how to make tangerine marmalade traditionally over a fire, it became essential for them to have a juicing machine to be able to make enough juice for producing reasonable quantities of marmalade in one day. In the end, we decided that one juicing machine would be given to the farmers to remain in the rural area and be shared by both associations. This turned out to have a large impact on the associations, and in particular one association where one engaged and motivated member has now created a learning center for teaching others about food preservation. The biggest lesson learned here was that researchers should really question if it is fair or not to introduce new technologies to people and take them away again. This should be thoroughly thought through before starting the experiments to ensure that both parties obtain either technology or knowledge that makes their lives better, and not worse.

7.6 Environmental aspects

SAP is an eco-friendly drying method that promotes sustainable global development. The evaporation of water is driven by solar energy, which means the environmental impact and carbon footprint are reduced compared to the traditional method (i.e. boiling over a fire).

One beneficial aspect of the SAP process is that less water is transported compared to transporting whole fruits. For example, 100 jars of marmalade (425 g per jar) with a soluble solids content of 65 °Bx can be produced from approximately 93 kg of fresh tangerine juice (at 11 °Bx) and 17 kg of sugar. This gives a total starting juice plus sugar mass of 110 kg (at 25 °Bx). To produce marmalade with a final soluble solids content of 65 °Bx, 68 kg of water must be removed. Assuming that the mass of the glass jar and lid used for packaging are 200 g and 10 g, respectively, this gives a jar plus marmalade mass of 635 g and a total mass of 64 kg for 100 jars of marmalade. Since the original mass of the tangerine juice used to produce this marmalade was 93 kg, this means that the one would transport an extra 29 kg of water if the same tangerines were transported as whole fruits compared to marmalade in glass jars. This 33% reduction in mass includes the mass of the jars and lids, but does not include the peels and seeds that would be included when transporting whole fruits. This means that a 33% mass reduction is a conservative estimate. Considering that carbon dioxide emissions are directly proportional to size and weight of the transported item (Cefic and ECTA, 2011), marmalade transport would result in less CO_2-emissions compared to transporting the same amount of nutrients in whole, in-tact fruits. Reducing the amount of transported water is therefore a way to reduce the carbon dioxide emissions. This analysis only considers transport and does not consider CO_2-emissions produced during other parts of the SAP process.

One disadvantage of the current SAP process is that some firewood is still required to pasteurise the juice and marmalade before and after drying, respectively. However, because this pasteurisation step only requires sensible heat as opposed to latent heat, the energy requirement is reduced. As an example, if one were to produce 100 jars of marmalade (i.e. where each jar contains 425 g of the 65 °Bx marmalade described above) with 100 membrane pouches, the sensible heat requirement for both pasteurisation steps (i.e. before and after drying by SAP) would be 37 MJ (i.e. 30 MJ before, 7 MJ after). This corresponds to 25 kg of dry firewood assuming a firewood conversion efficiency of 8%[7]. To produce 100 jars of marmalade with the traditional method, it would take 153 MJ of energy, corresponding to 102 kg of dry firewood. Therefore, only 24% of the firewood is needed with the SAP method compared to the traditional method to remove the same amount of water for

---

[7] The heat value and conversion efficiency for firewood were obtained from Keita (1987).

producing 100 jars of marmalade. It is still feasible to produce 100 jars of marmalade with the traditional method, but the SAP process would be an improvement. A further improvement would be to strive to eliminate the need for firewood altogether. This is because the use of firewood can lead to deforestation and strain on the environment, can cause health problems from exposure to smoke, and may require that women travel long distances to collect the firewood (Boonstra, 2008; Patrick, 2007). The latter is not only laborious, but can also be dangerous for women (i.e. due to sexual violence) (Patrick, 2007). The SAP process is still an improvement compared to the traditional method as it reduces the amount of firewood that needs to be collected. It is a step forward in making small-scale marmalade production methods more sustainable and safer for women.

There are three main environmental challenges with the current SAP process. The first is the biodegradable nature of the pouch as mentioned earlier. The second is that firewood or charcoal are still required in the current process. It would be beneficial in the future to strive towards a process that is completely free of non-renewable energy sources. This could be achieved, for example, by developing a solar-driven pasteurisation unit for rural areas. A third environmental challenge with the current process is that there are fruit peels, seeds and pulp leftover as waste. There is currently no value-added application for these waste products, but it could be possible in the future to use this waste as another energy source (e.g. to create bio-gas to replace the firewood currently needed for the pasteurisation step) or for composting. It is recommended to aim for a zero-emissions concept in the future.

7.7 Summary of the overall suitability

The overall suitability of the SAP process for use in rural areas of Mozambique and other tropical countries is summarised in Table 7.

Table 7 Summary of the overall suitability of the SAP process in tropical areas.

	Advantages/Opportunities	Disadvantages/Challenges
Membrane pouch	Unsupported membrane material is food grade and can be used to produce safe tangerine marmalades in 3-6 days Pouch design with two handles and plastic clip accepted by the farmers	Unsupported membrane material is not UV-stable and not biodegradable Current design requires two people for filling; semi-automated filling machine is recommended for increased productivity
Process from raw fruit to shelf-stable product	Can be performed in rural areas Less supervision of the process is required compared to traditional marmalade-making over a fire Greater quantities of marmalade can be produced per unit time compared to what is possible by boiling many pots over many fires	Collection and transport of the fruit is laborious Clean, hot water is obtained by boiling over a fire; solar water heater is recommended Final step of pasteurisation plus hot filling into sterilised jars not practical and potentially unsafe; stainless steel pot with spout preferred
Logistical and commercial considerations	Potential for extra income to be earned by utilising fruit resources that otherwise spoil Low operating costs and capital investment cost compared to large factories	Transport of the pouches to the rural areas and transport of the finished marmalades to the point of sale unclear and challenging Pouch production logistics unclear Farmers will need to purchase the pouches (re-curring operating cost) Target market and point of sale unclear Commercial potential unclear
Socio-economic aspects	Poverty reduction through economic growth at the farmer level Improved food security	Famers have limited time for extra tasks Need to avoid negatively impacting already well-established businesses (e.g. cassava processing)
Social and ethical aspects	Opportunity to change gender roles and relations and empower women by introducing new processing steps and technologies Knowledge transfer about preservation and food safety Creation of marmalade-making small businesses and learning centers	Some steps in the process already defined for men and women Farmers are concerned about theft and vandalism Children may be required to help, which could force them to stay home from school
Environmental aspects	Solar energy used to evaporate water rather than firewood Maximising the use of agricultural resources Excess water is not transported since water removal done close to harvest point Refrigerated transport/storage not needed	Pouch material is not biodegradable Current process still requires some firewood for pasteurising the juice and sterilising water/jars Tangerine peels currently considered as waste; finding a use for the peels is recommended (e.g. bio-gas, compost)

8 Conclusions

The aim of this research was to develop and evaluate a safe and practical fruit juice concentration process for rural and remote areas of tropical countries. The process was termed Solar Assisted Pervaporation (SAP). With this process, water vapour permeable membrane pouches are filled with fruit juices and then dried in the open sun or in a solar dryer until enough water is removed that a shelf-stable juice concentrate or marmalade remains. There were five main objectives investigated as part of this research regarding the evaluation of the process. A summary of how each objective was achieved is given below.

1. **Evaluate the feasibility of the process in terms of drying time, drying flux and fruit compatibility (Paper I and Paper II)**

   Realistic total drying times of 2 to 3 days were achieved (i.e. assuming 8 hours of radiant exposure per day) when solar drying conditions were simulated with two laboratory setups. In simulated open sun drying, drying flux was directly proportional to solar irradiance (W/m^2). However, drying flux was negatively affected by the forced convective airflow when the air was not pre-heated (i.e. when the air temperature was the same as the temperature of the ambient surroundings). Simulated indirect active solar drying resulted in higher drying fluxes than simulated open sun drying in the ambient air because the air in the simulated indirect dryer was pre-heated. A preliminary assessment showed that a number of fruits are compatible with the membrane pouches based on water activity (i.e. achieving a water activity < 0.7), including citrus fruits and an indigenous Mozambican fruit called *Vangueria infausta* (African medlar).

2. **Evaluate the possible effects of internal mass transport on food safety (Paper III)**

   Neutron radiography was shown to be a potential technique for investigating the concentration/dehydration of fruit juices and purées in membrane pouches. When apple and banana purées were dried by simulated open sun drying in a neutron beamline, the neutron radiographs showed that the purées dried inhomogeneously, resulting in small zones of high moisture in various parts of the purées after drying. These zones could introduce a food safety risk since the water activity could be high enough in these zones for microbial growth to occur. The drying behaviour of apple juice (low insoluble solids content) was different from apple purée (high insoluble solids content). Localised high moisture zones were not observed when concentrating apple juice in a membrane pouch. The juice dried uniformly, which suggests that a low insoluble solids content is favourable for homogenous drying in membrane pouches. Furthermore, by using heavy water (D_2O) as a tracer, it was also possible to investigate the mass transport of water in apple purées during drying. The results confirmed that the mass transport of water occurred by diffusion in the apple purées. The neutron radiography experiments indicated that it may be more difficult to control microbial growth when drying fruit purées in membrane pouches. For this reason, citrus fruits were focused on in the remainder of the research.

3. **Evaluate the solar drying performance under controlled laboratory settings (Paper IV)**

   A laboratory method was developed and statistically validated (precision of 95% or more) to assess the indirect solar drying performance of the SAP process. Since the method allowed for relative humidity control, it was possible to identify a two-level factorial regression model for drying flux that included the coupling effect between temperature and relative humidity. By considering a constant boundary condition on the inside of the membrane (i.e. a water activity of 1.0), the heat and mass transfer phenomena occurring inside the membrane and between the pouch and surrounding air could be isolated. This allowed for the process parameters that are important during constant rate drying to be identified, and for the drying fluxes that could be expected under realistic conditions in Mozambique to be predicted. Air velocity was found to have a positive effect on the drying flux. This showed that the overall drying flux was not limited by the membrane resistance within the velocity ranges tested, and that boundary layer thicknesses outside the pouch could be decreased by increasing the air velocity.

4. **Evaluate how solar drying setup and choice of juice pre-treatment determine the drying flux under realistic conditions in Mozambique (Paper V)**

   The results of the field study in Mozambique confirmed that it was possible to produce tangerine marmalades with a soluble solids content of at least 65 °Bx by concentrating tangerine juices (with or without added sucrose) in membrane pouches that were placed in the open sun or in a solar dryer. By using a direct active or tilted passive solar dryer, the drying time was reduced from 6 days (open sun drying) to 3 days. This was due to a lowering of the partial pressure of water vapour (i.e. greater driving force for mass transfer) in the air inside the solar dryers. The highest drying fluxes were achieved in the active dryer due to higher convective airflows in this dryer versus the passive dryer. The convective airflow in the active dryer can also explain why the effect of the internal conditions on the drying flux was more prominent in the active solar dryer compared to the other solar drying setups. Specifically, there was a greater difference between the drying fluxes for samples with added sucrose compared to the drying fluxes for samples without added sucrose in the active dryer compared to the other solar drying setups. Since passive solar drying was found to be more sensitive to poor weather conditions than active solar drying, the recommendation is to use a direct active solar dryer to have better control over the drying process. A passive dryer is a good second choice if weather fluctuations are less common and/or a more economical solution is preferred. The addition of sucrose as a juice pre-treatment had negligible effect on the drying time and is also recommended as a way to increase the amount of marmalade produced per quantity of tangerines.

A preliminary assessment on how the changing internal conditions affect the mass transport was also completed with a resistance-in-series model, where the overall resistance was used to investigate how drying flux changes as a function of decreasing water activity. It was demonstrated that this type of model has the potential to be used for separating the effect of the driving force (i.e. water activity of the juice) from the effect of the internal mass transport resistance on the drying flux, to study how increasing viscosity of the juice concentrate affects the overall mass transport of water molecules.

5. **Evaluate how solar drying setup and choice of juice pre-treatment affect the microbiological quality under realistic conditions in Mozambique (Paper VI)**

In the same field study as mentioned above, it was shown that the SAP process can be used to produce tangerine marmalades with an acceptable microbiological quality for immediate consumption. Solar drying setup had a negligible effect on the total aerobic count but a significant effect on the yeast plate count. Open sun drying was found to increase the probability of fermentation by yeast, whereas active and passive solar drying resulted in low yeast counts in both trials and for all juice pre-treatments.

In terms of juice pre-treatment, pasteurisation lowered the total aerobic count and probability of fermentation. The addition of sucrose and/or lemon juice without pasteurisation had no beneficial effect on the total aerobic count, with an increase in the total aerobic count occurring in some cases. Samples with added lemon juice were also observed to ferment, suggesting that lowering the pH had no inhibitory effect on yeast growth and fermentation. Since the pH of the tangerine juice ranged from 3.36 to 3.83, a lowering of the pH is not required to prevent the growth of *Clostridium botulinum*. This means lemon juice does not need to be added to the juices before drying. Since sucrose has a beneficial effect on the quantity of marmalade produced, it is recommended to add sucrose in combination with a pasteurisation step before drying.

All lactic acid bacteria, mold and *Enterobacteriacea*e counts were low and on the same order of magnitude as the reference samples (i.e. < 1.0 Log CFU/g). Mold growth was observed on the outside of some pouches yet the resulting mold counts were still low. This shows that the membrane pouches provided a hygienic barrier to mold and prevented contamination during drying.

To extend the shelf-life of the marmalades, an additional sterile filling step is required, such as boiling the marmalade in a pot over an open fire after drying by SAP, and then hot filling the marmalade into sterilised re-useable glass jars. This sterile filling method was tested on-site and found to be effective for reducing the microbial counts to levels that are acceptable for commercial citrus marmalades. Since it was possible to produce marmalades by SAP with soluble solids contents of at least 65 °Bx, this means that SAP has the potential for producing marmalades with a reduced probability of spoilage by mold and yeast during unrefrigerated storage, even after opening.

In addition, it was found during the development of the SAP process that participatory research helped the researchers establish a better understanding of the needs and lifestyles of the farmers, and empowered the farmers to take an active role in the development of the process. It is therefore recommended to incorporate exercises based on the Participatory Rural Appraisal approach as much as possible when developing new technologies in the future.

9 Future Outlook

This research has been a step forward in making better use of underutilised fruit resources in tropical countries like Mozambique through the development and evaluation of a solar drying process called Solar Assisted Pervaporation (SAP). This process addresses the hygienic challenges of traditional sun/solar drying, and is suitable for juicy fruits, such as tangerines, that are particularly difficult to solar dry due to their high water content. Since there is enough food grown in the world to feed the human population but up to a third of this food spoils (FAO, 2011), methods like SAP are needed now and in the future to preserve food in a more efficient way with renewable resources like solar energy.

Even though the SAP process still requires more research before it will be ready for widespread use, a considerable amount of knowledge has been gained about how to preserve fruits with solar energy in better ways in the future. This includes technical knowledge as well as knowledge related to logistical, socio-economic, social, ethical and environmental aspects. One recommendation that can be made to researchers and organisations based on this acquired knowledge is that a holistic approach can be beneficial for technology development. The approach should include all parts of the process from raw to finished product, as well as many different types of people and organisations who can each contribute with a unique viewpoint. One example of why a holistic approach is beneficial is related to how the farmers specified that transporting the fruits would be the most difficult step in the process. The difficulty of transport was underestimated by the researchers who were focused on the membrane pouches and solar dryers. The transport of the fruits turned out to be one of the most critical elements of the process and this was only discovered after engaging the farmers in the technology development. Another recommendation in terms of holistic process design would be use a zero waste/emissions concept, to improve the use of waste streams generated in the process. For example, the tangerine peels are a waste stream but also a valuable source of biomass. Taking a holistic approach when designing the process would allow for this valuable biomass to be utilised in another way, such as with composting or for the production of bio-gas. This type of approach can be recommended for future development projects.

Another aspect to consider in the future is the use of firewood. The recommended SAP process includes an initial pasteurisation step before adding the juices to the pouches, and a final pasteurisation step before sterile filling for long-term storage. In both steps, firewood is currently being used to generate the sensible heat needed to increase the temperature of the juice. Even though less firewood is required compared to the traditional marmalade-making process (i.e. boiling over a fire for many hours – see section 7.6), the extensive use of firewood may not be a sustainable solution for the future since there can be a negative impact on the environment (e.g. deforestation) and/or a negative social impact (e.g. women and girls may be forced to travel long distances to collect firewood, which may be dangerous) (Boonstra, 2008). Two possible alternatives include the use of fuel-efficient stoves or alternative fuels (Patrick, 2007). Another alternative is a solar-driven pasteurisation unit. This unit could be designed, for example, like a shallow evaporator pan unit for reducing maple sap into maple syrup. Since only sensible heat is required for the pasteurisation, and not latent heat, it is possible that solar energy could drive the pasteurisation process. These alternatives are just a few examples of potential solutions that could be explored to reduce the use of firewood. It is recommended that researchers strive towards eliminating the use of firewood in the future, regardless of the food preservation process being considered.

One of the current limitations with the SAP process is that the membrane material is not biodegradable. If a biodegradable material was obtained in the future, other non-food applications could also be possible, such as the dehydration of sludge or human excrement. For both food and non-food applications, a better understanding of the transport phenomena occurring inside and outside the pouch as well as in the membrane during drying could be achieved by expanding on the statistical and resistance models developed in this research. In particular, investigating the internal mass transport phenomena would provide more information on the type of mass transport occurring (i.e. diffusive or convective) inside the liquid during the concentration process. By knowing the process conditions that promote convective mass transport and convective mixing inside the pouch, the SAP process could be designed and optimised in a way to achieve uniform drying. Another question that also remains to be answered is where the majority of the evaporation occurs (i.e. from the top or bottom side of the pouch). This would have relevance for the design of the pouch and solar dryer for any application. In addition, further optimisation of the pouch design and process could be achieved in the future by developing a heat and mass transport model for the process with COMSOL Multiphysics software. With this software, it is also possible to incorporate microbial death models, which would allow for the food safety risks in the process to be further studied and evaluated.

A final recommendation that is valuable to remember for the future is that it is important to think about the consequences of introducing new technologies and taking them away again. When conducting research and development work in rural areas, researchers should ensure that all participants involved obtain some kind of new knowledge/technology that makes their lives better, and not worse.

Acknowledgements

I would first like to acknowledge the **Swedish Research Council** (Vetenskapsrådet, VR) for providing the funding for this research (grant numbers Dr.n. 2013-6290, 2017-05625).

My next words of gratitude go out to my supervisors. Wow what a journey! The past five years have been some of the most challenging years of my life, and I am truly grateful to have had you all there supporting me along the way.

Professor Marilyn Rayner (main supervisor) – you have no idea how much it helped when you told me you were not worried about my plans (even if these plans were sometimes too optimistic). I think you have a great ability to keep people focused on the most important tasks to be done, while also showing a lot of consideration for the well-being of others. Thank you for caring and for always finding the time to help and give advice when I needed it.

Associate Professor Ingegerd Sjöholm (co-supervisor) – thank you so much for introducing me to the world of drying! I still think it is amazing that my drying adventure began with the drying of moose meat in a clothes dryer (torkskåp). I have really appreciated your many creative ideas and your passion for food science and engineering, as well as your strong drive to share this passion with others. Thanks for your support and dedication even after your retirement, and for introducing the department to sous-vide apples.

Dr. Karolina Östbring (co-supervisor) – I am so glad that you became one of my supervisors during the latter half of my project. You brought so much energy and excitement to our supervisor meetings, and it was wonderful that you always questioned when something I said was not clear. Many thanks for the help with the microbiological analyses, and for teaching me to include the most important result in the first sentence of a paragraph, as this really improved my writing.

Dr. Lucas Tivana (co-supervisor at University Eduardo Mondlane) – it was really an honour to get to know you and your family and live at your house while completing the fieldwork in Mozambique. I felt at home from the first time I arrived and it was because you, Anabela, Chipa, Sara and Jack were so kind and generous and always made me feel welcome. Thank you for also doing a fantastic job coordinating the fieldwork. I know you put a lot of time into this, and the excellent results that we achieved definitely reflect your efforts. Thank you as well for translating the popular science summary to Portuguese, and an extra thanks to Anabela for the additional feedback on the summary. Hope we can continue to work on improving post-harvest practices in Mozambique in the future.

Professor Emeritus Petr Dejmek (previous co-supervisor) – thank you for the support during the first half of my project. I enjoyed the intellectual challenge that you brought to discussions and I think more critically now because of this.

A big thank you also goes out to all of my colleagues, present and past, at the Department of Food Technology, Engineering and Nutrition at Lund University for making my time as a PhD student memorable. I will never forget our Thanksgiving celebrations, the gingerbread house making contests, Lucia concerts, away days, crayfish parties, potlucks, movie nights, Tuesday innebandy matches and public speaking sessions, to name a few. A few people/groups I would like to specifically acknowledge are:

Klara Sjölin – thank you for five wonderful years together as officemates! Before I started my PhD, I never imagined that I would have so much in common with my officemate and that we would become such great friends. I am going to miss seeing you every day and discussing our life challenges with each other. I am so grateful for all of the support you have given me throughout this project, and additionally for our many Tuesday and Thursday Swedish days.

Dr. Ali Marefati – thank you for always making time to listen, and for all of the help and support when it was really needed (the chocolate bar really saved me).

Dan Johansson – thank you for the endless support in the lab and pilot hall. I am impressed by how you can solve equipment problems so creatively.

Hans Bolinsson – thank you for helping me with my many computer issues, with the water activity meter, and with the ordering of supplies.

Peter Eklöv – thank you for helping me with many problematic invoices and for answering all of my financial-related questions over the years.

Liselotte Eriksson – thanks so much for the administrative support, quick replies, and eagerness to help.

All the **PhD students** at the department – thank you for keeping me motivated and for helping to build a strong PhD student network.

The **Microbiology Group** – thank you for being so patient with me and answering all of my questions when I was learning how to use the autoclave and perform viable plate count analyses. I am really impressed with the way that you work and the way you keep your labs so organised.

Ferawati and **Gayatri Dhulappanavar** (previous Master's students) – thank you for your help with my project and the many hours you spent in the lab.

Cecilia Ahlström – thank you for helping me create a super efficient water activity/photobox analysis method. You saved me weeks of analysis time.

Maria Rosenlöw (formerly Hedlund) – I am very grateful for the support and advice I received from you on stress management. It helped me so much, especially in these last crucial six months when finishing this thesis. Many hugs!

Dr. Frida Lewerentz (formerly Gustavsson) – thank you for really making me feel at home here in Sweden from the time I arrived in 2009. I really appreciate your friendship the past 10 years and how you tried to give me opportunities to experience Swedish culture by inviting me to your parents' home and summer cottage. I also love how Guelph is the thing that originally connected us, yet we have never actually been in Guelph together at the same time.

A special thanks as well goes out to the Solar Food Project group:

Dr. Pia Otte – thank you for teaching me so much about participatory research and the importance of involving as many different types of people as possible in a technology development process. I look at the world completely differently now, and one reason is because of the experience I gained working with you. You are an amazing friend and I really appreciate how you continue to share new and inspiring books, websites and ideas with me to keep challenging my worldview.

Dr. Henrik Davidsson and **Dr. Ricardo Bernardo** from Energy and Building Design at Lund University – thank you so much for the help with the experiments at the A building and for coordinating the building and testing of the solar dryers. It was great to share so many great memories together in Mozambique, including our work in Inharrime, stay at the Jolly Roger, visit to the fish market in Maputo and trips to Zavora.

Dr. Lars-Henrik Ståhl – thanks for bringing another perspective to the project with the documentary film. It has been inspiring working with you and seeing our project from another angle.

I would also like to acknowledge the **agricultural associations of the Nhanombe locality** in the Inharrime district of Inhambane, Mozambique for their assistance during the field study. I am additionally grateful for the help of the University Eduardo Mondlane students who helped me with the fieldwork in Mozambique. Thank you **Imaculada Jeje**, **Deize Guibundana**, **Mario Tune** and **Elísio Matusse** for all of your dedication and hard work during the many days/weeks of the experiments. A very big thank you as well to **Gilda Monjane** and the **Comida Solar** group in Maputo for letting me be a part of your entrepreneurial journey. A special thanks to **Paula Viola** for helping me with the experiments in Maputo, for taking care of the administrative paperwork for my trips to Mozambique, and for the feedback on the Portuguese popular science summary. It is so great that you are now here in Lund and will continue working on solar food drying in Mozambique.

A few other Mozambican friends that I would like to acknowledge are **Eulália Chiau** – for the many laughs we shared in your office and for allowing me to be a part of your *Vangueria infausta* research. I am so glad that I got a chance to get to know you, and I will never forget the way you always said “Rannnndiiiii”. Also to **Irene Stuart Torrié de Carvalho** - for always making time to meet with me and take me for lunch whenever I was in Mozambique.

A part of this research took place at Paul Scherrer Institute (PSI) in Switzerland and so I would like to greatly acknowledge the contributions and support of the Paul Scherrer Institute NEUTRA support team, in particular **Peter Vontobel**. Thank you as well to **Stefan Carl** for the assistance with the neutron experimental setup. I am also very grateful to **Thijs Defraeye** and **Dominique Derome** from the Swiss Federal Laboratories for Materials Science and Technology (Empa) for giving me the opportunity to come to Switzerland and take part in such an amazing set of experiments. Additional thanks to Thijs for showing me how to document experimental work so efficiently, and for the help and feedback with the Short Communication paper.

In the first half of this project, we also collaborated with **Smart Textiles** (**Textilhögskolan**) and **Swerea IVF**. I am very grateful for all of the time these organisations put into this project and for the assistance with identifying and testing suitable membrane films and textiles.

I would additionally like to acknowledge the support of **Prototypverkstaden** at Medicon Village. It is always a pleasure to work with you and see how you come up with very creative design ideas and construction solutions.

Furthermore, I would like to acknowledge many family members and friends in various countries around the world.

I grew up in a small town called Keewatin (now part of the city of Kenora) in the province of Ontario, Canada. When I was a child, the population of the Kenora area was 15 000. Looking back, I now see how lucky I was to grow up in Keewatin/Kenora, where the entire community was there to support me like one big family. The main pillars of this support network were my parents (**Herm and Ellen**), who provided me with a wonderful and loving environment for growing up, and who gave me every opportunity I could imagine for developing my intellectual, creative and social capabilities. Everything from science projects at home to ice hockey to piano lessons to volunteering in the community. All of these experiences made my childhood exciting and stimulating and also made me believe that I could do anything if I put my mind to it. Thank you Mom and Dad for always supporting me, and encouraging me to see the world and be whatever I wanted to be. I would not be where I am today without you.

Another pillar of this network has been my brother, **Myles.** I feel so fortunate to have a sibling who I am so close with, who understands how I think, and who has a similar positive outlook on life as I do. Your words of support are always a huge help for me, My, as they keep my spirits high at times when I really need to dig deep to get things done. Thank you for the many Skype chats all these years and the many discussions about life balance, fitness and goal setting. It is really an honour to be your sister. A huge thank you as well to **Sara** for all of your support throughout my PhD journey. I really appreciated the sushi nights and debriefs with you both, as they really helped with managing stress.

I would also like to extend my sincerest thanks to my grandparents in Keewatin. It was wonderful to grow up with you all only a few streets away. You have all taught me many valuable lessons that I have taken with me throughout my life.

> To my **Grandpa Quinn (1929-2016) and Grandma Quinn** – thank you for teaching me about the importance of helping others and giving back to the community. My strong desire to help others stems from the fact that you and many other family members actively volunteer in the community on a regular basis. I believe this is one reason why I was motivated to take on this PhD project, to make a difference in the world and help as many people as possible.
>
> To **Amma** – thank you for sharing your life experiences with me through your stories, for teaching me valuable life lessons (like patience is a virtue – this one in particular helped me get through my PhD project), and for helping me become a strong, independent women who never gives up even when things get tough.

I would also like to thank my **aunts, uncles, cousins** and **extended family** in Canada, the U.S. and Sweden for all of the support and guidance the past thirty-one years of my life. The card games, car rides, meals, scones, movies, laughs and great advice are some of the things I am particularly thankful for and will never forget.

A special thanks as well to **Joelle Thorgrimson**, who I have been friends with since I was a child. Thank you, Joelle, for teaching me why it is important to take the time to reflect, for introducing me to the Myers–Briggs personality test, and for continuing to inspire me with the activities and challenges that you take part in.

I am also very grateful for the support given by my Guelph Engineering friends – **Melody, Yusra, Krista, Jen, Sarah and Kat**. You give me an energy boost whenever I return to the Guelph area and I am so glad we have stayed in touch the past years.

Before starting my PhD in Sweden, I lived in the Netherlands for a little more than 2 years. The time I spent in the Netherlands had a large impact on my life, as I met many inspiring people who have continued to inspire me since the day I left. My biggest inspiration has come from my former running group – **Vitality Runners Vlaardingen (VRV)**. It was because of the members of the VRV that I started taking part in endurance sports, that I purchased a racing bicycle, that I fell in love with

running, and that I learned I can do much more than my mind tells me I can. For five years, I have kept in touch with the members of the VRV and I am so incredibly grateful for this. A big thank you to the VRV for letting me be a part of your Whatsapp group all these years and for keeping me inspired even though we were physically apart from each other. A special thanks to:

> **Kees** (also my former Master's thesis supervisor) – for always giving me positive feedback and encouragement no matter what the challenge is that I get myself into, and for teaching me that perfect is the enemy of very good.
>
> **Jaap** (former VRV coach) – for the many wonderful discussions about life and sports, and for teaching me to always be careful to avoid burning out (in sports and in life).
>
> **Margaretha and Gijsbert** – for sharing your love of sports with me, inspiring me to take on new challenges, and for the continuous support throughout my PhD.
>
> **Katherine** – for the many wonderful running sessions that we have shared together over the years, for always finding time to meet with me when I return to the Netherlands, and for showing me the power of the phrase "no excuses".
>
> **Chiharu** – for the inspiration in sports and volunteer activities, and for also introducing me to Toastmasters.
>
> **Sandra** – for understanding what I have been going through as a PhD student and offering advice and support when it was needed.
>
> **Anja** – for getting me into long-distance cycling tours and passing on valuable knowledge about endurance cycling/sports that was also useful for a PhD project.

Other friends from the Netherlands that I would like to acknowledge are:

> **Anouk** – for being such a great friend and for supporting me throughout this PhD project. It still means so much to me that you and Laurens came for my half-way defence.
>
> **Isabelle** – for teaching me to follow my heart and for giving me the confidence I needed to start singing in a choir.
>
> **Catherine** – my baking buddy. Thank you for sharing your ex-pat experience with me, for teaching me many valuable life lessons, and for continuing to inspire me all these years with your courage and drive to try new things.

During my time as a PhD student, I was fortunate to meet my boyfriend and one of my best friends, **Rune**. Thank you so much, Rune, for the continuous support throughout this long journey! No matter how stressed I was, you were always there to keep me calm and help me re-focus. Thank you as well for inspiring me to learn more about the business world and entrepreneurship, as this has really helped me to reflect on how I can make an even bigger impact in the world. You compliment me so well and I only look forward to the next adventures we will tackle together.

While living in Sweden, I have also been very fortunate to become a part of other families nearby who have fully supported me in all of my endeavours.

The first to mention is my “Swedish” family – **Justyna, Stefan, Alexander and Gustav**. I am so incredibly grateful for everything you have done for me, including helping me move, providing me with accommodation when I needed it, inspiring me with new books and new ideas, and giving me the emotional support I needed as I was going through his PhD journey. I am so grateful to have you all in my life.

Another family close by is my “Danish” family – the Kokholm’s (and extended family/partners). A big thank you to **Hanne, Thorkild, Leif, Lars, René, Dandara, Cecilie, Sophia, Tristan** and **Isabelle** for your positive energy and words of encouragement the past years as I made my way to the end of this PhD journey. Thank you for making me feel like a part of your family from the first time we met.

Thank you as well to **Stina** and **Truls Helstad** for making me feel like a part of your family and always passing on so much energy to me every time we met. Your kindness, generosity and magical sauna have helped me in many ways during my PhD journey.

I would also like to acknowledge **Monika Lekander**, who has been an enthusiastic business partner, exceptional mentor and caring friend to me the past four years. I have learned so much from you, Monika, not only about business but also about life, the world and the importance of creating value. I feel so grateful to have met you and I can say that I always leave our visits feeling inspired and knowing what I need to do next. Thank you for supporting me through this process and for always taking the time to share your advice and experiences.

Looking back, I can also say that I was incredibly fortunate to have such amazing teachers throughout my entire educational journey. In primary school, I remember feeling challenged and inspired by all of my teachers, which helped me develop a love for studying and learning. In high school, I became even more inspired to learn, with a few teachers in particular having a lasting impression on me.

> The first I would like to acknowledge is **Anastasia Wojtyniak.** I still remember the day, Ms. Wojtyniak, when you told me at the end of Chemistry class that you had no doubt I could complete a PhD degree one day. I have never forgotten your words of encouragement and I remembered them often as I worked towards finishing this thesis. I was very prepared for Chemistry and university in general thanks to you because you set the bar high and then gave us the tools to reach it. Thanks for being such a fantastic teacher and encouraging me to do a PhD.

The second high school teacher I would like to acknowledge is **Randy (RJ) Moran**. Thank you, RJ, for sharing your passion for math with me and for developing a teaching curriculum where you offered so many different ways to challenge your students. Math Olympics, Intramurals, and “chits” are just a few of the ways that come to mind. I think you have a great ability to present information in a pedagogic way, while transferring your energy and passion for the subject to your students. Thanks for bringing a new dimension to math (no pun intended) and for continuing to inspire me even after I finished high school.

My Engineering education at the University of Guelph was also exceptional. Many professors had a lasting impression on me due to their enthusiasm for their subjects and their teaching styles. A few professors in particular that I would like to acknowledge are **Dr. Gauri Mittal**, **Dr. Ralph Brown** and **Dr. Valerie Davidson**. Thank you for sharing your excitement on food/biological engineering with me, and for providing an educational style that only further increased my curiosity for the subjects.

Related to teaching and learning, I would also like to thank my **Toastmasters friends** for helping me to develop as a strong leader and public speaker. I love how we are all teachers and learners at the same time at Toastmasters, and how I get so much energy from you all at our bi-weekly meetings.

My last very big thank you goes out to **Paula Leckius** and the **Media-Tryck** team for being so patient and efficient while preparing this thesis for printing. I think it is amazing that we have such a skilled and encouraging printing team here at Lund University, because when the deadline is approaching, a PhD student really needs this kind of support.

References

Adams, M. R., & Moss, M. O. (2000). *Food Microbiology* (2nd ed.). Cambridge: The Royal Society of Chemistry.

Affognon, H., Mutungi, C., Sanginga, P., & Borgemeister, C. (2015). Unpacking Postharvest Losses in Sub-Saharan Africa: A Meta-Analysis. *World Development, 66*, 49-68. doi:10.1016/j.worlddev.2014.08.002

Akinboro, F., Adejumobi, L., & Makinde, V. (2012). Solar energy installation in Nigeria: Observations, Prospect, problems, and solution. *Transnational Journal of Science and Technology, 2*(4), 73-84.

Al-Asheh, S., Jumah, R., Banat, F., & Hammad, S. (2003). The use of experimental factorial design for analysing the effect of spray dryer operating variables on the production of tomato powder. *Food and bioproducts processing, 81*(2), 81-88.

Amlani, A. (2018). *African countries lead the way on banning plastic bags*. ACCA The global body for professional accountants. Retrieved from https://www.accaglobal.com/an/en/member/member/accounting-business/2018/05/in-focus/plastic-bags.html

Aregawi, W., Defraeye, T., Saneinejad, S., Vontobel, P., Lehmann, E., Carmeliet, J. Nicolai, B. (2013). Dehydration of apple tissue: Intercomparison of neutron tomography with numerical modelling. *International Journal of Heat and Mass Transfer, 67*, 173-182. doi:10.1016/j.ijheatmasstransfer.2013.08.017

Aregawi, W., Defraeye, T., Saneinejad, S., Vontobel, P., Lehmann, E., Carmeliet, J. Nicolai, B. (2014). Understanding forced convective drying of apple tissue: Combining neutron radiography and numerical modelling. *Innovative Food Science & Emerging Technologies, 24*, 97-105. doi:10.1016/j.ifset.2013.10.014

Asadi, R. Z., Suja, F., Tarkian, F., Mashhoon, F., Rahimi, S., & Jameh, A. A. (2012). Solar desalination of Gas Refinery wastewater using membrane distillation process. *Desalination, 291*, 56-64.

Bains, M., Ramaswamy, H., & Lo, K. (1989). Tray drying of apple puree. *Journal of Food Engineering, 9*(3), 195-201.

Balaskó, M., Kőröusi, F., & Farkas, I. (2002). Applying Dynamic Neutron Radiography in In-Situ Monitoring of the Drying Processes of Apple. *Developments in Chemical Engineering and Mineral Processing, 10*(3-4), 247-260. doi:10.1002/apj.5500100403

Banhart, J. (2008). *Advanced tomographic methods in materials research and engineering* (Vol. 66). Oxford: Oxford University Press.

Bennett, M. (1996). *Pervaporation using modified polysiloxanes: Removal of organic contaminants from aqueous streams* (PhD Thesis). UK: University of Bath.

Binning, R., Lee, R., Jennings, J., & Martin, E. (1961). Separation of liquid mixtures by permeation. *Industrial & Engineering Chemistry, 53*(1), 45-50.

Blackburn, C. d. W. (2006). Introduction. In C. de W. Blackburn (Ed.), *Food spoilage microorganisms*. Cambridge: Woodhead Publishing Limited.

Boddy, L., & Wimpenny, J. (1992). Ecological concepts in food microbiology. *Journal of Applied Bacteriology, 73*, 23s-38s.

Boonstra, J. (2008). *The Dangers of Firewood*. UN Dispatch United Nations News & Commentary Global News Forum. Retrieved from https://www.undispatch.com/the-dangers-of-firewood/

Bourne, M. (2002). *Food Texture and Viscosity* (2nd ed.). London: Academic Press.

Brenndorfer, B., Kennedy, L., Bateman, C. O., Trim, D., Mrema, G., & Wereko-Brobby, C. (1987). *Solar dryers: their role in post-harvest processing*. London: Commonwealth Secretariat.

Catarino, M., Ferreira, A., & Mendes, A. (2009). Study and optimization of aroma recovery from beer by pervaporation. *Journal of Membrane Science, 341*(1-2), 51-59.

Cefic and ECTA. (2011). *Guidelines for Measuring and Managing CO_2 Emission from Freight Transport Operations*. Brussels: The Chemical Logistics Association (ECTA) and the European Chemical Industry Council (Cefic). Retrieved from https://www.ecta.com/resources/Documents/Best%20Practices%20Guidelines/guideline_for_measuring_and_managing_co2.pdf

Centre for Food Safety. (2014). *Microbiological Guidelines for Food: For ready-to-eat foods in general and specific food items*. Hong Kong: Center for Food Safety, Food and Environmental Hygiene Department. Retrieved from https://www.cfs.gov.hk

Chaignon, J., & Davidsson, H. (2017). *Modeling of a solar dryer for fruit preservation in developing countries*. Paper presented at the Solar World Congress 29 Oct – 02 Nov 2017 in Abu Dhabi, UAE.

Chen, F., Shi, X., Chen, X., & Chen, W. (2018). Preparation and characterization of amphiphilic copolymer PVDF-g-PMABS and its application in improving hydrophilicity and protein fouling resistance of PVDF membrane. *Applied Surface Science, 427*, 787-797. doi:10.1016/j.apsusc.2017.08.096

Chiau, E. (2015). *Utilization of Wild Fruit in Mozambique: Drying of Vangueria infausta (African medlar)* (PhD Thesis). Lund University, Sweden.

Chinachoti, P., & Schmidt, S. J. (1991). Solute-Polymer-Water Interactions and Their Manifestations. In H. Levine & L. Slade (Eds.), *Water Relationships in Foods: Advances in the 1980s and Trends for the 1990s* (Vol. 302, pp. 561). New York: Springer Science+Business Media.

Chua, K., & Chou, S. (2003). Low-cost drying methods for developing countries. *Trends in Food Science & Technology, 14*(12), 519-528.

Codex Alimentarius. (2009). Codex Standard for Jams, Jellies and Marmalades (CODEX STAN 2962009). In *3.2 Soluble Solids* (pp. 10). Rome: Codex Alimentarius. Retrieved from www.fao.org/input/download/standards/11254/CXS_296e.pdf

Côté, P., & Lipski, C. (1988). Mass transfer limitations in pervaporation for water and wastewater treatment. *Proceedings of third international conference on pervaporation processes in the chemical industry* (Bakish Material Corp, Englewood), pp. 449-462.

Dawiec-Liśniewska, A., Podstawczyk, D., & Witek-Krowiak, A. (2018). Concentration of fruit juice aroma compound from model multicomponent solution and natural apple juice hydrolate: Optimization and modeling by design of experiment. *Journal of Food Process Engineering, 41*(3), e12669.

Deak, T. (2004). Spoilage yeasts. In R. Steele (Ed.), *Understanding and measuring the shelf-life of food*. Cambridge, England: CRC Press Woodhead Publishing Limited.

Deak, T., & Beuchat, L. R. (1996). *Handbook of Food Spoilage Yeasts*. Boca Raton, Florida: CRC Press.

Defraeye, T., Aregawi, W., Saneinejad, S., Vontobel, P., Lehmann, E., Carmeliet, J., Nicolaï, B. (2013). Novel Application of Neutron Radiography to Forced

Convective Drying of Fruit Tissue. *Food and Bioprocess Technology, 6*(12), 3353-3367. doi:10.1007/s11947-012-0999-y

Defraeye, T., Nicolaï, B., Mannes, D., Aregawi, W., Verboven, P., & Derome, D. (2016). Probing inside fruit slices during convective drying by quantitative neutron imaging. *Journal of Food Engineering, 178*, 198-202. doi:10.1016/j.jfoodeng.2016.01.023

Dobrzynski, L., & Blinowski, K. (1994). *Neutrons and solid state physics.* New York: Prentice Hall.

Esser, H. G., Carminati, A., Vontobel, P., Lehmann, E. H., & Oswald, S. E. (2010). Neutron radiography and tomography of water distribution in the root zone. *Journal of Plant Nutrition and Soil Science, 173*(5), 757-764.

Eswara, A. R., & Ramakrishnarao, M. (2013). Solar energy in food processing - a critical appraisal. *Journal of food science and technology, 50*(2), 209-227.

FAO. (2011). *Global food losses and food waste – Extent, causes and prevention*. Rome.

FAO. (2019). *FAO in Mozambique - Mozambique at a glance*. Retrieved from http://www.fao.org/mozambique/fao-in-mozambique/mozambique-at-a-glance/en/

Farhadi, M., Pazuki, G., & Raisi, A. (2018). Modeling of the pervaporation process for isobutanol purification from aqueous solution using intelligent systems. *Separation Science and Technology, 53*(9), 1383-1396. doi:10.1080/01496395.2017.1405987

Farkas, D. F. (2003). Food Engineering History. In D. R. Heldman (Ed.), *Encyclopedia of Agricultural, Food, and Biological Engineering* (pp. 346-349). New York: CRC Press and Marcel Dekker, Inc.

Farkas, J. (1997). Physical Methods of Food Preservation. In M. P. Doyle, L. R. Beuchat, & T. J. Montville (Eds.), *Food Microbiology: Fundamentals and Frontiers* (pp. 497-519). Washington D. C.: American Society for Microbiology.

FDA. (2015). CPG Sec. 550.575 Marmalade. *Compliance Policy Guides.* U.S. Food & Drug Administration Retrieved from https://www.fda.gov/iceci/compliancemanuals/compliancepolicy guidancemanual/ucm074536.htm

Ferawati, F. (2016). *Understanding and Identifying Ranges for Critical Parameters of Orange Juice Concentrate during Drying by Using Solar Assisted Pervaporation (SAP) Fruit Preservation Technique* (MSc Thesis). Lund University, Sweden.

Fontana, A. J. Jr. (2007). Appendix D Minimum Water Activity Limits for Growth of Microorganisms. In G. V. Barbosa-Cánovas, A. J. Jr. Fontana, S. J. Schmidt, & T. P. Labuza (Eds.), *Water Activity in Foods: Fundamentals and Applications* (1st ed., pp. 405). Arnes: Blackwell Publishing.

Fröhlich-Wyder, M.-T. (2003). Yeasts in dairy products. In T. Boekhout & V. Robert (Eds.), *Yeasts in food: Beneficial and detrimental aspects* (pp. 209-238). Cambridge, England: CRC Woodhead Publishing Limited.

FSANZ. (2018). *Compendium of Microbiological Criteria for Food* Food StandardsAustralia & New Zealand. Retrieved from http://www.foodstandards.gov.au.

Gekas, V. (1992). *Transport Phenomena of Foods and Biological Materials*. Florida: CRC Press.

Ghoreyshi, A. A., Jahanshahi, M., & Peyvandi, K. (2008). Modeling of volatile organic compounds removal from water by pervaporation process. *Desalination, 222*(1-3), 410-418. doi:10.1016/j.desal.2007.01.174

Governo do distrito de Inharrime. (2012). *Plano Estratégico de desenolvimento do distrito de Inharrime 2011-2015*. Inharrime. Retrieved from https://issuu.com/artpublications/docs/peddii_del_inharrime/102

Gudernatsch, W., Menzel, T., & Strathmann, H. (1991). Influence of composite membrane structure on pervaporation. *Journal of Membrane Science, 61*, 19-30. doi:10.1016/0376-7388(91)80003-O

Hartnig, C., & Manke, I. (2009). Measurement Methods | Structural Properties: Neutron and Synchrotron Imaging, In-Situ for Water Visualization. In J. Garche (Ed.), *Encyclopedia of Electrochemical Power Sources* (pp. 738-757). Amsterdam: Elsevier.

Hassan, Z., Lesmayati, S., Qomariah, R., & Hasbianto, A. (2014). Effects of wax coating applications and storage temperatures on the quality of tangerine citrus (Citrus reticulata) var. Siam Banjar. *International food research journal, 21*(2), 641.

Heldman, D. R., & Nesvadba, P. (2003). Food Freezing History. In D. R. Heldman (Ed.), *Encyclopedia of Agricultural, Food, and Biological Engineering* (pp. 350-352). New York: CRC Press and Marcel Dekker, Inc.

Heldman, D. R., & Singh, R. P. (1981). Food dehydration. In *Food process engineering* (pp. 261-331). Netherlands: Springer.

Hoffmann, V., Probst, K., & Christinck, A. (2007). Farmers and researchers: How can collaborative advantages be created in participatory research and technology development? *Agriculture and human values, 24*(3), 355-368.

Horie, T. (2005). Estimation of the volumetric water content in chrysanthemum tissues. *Journal of radioanalytical and nuclear chemistry, 264*(2), 325-328.

Iglesias, H. A., & Chirife, J. (1982). *Handbook of food isotherms : water sorption parameters for food and food components*. New York: Academic Press.

Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). *Fundamentals of Heat and Mas Transfer* (6th ed.). New York: John Wiley & Sons.

Jay, J. M. (1996). *Modern Food Microbiology* (5th ed.). New York: Chapman & Hall.

Jonquières, A., Clément, R., Lochon, P., Néel, J., Dresch, M., & Chrétien, B. (2002). Industrial state-of-the-art of pervaporation and vapour permeation in the western countries. *Journal of Membrane Science, 206*(1), 87-117. doi:10.1016/S0376-7388(01)00768-2

Kak, A. C., Slaney, M., & Wang, G. (2002). Principles of computerized tomographic imaging. *Medical Physics, 29*(1), 107-107.

Kalogirou, S. (1997). Solar water heating in Cyprus: current status of technology and problems. *Renewable Energy, 10*(1), 107-112.

Kalogirou, S. A. (2014). Industrial Process Heat, Chemistry Applications, and Solar Dryers. In S. A. Kalogirou (Ed.), *Solar energy engineering: processes and systems* (2nd ed., pp. 397-430). Oxford: Elsevier Inc.

Kang, Z. (2017). *ENGG*3280 Group 8 - QuikJuice*. Retrieved from https://www.youtube.com/watch?v=oS0vVhEjeKU&list=PLuurPZt iC1eL83bHzaraOLEWhZCKnDRVU&index=12

Kardjilov, N., Manke, I., Hilger, A., Strobl, M., & Banhart, J. (2011). Neutron imaging in materials science. *Materials Today, 14*(6), 248-256. doi:10.1016/S1369-7021(11)70139-0

Keita, J. D. (1987). Wood or charcoal - which is better? In R. Pardo (Ed.), *Unasylva - No. 157-158 - Small-scale forest enterprises - An international journal of forestry and forest industries* (Vol. 39). Rome: FAO - Food and Agriculture Organization of the United Nations.

Kimball, D. A. (1991). *Citrus Processing: Quality Control and Technology*. New York: Springer Science+Business Media LLC.

Kindon, S., Pain, R., & Kesby, M. (2009). Participatory Action Research. In *International Encyclopaedia of Human Geography* (pp. 90-95). Amsterdam, London: Elsevier.

Knecht, R. L. (1990). Properties of Sugar. In N. L. Pennington & C. W. Baker (Eds.), *Sugar: A User's Guide to Sucrose* (pp. 51-52). New York: Van Nostrand Reinhold.

Kober, P. A. (1917). Pervaporation, perstillation and percrystallization.1. *Journal of the American Chemical Society, 39*(5), 944-948. doi:10.1021/ja02250a011

Kroos, K. A., & Potter, M. C. (2015). *Thermodynamics for Engineers* (SI Edition ed.). Stamford: Cengage Learning.

Labuza, T., Kaanane, A., & Chen, J. (1985). Effect of temperature on the moisture sorption isotherms and water activity shift of two dehydrated foods. *Journal of Food Science, 50*(2), 385-392.

Labuza, T. P. (1975). Sorption phenomena in foods: theoretical and practical aspects. In *Theory, determination and control of physical properties of food materials* (pp. 197-219). Netherlands: Springer.

Ladanyia, M. (2008). Nutritive and Medicinal Value of Citrus Fruits. In M. Ladanyia (Ed.), *Citrus Fruit: Biology, Technology and Evaluation*. Online: Elsevier Inc.

Lehmann, E. H., Vontobel, P., & Kardjilov, N. (2004). Hydrogen distribution measurements by neutrons. *Applied Radiation and Isotopes, 61*(4), 503-509. doi:10.1016/j.apradiso.2004.03.075

Lehmann, E. H., Vontobel, P., & Wiezel, L. (2001). Properties of the radiography facility NEUTRA at SINQ and its potential for use as European reference facility. *Nondestructive Testing and Evaluation, 16*(2-6), 191-202. doi:10.1080/10589750108953075

Li, B. W., Andrews, K. W., & Pehrsson, P. R. (2002). Individual Sugars, Soluble, and Insoluble Dietary Fiber Contents of 70 High Consumption Foods. *Journal of Food Composition and Analysis, 15*(6), 715-723. doi:10.1006/jfca.2002.1096

Li, Y., Cui, X., Zhao, M., Xu, Y., Chen, L., Cao, Z., & Wang, Y. (2019). Facile preparation of a robust porous photothermal membrane with antibacterial activity for efficient solar-driven interfacial water evaporation. *Journal of Materials Chemistry A, 7*(2), 704-710.

Lindner, E., Gyurcsányi, R. E., & Buck, R. P. (2006). Membranes in Electroanalytical Chemistry: Membrane-Based Chemical and Biosensors. In P. Somasundaran (Ed.), *Encyclopedia of surface and colloid science* (Vol. 5, pp. 3580-3602): CRC press.

Lipnizki, F., & Field, R. W. (1999). Simulation and process design of pervaporation plate-and-frame modules to recover organic compounds from waste water. *Chemical Engineering Research & Design, 77*(A3), 231-240. doi:10.1205/026387699526142

Lipnizki, F., Field, R. W., & Ten, P.-K. (1999). Pervaporation-based hybrid process: a review of process design, applications and economics. *Journal of Membrane Science, 153*(2), 183-210. doi:10.1016/S0376-7388(98)00253-1

Lipnizki, F., Olsson, J., Wu, P., Weis, A., Trägårdh, G., & Field, R. (2002). Hydrophobic pervaporation: influence of the support layer of composite membranes on the mass transfer. *Separation Science and Technology, 37*(8), 1747-1770.

Lipnizki, F., & Trägårdh, G. (2001). Modelling of pervaporation: models to analyze and predict the mass transport in pervaporation. *Separation and Purification Methods, 30*(1), 49-125.

Liu, M. G., Dickson, J. M., & Cote, P. (1996). Simulation of a pervaporation system on the industrial scale for water treatment .1. Extended resistance-in-series model. *Journal of Membrane Science, 111*(2), 227-241. doi:10.1016/0376-7388(95)00234-0

Liu, Y., Heying, E., & Tanumihardjo, S. A. (2012). History, global distribution, and nutritional importance of citrus fruits. *Comprehensive Reviews in Food Science and Food Safety, 11*(6), 530-545.

Livsmedelsverket (National Food Agency of Sweden). (2003). *Livsmedelsverkets föreskrifter om sylt, gelé och marmelad LIVSFS 2003:17*. Sweden. Retrieved from https://www.livsmedelsverket.se/globalassets/om-oss/lagstiftning/marknadsordn---handelsnorm---varustand/livsfs-2003-17-kons-tom-2014-15.pdf

Lokshin, M., & Mroz, T. (2003). *Gender and Poverty: A Life Cycle Approach to the Analysis of the Differences in Gender Outcomes* (# WPS3153). Retrieved from https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-3153

López-Malo, A., & Ríos-Casas, L. (2008). Solar Assisted Drying of Foods. In Y. H. Hui, C. Clary, M. M. Farid, O. O. Fasina, A. Noomhorm, & J. Welti-Chanes

(Eds.), *Food drying science and technology: microbiology, chemistry, applications*. Pennsylvania: DEStech Publications, Inc.

Magaia, T. (2015). *Chemical analysis to promote the use of wild fruits from Mozambique* (PhD Thesis). Lund University, Sweden.

Magaia, T., Uamusse, A., Sjöholm, I., & Skog, K. (2013). Dietary fiber, organic acids and minerals in selected wild edible fruits of Mozambique. *SpringerPlus, 2*(1), 88.

Mahiri, I. (1998). Comparing transect walks with experts and local people. *PLA notes, 31*(4), 4-8.

Mannes, D., Josic, L., Lehmann, E., & Niemz, P. (2009). Neutron attenuation coefficients for non-invasive quantification of wood properties. In *Holzforschung* (Vol. 63, pp. 472).

Mapsopensource. (n.d.).*Mozambique Provinces Map*. Licensed under a Creative Commons Attribution 3.0 Unported License. Retrieved from http://mapsopensource.com/mozambique-provinces-map.html

Mapsopensource. (n.d.).*Mozambique Location Map In Africa*. Licensed under a Creative Commons Attribution 3.0 Unported License. Retrieved from http://mapsopensource.com/mozambique-location-map-in-africa.html

Maria, T. (1968). Collapsible solar still with water vapor permeable membrane. In: Google Patents. U. S. Patent # 3,415,719, United States Patent Office.

Matsushima, U., Kawabata, Y., Hino, M., Geltenbort, P., & Nicolai, B. (2005). Measurement of changes in water thickness in plant materials using very low-energy neutron radiography. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 542*(1-3), 76-80.

Mauersberger, S., Ohkuma, M., Schunck, W.-H.-., & Takagi, M. (1996). Candida maltosa. In K. Wolf (Ed.), *Nonconventional Yeasts in Biotechnology: A Handbook* (pp. 411-580). Berlin Heidelberg: Spring-Verlag.

Menon, M., Robinson, B., Oswald, S. E., Kaestner, A., Abbaspour, K. C., Lehmann, E., & Schulin, R. (2007). Visualization of root growth in heterogeneously contaminated soil using neutron radiography. *European Journal of Soil Science, 58*(3), 802-810.

METER Group. (2019). *Meter Food - Benchtop Water Activity Meter*. Retrieved from https://www.metergroup.com/food/products/aqualab-4te-water-activity-meter/

Mohammadi, T., & Rezaeian, M. P. (2009). Separation of Isomeric Xylenes: Experimental and Modeling. *Separation Science and Technology, 44*(4), 817-840. doi:10.1080/01496390802697072

Montville, T. J. (1997). Principles Which Influence Microbial Growth, Survival, and Death in Foods. In M. P. Doyle, L. R. Beuchat, & T. J. Montville (Eds.), *Food Microbiology: Fundamentals and Frontiers* (pp. 13-29). Washington D. C.: American Society for Microbiology.

Moradi, A. B., Carminati, A., Vetterlein, D., Vontobel, P., Lehmann, E., Weller, U., & Oswald, S. E. (2011). Three-dimensional visualization and quantification of water content in the rhizosphere. *New Phytologist, 192*(3), 653-663.

Mulder, M. (1996). *Basic principles of membrane technology* (2nd ed.). The Netherlands: Kluwer Academic Publishers.

Murray, U., Gebremedhin, Z., Brychkova, G., & Spillane, C. (2016). Smallholder farmers and climate smart agriculture: Technology and labor-productivity constraints amongst women smallholders in Malawi. *Gender, Technology and Development, 20*(2), 117-148.

Myers, R. H., Montgomery, D. C., & Anderson-Cook, C. M. (2016). *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*. New Jersey: John Wiley & Sons, Inc.

Nakanishi, T. M., & Matsubayashi, M. (1997). Nondestructive water imaging by neutron beam analysis in living plants. *Journal of Plant Physiology, 151*(4), 442-445. doi:10.1016/S0176-1617(97)80009-0

Néel, J. (1995). Pervaporation. In R. D. Noble & S. A. Stern (Eds.), Membrane Separations Technology, Principles and Applications (Vol. 2, pp. 143-211). Online: Elsevier Science B.V.

Nijegorodov, N., Devan, K., Simao, H., & Mabbs, R. (2003). Comprehensive study of solar conditions in Mozambique: the effect of trade winds on solar components. *Renewable Energy, 28*(12), 1965-1983.

Olsson, J., & Trägårdh, G. (1999). Influence of feed flow velocity on pervaporative aroma recovery from a model solution of apple juice aroma compounds. *Journal of Food Engineering, 39*(1), 107-115. doi:10.1016/S0260-8774(98)00154-X

Olsson, J., Trägårdh, G., & Lipnizki, F. (2002). The influence of permeant and membrane properties on mass transfer in pervaporation of volatile organic compounds from dilute aqueous solutions. *Separation Science and Technology, 37*(6), 1199-1223.

Oswald, S. E., Menon, M., Carminati, A., Vontobel, P., Lehmann, E., & Schulin, R. (2008). Quantitative imaging of infiltration, root growth, and root water uptake via neutron radiography. *Vadose Zone Journal, 7*(3), 1035-1047.

Otte, P. P., Bernardo, R., Phinney, R., Davidsson, H., & Tivana, L. D. (2018). Facilitating integrated agricultural technology development through participatory research. *The Journal of Agricultural Education and Extension, 24*(3), 285-299.

Otte, P. P., Tivana, L. D., Phinney, R., Bernardo, R., & Davidsson, H. (2018). The importance of gender roles and relations in rural agricultural technology development: a case study on solar fruit drying in Mozambique. *Gender, Technology and Development, 22*(1), 40-58.

Pangarkar, V. G., & Ray, S. K. (2015). Pervaporation: Theory, Practice, and Applications in the Chemical and Allied Industries. In A. K. Pabby, S. S. H. Rizvi, & A. M. S. Requena (Eds.), *Handbook of Membrane Separations: Chemical, Pharmaceutical, Food and Biotechnological Applications* (2nd ed., pp. 181-214). Boca Raton: CRC Press.

Pantelic, J., Teitelbaum, E., Bozlar, M., Kim, S., & Meggers, F. (2018). Development of moisture absorber based on hydrophilic nonporous membrane mass exchanger and alkoxylated siloxane liquid desiccant. *Energy and Buildings, 160*, 34-43. doi:10.1016/j.enbuild.2017.10.093

Patrick, E. (2007). Sexual violence and firewood collection in Darfur. *Forced Migration Review, 27*, 40-41.

Pereira, C. C., Rufino, J. R. M., Habert, A. C., Nobrega, R., Cabral, L. M. C., & Borges, C. P. (2005). Aroma compounds recovery of tropical fruit juice by pervaporation: membrane material selection and process evaluation. *Journal of Food Engineering, 66*(1), 77-87. doi:10.1016/j.jfoodeng.2004.02.037

Pott, I., Neidhart, S., Mühlbauer, W., & Carle, R. (2005). Quality improvement of non-sulphited mango slices by drying at high temperatures. *Innovative Food Science & Emerging Technologies, 6*(4), 412-419.

Qing, W. H., Wu, J. Q., Deng, Y. J., Liu, L. L., & Zhang, W. D. (2017). A novel catalytically active membrane with highly porous catalytic layer for the conversion enhancement of esterification: Focusing on the reduction of mass transfer resistance of the catalytic layer. *Journal of Membrane Science, 539*, 359-367. doi:10.1016/j.memsci.2017.05.065

Quinones-Bolanos, E., & Zhou, H. D. (2006). Modeling water movement and flux from membrane pervaporation systems for wastewater microirrigation. *Journal of*

Environmental Engineering-Asce, 132(9), 1011-1018. doi:10.1061/(asce)0733-9372(2006)132:9(1011)

Rajagopalan, N., & Cheryan, M. (1995). Pervaporation of grape juice aroma. *Journal of Membrane Science, 104*(3), 243-250. doi:10.1016/0376-7388(95)00039-F

Samuelsson, P., & Deslandes, E. (2017). *Testing of solar fruit driers in laboratory and in Mozambique* (MSc Thesis). Lund University, Sweden.

Schillinger, B., Lehmann, E., & Vontobel, P. (2000). 3D neutron computed tomography: requirements and applications. *Physica B: Condensed Matter, 276-278*, 59-62. doi:10.1016/S0921-4526(99)01254-5

Schmidt, S. J., & Fontana, A. J. J. (2007). Appendix E Water Activity Values of Select Food Ingredients and Products. In G. V. Barbosa-Cánovas, A. J. J. Fontana, S. J. Schmidt, & T. P. Labuza (Eds.), *Water Activity in Foods: Fundamentals and Applications* (pp. 407-420). Arnes: Blackwell Publishing.

Scott, W. (1957). Water relations of food spoilage microorganisms. In G. F. S. E.M. Mrak (Ed.), *Advances in food research* (Vol. 7, pp. 83-127). New York: Elsevier.

Sedighi-Gilani, M., Griffa, M., Mannes, D., Lehmann, E., Carmeliet, J., & Derome, D. (2012). Visualization and quantification of liquid water transport in softwood by means of neutron radiography. *International Journal of Heat and Mass Transfer, 55*(21), 6211-6221. doi:10.1016/j.ijheatmasstransfer.2012.06.045

Shackleton, C. M., Dzerefos, C. M., Shackleton, S. E., & Mathabela, F. R. (2000). The use of and trade in indigenous edible fruits in the Bushbuckridge savanna region, South Africa. *Ecology of Food and Nutrition, 39*(3), 225-245. doi:10.1080/03670244.2000.9991616

Shepherd, A., Habert, A. C., & Borges, C. P. (2002). Hollow fibre modules for orange juice aroma recovery using pervaporation. *Desalination, 148*(1), 111-114. doi:10.1016/S0011-9164(02)00662-8

Sida. (2007). *Towards Gender Equality in Mozambique*. Retrieved from https://www.sida.se/contentassets/80caaf7d1aaf48738b7b70386574b59e/towards-gender-equality-in-mozambique_693.pdf

Singh, R. P., & Heldman, D. R. (2014). *Introduction to Food Engineering* (5th ed.). London: Academic Press.

Skjöldebrand, C. (1980). Convection oven frying: heat and mass transfer between air and product. *Journal of Food Science, 45*(5), 1354-1358. doi:10.1111/j.1365-2621.1980.tb06553.x

Smoot, L. M., & Pierson, M. D. (1997). Indicator Microorganisms and Microbiological Criteria. In M. P. Doyle, L. R. Beuchat, & T. J. Montville (Eds.), *Food Microbiology: Fundamentals and Frontiers* (pp. 66-80). Washington D. C.: American Society for Microbiology.

Sodha, M. S., & Chandra, R. (1994). Solar drying systems and their testing procedures: a review. *Energy Conversion and Management, 35*(3), 219-267.

Spector, B. I., Schloss, M., Green, S., Hart, E., & Ferrell, T. (2005). *Corruption Assessment: Mozambique, Final Report*. USAID. Retrieved from http://www1.worldbank.org/publicsector/anticorrupt/MozambiqueCorAsm.pdf

Stewart-Withers, R., Banks, G., McGregor, A., & Meo-Sewabu, L. (2014). Chap. 4 Qualitative Research. In R. Scheyvens (Ed.), *Development Fieldwork: A Practical Guide* (2nd ed.). London: SAGE.

Stürken, K., Wenzlaff, A., & Böddeker, K. W. (1993). Widerstandsmodell für die Pervaporation organischer Stoffe aus wäßriger Lösung. *Chemie Ingenieur Technik, 65*(8), 956-959.

Tamhane, A. C. (2009). *Statistical Analysis of Designed Experiments: Theory and Applications*. Hoboken: John Wiley & Sons.

Tauro, P., Kapoor, K. K., & Yadav, K. S. (2004). *An Introduction to Microbiology* (2nd ed.). New Delhi: New Age International (P) Limited.

Taylor, A. (2017). *ENGG*3250 Machine Design Group 7-Automatic Bag Sealer*. Retrieved from https://www.youtube.com/watch?v =pdDwaMZcHeE&index =31&list=PLuurPZtiC1eL83bHzaraOLEWhZCKnDRVU

The Jam and Similar Products (England) Regulations 2003, (2003). No. 3120. United Kingdom: The Stationary Office Limited. Retrieved from http://www.legislation.gov.uk/uksi/2003/3120/contents/made

The World Bank Group. (2017). *World Development Indicators database - Mozambique*. The World Bank Group. Retrieved from https://data.worldbank.org/country/mozambique

The World Bank Group. (2019). Mozambique - Climate Data. *Climate Change Knowledge Portal.* The World Bank Group. Retrieved from https://climateknowledgeportal.worldbank.org/

Tijing, L. D., Woo, Y. C., Choi, J.-S., Lee, S., Kim, S.-H., & Shon, H. K. (2015). Fouling and its control in membrane distillation - A review. *Journal of Membrane Science, 475*, 215-244. doi:10.1016/j.memsci.2014.09.042

Tivana, L., Chamblue, A., Madzara, M., Monjane, I. (2014). *Towards a Specific Post-harvest Loss Management Policy and Strategy for Mozambique*. Maputo: Food, Agriculture, and Natural Resources Policy Analysis Network (FANRPAN). Retrieved from https://www.fanrpan.org/sites/default/files/publications/Mozambique _PHM_Policy_Brief.pdf

Universal Industrial Gases (UIG). (2019). *Psychrometric Calculator Properties of Air*. Bethlehem, Pennsylvania: Universal Industrial Gases, Inc. (UIG). Retrieved from http://www.uigi.com/WebPsycH.html

USDA. (1974). *United States Standards for Grades of Orange Marmalade*. §52.1451 Product description. Washington, D.C.: United States Department of Agriculture. Retrieved from https://www.eacce.org.ma/wp-content/uploads/2016/05/Orange-Marmalade.pdf

USDA. (2011). *Mozambique: FY 2011 - 2015 Multi-Year Stategy*. Feed the Future: U.S. Gov. Global Hunger & Food Security Initiatve. Retrieved from Online: www.feedthefuture.gov

U. S. Government (2012). Feed the Future - Mozambique Fact Sheet Retrieved from https://www.feedthefuture.gov/

Wang, Q., Li, N., Bolto, B., Hoang, M., & Xie, Z. (2016). Desalination by pervaporation: A review. *Desalination, 387*, 46-60.

Wojtczak, M., Biernasiak, J., & Papiewska, A. (2012). Evaluation of microbiological purity of raw and refined white cane sugar. *Food Control, 25*(1), 136-139.

Wolf, W., Spieβ, W. E. L., & Jung, G. (1973). Wasserdampf-sorptionsisothermen von pampelmuse (45°C). In W. Wolf, W. E. I. Spieβ, & G. Jung (Eds.), *Wasserdampf-sorptionsisothermen von lebensmitteln* (Vol. 18, pp. 338-339). Frankfrut: VDMA.

Wu, D., Gao, A., Zhao, H., & Feng, X. (2018). Pervaporative desalination of high-salinity water. *Chemical Engineering Research and Design, 136*, 154-164. doi:10.1016/j.cherd.2018.05.010

Wu, Y., Xiao, Z. Y., Huang, W. X., & Zhong, Y. H. (2005). Mass transfer in pervaporation of active fermentation broth with a composite PDMS membrane.

Separation and Purification Technology, 42(1), 47-53. doi:10.1016/j.seppur.2004.06.003

Yahaya, A.-K., & Amoah, S. T. (2013). Bushfires in the Nandom district of the Upper West Region of Ghana: perpetual threat to food crop production. *J Environ Earth Sci, 3*(7), 10-15.

Yamamoto, S., Morihiro, T., Ariyoshi, K., & Aktas, T. (2005). Effects of surface concentration on drying behavior of carbohydrate solutions. *Drying technology, 23*(6), 1319-1330.

Yee, A. (2018). *In Sweden, Trash Heats Homes, Powers Buses and Fuels Taxi Fleets*. Online: The New York Times. Retrieved from https://www.nytimes.com /2018/09/21/climate/sweden-garbage-used-for-fuel.html

Zimmerman, D. W. (2004). A note on preliminary tests of equality of variances. *British Journal of Mathematical and Statistical Psychology, 57*(1), 173-181.

Ziobrowski, Z., & Rotkegel, A. (2017). Application of a Hydrophobic Polymeric Membrane for Carbon Dioxide Desorption from a Mea-Water Solution. *45*(2), 45. doi:10.1515/hjic-2017-0020

Zwijnenberg, H., Koops, G., & Wessling, M. (2005). Solar driven membrane pervaporation for desalination processes. *Journal of Membrane Science, 250*(1-2), 235-246.

What if we could reduce the amount of spoiled fruit in the world with breathable pouches and solar energy?

The research presented in this thesis has looked at answering this question by challenging the traditional view on solar drying with a process called Solar Assisted Pervaporation (SAP). With this process, fruit juices are concentrated into marmalade by filling breathable membrane pouches with juices and then solar drying the pouches for a number of days.

The process was developed and evaluated in Sweden at Lund University and in Mozambique with researchers from University Eduardo Mondlane and smallholder farmers in a rural area in the province of Inhambane. In Sweden, the work consisted of controlled laboratory experiments and mathematical modelling to gain insight into the heat and mass transport phenomena occurring inside and outside the pouch during simulated solar drying. In Mozambique, the focus was on evaluating the performance of the membrane pouches with citrus fruit juices under realistic, outdoor conditions to determine how solar drying setup and choice of juice pre-treatment affect the drying flux and microbiological quality. The results of the field study showed that it is possible to produce safe and shelf-stable citrus marmalades after 3 to 6 days of solar drying.

The recommended process is to add sucrose and pasteurise the juice before adding it to the pouches, and then use an active solar dryer to reduce the drying time and probability of fermentation. The knowledge gained both technically and socially in this project is valuable to researchers who plan to carry out agricultural development projects in the future.

Printed by Media-Tryck, Lund 2019 NORDIC SWAN ECOLABEL 3041 0903

LUND UNIVERSITY

ISBN: 978-91-7422-666-9

Food Technology, Engineering and Nutrition
Faculty of Engineering
Lund University

9 789174 226669