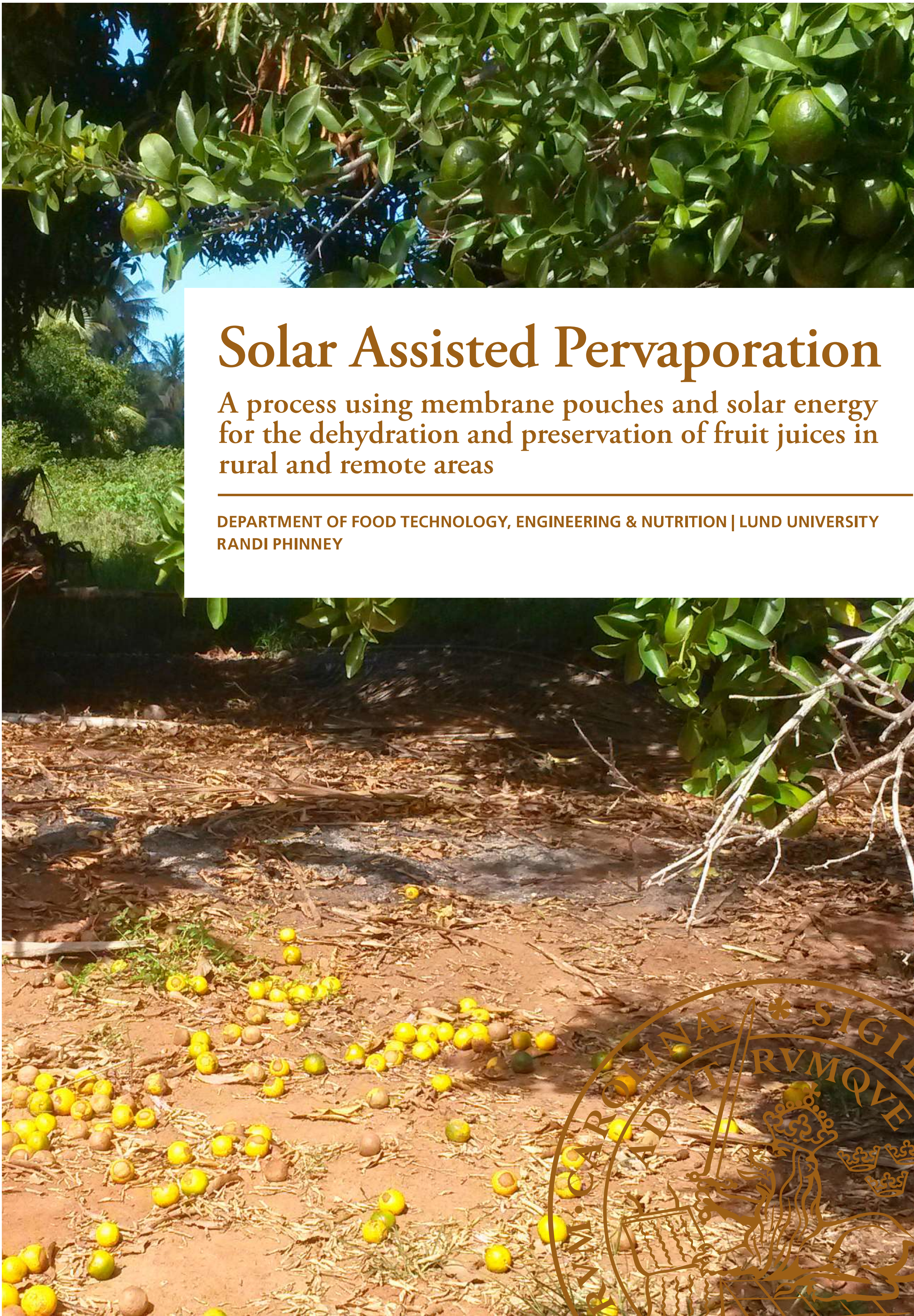
Solar Assisted Pervaporation (SAP)

A process using membrane pouches and solar energy for the dehydration and preservation of fruit juices in rural and remote areas

Phinney, Randi



Solar Assisted Pervaporation

A process using membrane pouches and solar energy for the dehydration and preservation of fruit juices in rural and remote areas

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

Solar Assisted Pervaporation

A process using membrane pouches and solar energy for the dehydration and preservation of fruit juices in rural and remote areas

Randi Phinney

LUND UNIVERSITY

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

LICENTIATE DISSERTATION

by due permission of the Faculty of Engineering, Lund University, Sweden.

To be defended at the Centre for Chemistry and Chemical Engineering, Naturvetarvägen 14, Lund, Sweden for the degree of Licentiate in Engineering.

Friday, April 21st, 2017 at 13.15 in Lecture Hall B

Faculty opponent

Professor Emeritus Vassilis Gekas

Cyprus University of Technology, Limassol, Cyprus

Organization
LUND UNIVERSITY

Department of Food Technology, Engineering and Nutrition

P.O. Box 124, SE-221 00 Lund, Sweden
Author: Randi Phinney

Document name
LICENTIATE DISSERTATION

Date of issue
2017-04-21

Sponsoring organization
Swedish Research Council (VR grant number Dr.n. 2013-6290)

Solar Assisted Pervaporation: A process using membrane pouches and solar energy for the dehydration and preservation of fruit juices in rural and remote areas

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 the 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. A contamination risk still remains, however, unless an air filter is used to remove microorganisms from the air before it contacts the products.

The overall aim of this research is to develop a safe and practical fruit preservation technology that is suitable for rural and remote areas of developing countries. The technology under development is termed Solar Assisted Pervaporation (SAP) and involves solar drying of membrane pouches filled with fruit juices to create shelf-stable fruit concentrates. 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 technology is meant for small-scale use and could be especially suitable for rural and remote areas of developing countries where infrastructure is limited and fruit spoilage is high.

This licentiate thesis has focused on assessing the feasibility of the process under realistic drying conditions, evaluating the possible effects of internal mass transport on food safety, and investigating the transport phenomena that describe the system. SAP involves complex heat and mass transfer where the principles of drying are combined with membrane transport theory. The rate limiting step for the evaporation process can be one of three mechanisms: the internal diffusion mass transport of water from the center to the inner surface of the membrane, the permeation of water through the membrane or the external transport of water from the outer surface of the membrane to the air. Due to the complexity of the system, certain mechanisms were studied in isolation. Internal mass transport was investigated from a food safety perspective. External mass transport and the permeation through the membrane were studied together using water as a model substance in order to identify the rate limiting step that would be expected during the constant rate drying period of a fruit juice/purée drying process.

In terms of process feasibility, the findings indicate that reasonable drying times can be achieved (i.e. 2 to 3 days assuming only 8 hours of active solar drying per day) with realistic drying conditions. When testing was performed with a solar simulating lamp, there was a negative effect on the drying flux when ambient air under forced convection was applied. This was due to the cooler air reducing the amount of energy available for the latent heat of evaporation. Drying fluxes in an indirect solar dryer simulator at 40.9°C, 13.9% relative humidity and 51.6°C, 7.5% relative humidity were comparable to the fluxes obtained at 620 W/m2 without forced air convection. This motivated the choice to further investigate the SAP pouch transport phenomena in an indirect solar dryer since drying fluxes are comparable and photo-oxidation of the product no longer plays a role.

With regards to food safety, it was found that viscous, fibrous and starchy fruit purées are more likely to dry inhomogeneously compared to fruit juices. The inhomogeneous drying may result in local wet spots and/or crust formation which could pose as a food safety risk. The internal mass transport was studied with apple purée and found to be diffusive. This supports the local wet spot observation since a lack of internal mixing would prevent re-distribution of the wet spots.

The investigation into the limiting transport phenomena showed that for pouches dried in an indirect natural convection solar dryer simulator (within the following operational limits: 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity), the evaporation flux in the constant rate drying period was limited by the membrane resistance rather than the convective heat transfer from the air to the surface. Air velocity had a slight but statistically significant effect on the apparent convective mass transfer coefficient, which suggests that a boundary layer exists at these low air velocities and that the thickness of this boundary layer can be reduced by increasing the velocity of the air passing over the pouches. Temperature did not have any noticeable or statistically significant effect on the apparent convective mass transfer coefficient for the membrane-bulk transport. These findings have implications on the design of an indirect solar dryer as they show that the two inputs that should be controllable are the air velocity and the water vapour partial pressure difference between the inner surface of the membrane and the bulk air (Δp).

The findings above suggest that when drying a food matrix, such as a fruit juice/purée, in a SAP pouch, it may be possible to control the onset of crust formation and reduce uneven drying by controlling Δp and air velocity in an indirect solar dryer. This hypothesis will be tested in the second half of the doctoral studies.

Solar Assisted Pervaporation challenges the traditional view on open sun drying, and has the potential to help people in rural and remote areas add value to fruits that would otherwise spoil, and does so in an environmentally sustainable way.

Key words: membrane, pervaporation, fruit preservation, solar drying, heat and mass transfer, coupling effects

Classification system and/or index terms (if any)

Supplementary bibliographical information	Language: English
ISSN and key title	ISBN (print) 978-91-7422-514-3 ISBN (digital) 978-91-7422-515-0

Recipient's notes	Number of pages 124	Price
	Security classification	

Signature Randi Phinney   Date 2017-03-31

Solar Assisted Pervaporation

A process using membrane pouches and solar energy for the dehydration and preservation of fruit juices in rural and remote areas

Randi Phinney

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

Cover photos by Randi Phinney

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

ISBN (print) 978-91-7422-514-3
ISBN (digital) 978-91-7422-515-0

Printed in Sweden by Media-Tryck, Lund University
Lund 2017

To anyone who has ever given me guidance along the way –
never underestimate the power of words of encouragement

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 the 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. A contamination risk still remains, however, unless an air filter is used to remove microorganisms from the air before it contacts the products.

The overall aim of this research is to develop a safe and practical fruit preservation technology that is suitable for rural and remote areas of developing countries. The technology under development is termed Solar Assisted Pervaporation (SAP) and involves solar drying of membrane pouches filled with fruit juices to create shelf-stable fruit concentrates. 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 technology is meant for small-scale use and could be especially suitable for rural and remote areas of developing countries where infrastructure is limited and fruit spoilage is high.

This licentiate thesis has focused on assessing the feasibility of the process under realistic drying conditions, evaluating the possible effects of internal mass transport on food safety, and investigating the transport phenomena that describe the system. SAP involves complex heat and mass transfer where the principles of drying are combined with membrane transport theory. The rate limiting step for the evaporation process can be one of three mechanisms: the internal diffusion mass transport of water from the center to the inner surface of the membrane, the permeation of water through the membrane or the external transport of water from the outer surface of the membrane to the air. Due to the complexity of the system, certain mechanisms were studied in isolation. Internal mass transport was investigated from a food safety perspective. External mass transport and the permeation through the membrane were studied together using water as a model substance in order to identify the rate limiting step that would be expected during the constant rate drying period of a fruit juice/purée drying process.

In terms of process feasibility, the findings indicate that reasonable drying times can be achieved (i.e. 2 to 3 days assuming only 8 hours of active solar drying per day) with realistic drying conditions. When testing was performed with a solar simulating lamp, there was a negative effect on the drying flux when ambient air under forced convection was applied. This was due to the cooler air reducing the amount of energy available for the latent heat of evaporation. Drying fluxes in an indirect solar dryer simulator at 40.9°C, 13.9% relative humidity and 51.6°C, 7.5% relative humidity were comparable to the fluxes obtained at 620 W/m^2 without forced air convection. This motivated the choice to further investigate the SAP pouch transport phenomena in an indirect solar dryer since drying fluxes are comparable and photo-oxidation of the product no longer plays a role.

With regards to food safety, it was found that viscous, fibrous and starchy fruit purées are more likely to dry inhomogeneously compared to fruit juices. The inhomogeneous drying may result in local wet spots and/or crust formation which could pose as a food safety risk. The internal mass transport was studied with apple purée and found to be diffusive. This supports the local wet spot observation since a lack of internal mixing would prevent re-distribution of the wet spots.

The investigation into the limiting transport phenomena showed that for pouches dried in an indirect natural convection solar dryer simulator (within the following operational limits: 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity), the evaporation flux in the constant rate drying period was limited by the membrane resistance rather than the convective heat transfer from the air to the surface. Air velocity had a slight but statistically significant effect on the apparent convective mass transfer coefficient, which suggests that a boundary layer exists at these low air velocities and that the thickness of this boundary layer can be reduced by increasing the velocity of the air passing over the pouches. Temperature did not have any noticeable or statistically significant effect on the apparent convective mass transfer coefficient for the membrane to bulk air transport. These findings have implications on the design of an indirect solar dryer as they show that the two inputs that should be controllable are the air velocity and the water vapour partial pressure difference between the inner surface of the membrane and the bulk air (Δp).

The findings above suggest that when drying a food matrix, such as a fruit juice/purée, in a SAP pouch, it may be possible to control the onset of crust formation and reduce uneven drying by controlling Δp and air velocity in an indirect solar dryer. This hypothesis will be tested in the second half of the doctoral studies.

Solar Assisted Pervaporation challenges the traditional view on open sun drying. It has the potential to help people in rural and remote areas add value to fruits that would otherwise spoil, and does so in an environmentally sustainable way.

Popular Science Summary

Could it be possible to reduce fruit waste with membrane pouches and the sun? The aim of this research is to answer this question by determining if a food-grade membrane pouch can safely preserve fruit juices and purées by filling the pouches with juice/purée, sealing them and laying them in the sun to dry.

In many developing countries, there is actually enough food grown to feed the entire population yet many still go hungry. At the same time it seems that the amount of spoiled food in the world is constantly increasing. The Food and Agriculture Organization of the United Nations estimates that one third of food produced never makes it to our kitchens and instead spoils somewhere along the food chain. That is an incredible amount of food, but what are the reasons for this?

Just considering fruits, there are a few reasons. One reason is that fruits often ripen in a short period of time. In many developing countries, especially in the rural and remote areas of these countries, electricity and proper preservation equipment is not available or not affordable, and so the fruits that are not eaten simply spoil and go to waste. Sometimes open air sun drying is used, but it can be unhygienic since pests, insects, bacteria, dust, etc. can easily contact and contaminate the product while it is drying. Open air sun drying is also quite difficult to control due to frequent weather changes, which makes it difficult for farmers to rely on if they would like to sell their products commercially.

A second reason for the spoilage is that a lot of the fruits grown in developing countries are in rural and remote areas and it is difficult to transport these fruits to the larger urban centers. If a reliable transport system is not in place, the majority of the fruit will remain in the rural areas. Since the population density is not very high in these areas, a lot of fruit is leftover and spoils despite the fact that the local population is consuming it throughout the ripening period. If there is a reliable transport system in place, then another challenge is damage during transport which may make the fruits unsellable.

This research addresses these challenges by investigating a small-scale fruit preservation method termed Solar Assisted Pervaporation (SAP) in which membrane pouches are used to preserve fruit juices/purées made from fruits that would otherwise spoil. Each pouch has a membrane layer that allows water to pass through but not the other nutrients (i.e. carbohydrates, vitamins and minerals). This membrane layer is important as it also prevents insects, pests, dust and even bacteria and other microorganisms from getting inside. As water is removed from a pouch of juice, the sugar concentration increases which creates a self-preservative effect. This means that other preservatives do not need to be added. Depending on the type of fruit and how long the fruit juice/purée is dried, the final

dried product can be either a juice concentrate, marmalade or dried candy bar. If enough water is removed, the dried product can be stored without refrigeration for many months or years, similar to dried fruit products like raisins that are found on the non-refrigerated shelves of supermarkets.

By using SAP, farmers in rural areas could create value-added products from their fruits that normally spoil, and do so in a safe way. The technology does not require electricity, which is also often not available in these areas, and instead makes use of solar energy. Farmers would be able to preserve the fruit juices/purées as soon as the fruits are ripe and the process would be more hygienic and safer than open sun drying. Since more than 80% of the water is removed during drying, less weight needs to be transported to the markets and there is also no risk of damage during transport since the fruits are already in a dried form.

This research is a collaboration between Lund University and Eduardo Mondlane University in Mozambique. A prototype pouch has been developed and tested with farmers in Mozambique as part of the research, but there are many things that still need to be understood. The focus of this research is to determine the optimal way to dry fruit juices/purées with pouches and solar energy, which includes an understanding of how the size/shape of the pouch and the solar drying method affect the process. Possible methods include exposing the pouch directly to the sun or placing it in a type of drying cabinet that has warm air passing through it. The latter is known as indirect solar drying since the solar energy heats the air that is used to dry the product instead of directly transferring energy to the product. The challenge is to design a pouch and drying method that results in a process that is as fast and as safe as possible while giving farmers the control of the process they need to ensure the same final product quality is achieved each time.

This licentiate thesis is a compilation of the research that has been completed during the first half of the doctoral studies. The main findings are (1) realistic drying times of 2 to 3 days (assuming 8 hours of active solar drying per day) can be achieved with SAP pouches in an indirect solar dryer simulator, (2) the type of fruit plays a key role in the safety of the process since viscous, fibrous or starchy fruits are more susceptible to uneven drying and crust formation, and (3) an indirect solar dryer for SAP pouches operating within the limits of the parameters tested (i.e. 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity) should be designed for air velocity and relative humidity control.

Small-scale solar drying is still today relatively underdeveloped and one reason for this is hygiene since the surface of the product can be easily contaminated during drying. This research aims to challenge the existing view on small-scale solar drying by developing a technology that overcomes this contamination problem and at the same time, enables people to make better use of the agricultural resources they already have in an environmentally sustainable way.

Populärvetenskaplig Sammanfattning

Är det möjligt att minska fruktavfall med membranbelagda påsar och solen? Syftet med denna forskning är att svara på denna fråga genom att utforska om en speciell typ av livsmedelsgodkänd och membranbelagd påse kan konservera fruktsaft eller fruktpuré när man fyller påsarna med saft/puré, förseglar dem och lägger dem i solen för att torka.

I många utvecklingsländer, produceras det egentligen tillräckligt med mat för att täcka behovet för hela befolkningen ändå finns det människor som är hungriga. Mängden skämd mat i världen ökar och Livsmedels- och jordbruksorganisationer och FN uppskattar att en tredjedel av den mat som produceras aldrig når våra kök utan i stället förvinner längs matkedjan. Detta är en otrolig mängd mat! Hur kan vi förändra detta?

En anledning till att studera frukter är att de mognar under kort period och ofta kräver varsam hantering. I många utvecklingsländer, särskilt avlägsna områden saknas både el och konserveringsutrustning samt infrastruktur för att transportera mogen frukt till städer och marknader. På detta sätt går mycket frukt till spillo även om de lokala personerna förtär frukterna genom hela mogningsperioden så finns det frukt kvar sedan befolkningstätheten är så låg i dessa områden. Ibland kan det finnas utomhus soltorkning men då svårt att undvika regn, smuts, insekter, bakterier, svamptillväxt och djur som kan kontaminera produkten när den torkas.

Denna forskning tar upp dessa utmaningar genom att utforska en småskalig konserveringsmetod för fruktsaft som kallas Solar Assisted Pervaporation (SAP). SAP använder membranbelagda påsar för att konserva fruktsaft från frukter som annars skulle ha förstörts. Varje påse har ett membranlager som möjliggör att vatten kan passera ut medan resten (kolhydrater, vitaminer och mineraler) stannar kvar. Membranlagret är viktigt sedan det också hindrar insekter och bakteria att komma in i påsen. Medan vatten kommer ut från påsen, ökar sockerinnehållet vilket har en själv-konserveringseffekt. Detta innebär att andra konserveringsmedel inte måste tillsättas. Beroende av frukttypen och hur länge fruktsaften torkas, blir den slutliga produkten antingen ett saftkoncentrat, en marmelad eller en torkad fruktgodisstång. Om tillräcklig mängd vatten kommer ut från påsen, kan den torkade produkten förvaras utan kylning i flera månader eller år, jämför med russin som förvaras på icke-kylde hyllor i mataffären.

Med hjälp av SAP påsar kan bönder i lantliga områden producera fruktprodukter från en råvara som annars skulle ha ruttnat. Tekniken behöver ingen el, utan använder istället solenergi. Bönder skulle kunna konservera fruktsafterna så snart som frukterna är mogna och processen skulle vara mer hygienisk och säkrare än soltorkning i fria luften. Eftersom mer än 80% av vattnet försvinner under processen, blir det mindre mängd att transportera till marknaden och risken att frukterna kommer att bli skadade under transporten försvinner.

Projektet är ett samarbete mellan Lunds universitet och Eduardo Mondlanes universitet i Mocambique. En prototyp påse har utvecklas och testats med bönder i Mocambique men det finns många saker som fortfarande behöver studeras. Syftet med doktorandsprojektet är att identifiera det optimala sättet att torka fruktsafter med påsarna och solenergi, vilket inkluderar en förståelse av hur både påsens storlek och form samt soltorkningsmetoden påverkar torkningsprocessen. Denna metod kunde vara, till exempel, att lägga påsen direkt i solen eller att lägga den i ett torkskåp där varmluft passerar omkring påsen. Torkskåpsmetoden heter "indirect soltorkning" efersom solenergi används att värma upp luften som passerar omkring påsarna istället för att solenergien skall värma upp produkten direkt. Utmaningen är att designa en påse som tillsammans med vald torkningsmetod ger en snabb och säker process möjlig att styra så att bönderna kan producera samma produkt varje gång.

List of Papers

This thesis is based on the following papers which will be 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. and Dejmek, P. (2015). Solar assisted pervaporation (SAP) for preserving and utilizing fruits in developing countries. In: *3rd Southern African Solar Energy Conference (SASEC)*. [online] Kruger National Park: University of Pretoria, pp. 170-175. Available at: http://www.repository.up.ac.za/handle/2263/49551.

II. Phinney, R., Sjöholm, I. and Rayner, M. (2017). Solar Assisted Pervaporation (SAP): Quantification of the Influence of Temperature, Relative Humidity and Air Velocity on the Drying Performance of a Novel Fruit Juice Preservation Method
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, performed all of the experimental work, analysed the results, evaluated the results together with the co-authors and wrote the paper.

II. Randi Phinney designed the study together with the co-authors, constructed the testing apparatus with the help of one co-author, performed all of the experimental work, analysed the results, evaluated the results together with the co-authors and wrote the paper.

Related papers not included in the thesis

Chiau, E., Phinney, R. and Sjöholm, I. (2015). Convective drying (CD) versus solar assisted pervaporation (SAP) for preserving *Vangueria infausta* (African medlar)
Submitted

Otte, P.P., Bernardo, L.R., Phinney, R., Davidsson, H. and Tivana, L. (2016). Taking Participation to the next Level – Investigating the Potential of PRA (Participatory Rural Appraisal) for Integrated Agricultural Technology Development
Submitted

Otte, P.P., Bernardo, L.R., Phinney, R., Davidsson, H. and Tivana, L. (2016). The importance of gender relations in rural agricultural technology development - A case study on solar fruit drying in Mozambique
Submitted

Contributions to conferences and workshops

Phinney, R., Rayner, M., Sjöholm, I., Tivana, L. and Dejmek, P. (2015). Solar Assisted Pervaporation (SAP): Parametric study for optimisation of the technique. In: *12th International Congress on Engineering and Food (ICEF12)*. Quebec City, Canada, 14-18 Jun 2016. (Poster presentation)

Phinney, R., Sjölin, K., Sjöholm, I. and Rayner, M. (2015). Modelling of heat and mass transfer during the cooking of stuffed and unstuffed turkeys. In: *12th International Congress on Engineering and Food (ICEF12)*. Quebec City, Canada, 14-18 Jun 2016. (Poster presentation)

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

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

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

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

Abbreviations and Symbols

ANOVA	analysis of variance
a_w	water activity
RH	relative humidity [%]
T	air temperature [°C]
u	air velocity [m s^{-1}]
SAP	solar assisted pervaporation
°Bx	degrees Brix [°] = g sucrose in 100 g solution
OD	open dish
PSI	Paul Scherrer Institute
Δp	water vapour partial pressure driving force

Variable	Description	Units
$q''_{cond-juice,1}$	conduction heat transfer flux through the juice from the center to the top of the pouch	W m^{-2}
$q''_{cond-juice,2}$	conduction heat transfer flux through the juice from the center to the bottom of the pouch	W m^{-2}
$q''_{cond-memb,1}$	conduction heat transfer flux through the top membrane of the pouch	W m^{-2}
$q''_{cond-memb,2}$	conduction heat transfer flux through the bottom membrane of the pouch	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 memrane	W m^{-2}
$q''_{evap,1}$	heat flux corresponding to the latent heat of evaporation from the top of the pouch	W m^{-2}
$q''_{evap,2}$	heat flux corresponding to the latent heat of evaporation from the bottom of the pouch	W m^{-2}
$q''_{rad,net}$	net radiation transferred from the sun and surroundings to the top surface of the pouch	W m^{-2}
L(t)	thickness of the pouch as a function of time (t)	m
L_o	initial thickness of the pouch	m
t	drying time	s
T_a	temperature of the air	°C
$T_{a,K}$	temperature of the air	K
RH_a	relative humidity of the air	%
u	air velocity	m s^{-1}
h	convective heat transfer conefficient from the air to the surface of the open dish or pouch	W m^{-2} K^{-1}
$m''_{diff-memb,1}$	mass flux of water difussing through the top membrane	kg s^{-1} m^{-2}
$m''_{diff-memb,2}$	mass flux of water diffusing through the bottom membrane	kg s^{-1} m^{-2}
$m''_{diff-juice,1}$	mass flux of water diffusing through the juice from the center to the top	kg s^{-1} m^{-2}
$m''_{diff-juice,2}$	mass flux of water diffusing throught he juice from the center to the bottom	kg s^{-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}
k_m	apparent convective mass transfer coefficient	m s^{-1}
M_w	molecular weight of water	kg kmol^{-1}
R	universal gas constant	J kmol^{-1} K^{-1}
$p_{w,sat}(T_s)$	saturation partial pressure of water vapour on the inner side of the membrane or at the surface of the open dish	Pa
$p_{w,a}(T_a)$	partial presure of water vapour in the air equal to the saturation partial pressure of water vapour at the air temperature multiplied by the relative humidity	Pa
T_s	surface temperature	°C
$T_{s,K}$	surface temperature	K
q''_{conv}	lumped convective heat transfer flux from the bulk air to the inside surface of the membrane (Figure 2)	W m^{-2}
q''_{evap}	lumped heat flux correspondng to the latent heat of evaporation (Figure 2)	W m^{-2}
m''_{evap}	lumped mass flux for mass transport from the inner side of the membrane to the bulk air (Figure 2 and Eqn 2)	kg s^{-1} m^{-2}

Contents

1. Introduction

Food security is a major problem around the world today even though 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 (USDA, 2011; FAO 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 fruit (Affognon et al., 2015).

In many developing 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. This population is closely connected to nature and has knowledge that has been passed down from generation to generation on how to prepare, consume and store various types of fruits (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 population since they have so much knowledge about fruits to contribute. If this was successful, more fruits could be transported from rural areas to the larger 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, or in some extreme cases 0.6 if certain types of mold are present (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 and that are now widely available throughout the world.

Safely drying and preserving juicy fruits in rural and remote areas, however, can be difficult with traditional technologies. Open air sun drying has been used for thousands of years to dehydrate many types of fruits close to the point of harvest yet it still today remains underdeveloped and mainly on a smaller-scale. The main reasons for this are hygiene and food safety since microorganisms, insects and other pests can easily contaminate the surface of the product during drying. In theory, the hygienic design of the dying process could be controlled, but these hygienic considerations are often lacking in non-commercialised operations, especially those in rural and remote areas. Even if the hygienic nature of sun 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 that a simple and inexpensive solar drying technology is needed that is hygienic, suitable for juicy fruits and useable in rural and remote areas.

A technology that fulfills these requirements is Solar Assisted Pervaporation (SAP) which is the focus of the research presented in this licentiate thesis. SAP is a novel fruit preservation technology that uses membrane pouches and solar energy to dehydrate juices made from fruits that would otherwise spoil. Value-added shelf-stable products in the form of a juice concentrate, marmalade or dried fruit bar 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 much more hygienic than traditional open air sun drying and solar drying with unfiltered air. This research aims to challenge the traditional way of thinking about solar drying through the development of a novel, safe and practical fruit juice preservation technology that is suitable for rural and remote areas of developing countries. The long term vision is decreased fruit spoilage and improved food security in not only Mozambique, but in all developing and/or tropical countries where agricultural resources are underutilized and solar radiation is plentiful.

2. Background

2.1 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 technique that has been used for thousands of years to extend the shelf life of otherwise perishable items (Singh and 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. 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 describes 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. Water activity (a_w) is defined as:

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

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 whereas today, laboratory equipment based on dew point determination and psychrometrics is commonly available where one water activity measurement takes about five minutes.

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. In terms of drying and preservation, a water activity less than 0.7 usually results in a microbiologically stable product that can be stored without refrigeration. In some rare cases, *Monascus bisporus* (mould) and *Saccharomyces rouxii* (yeast) may be present and so a water activity less than 0.6 would then be required (Fontana, 2007).

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 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 and 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). 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 SI units kg s^{-1} m^{-2}) is constant, and one or more falling rate periods, in which the drying flux decreases with decreasing product moisture content. The onset of the 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 and Heldman, 2014).

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 drying. The latter is related to the focus of this research and will be discussed in more detail in the next section.

2.2 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 tropical and developing countries to dry crops such as fruits, vegetables, grains and tobacco by distributing the items on the ground and turning them at regular intervals until enough water has been removed that the products can be stored safely for later use (Sodha and Chandra, 1994). Some open sun drying methods are now employed on a commercial scale, with two notable examples being sun-dried raisins and sun-dried tomatoes.

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 (Sodha and Chandra, 1994). The drying process itself is also uncontrolled which means that it can be difficult to standardize the final product quality. As a result, many products can be under-dried and many over-dried.

One option to improve both the hygienic nature and control of open sun drying is to use a solar drying system. There are three main components of a solar dryer: a solar air collector that is used to heat ambient air, a drying unit 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 and 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 into more general solar dryer categories. Three general categories that are relevant to this work are: direct mode, indirect mode and mixed mode dryers. The dryer type can also be classified as active or passive depending on if the airflow is driven by forced convection (e.g. by a fan) or by natural convection (Kalogirou, 2013).

With a direct mode solar dryer, the product is enclosed in a container with black internal surfaces and a transparent cover or side panels. The product to be dried is placed inside the container and directly exposed to the sun. Air circulation is driven by natural convection. These types of dryers are most suitable for areas with lower relative humidity and high solar radiation. Indirect mode solar dryers do not expose the product to solar radiation and instead aim to pass solar-heated air over the produce to be dried in a type of cabinet, bin or tunnel. Mixed mode types incorporate both direct sun exposure and the flow of solar-heated air over the food product (Sodha and Chandra, 1994). Each mode has advantages and disadvantages with two advantages for the indirect type being that the product is not directly exposed to solar radiation which could promote unfavourable reactions like photo-oxidation. The drying conditions should also be easier to control since the airflow rate can be used to control the temperature of the air in the drying chamber or tunnel. Direct mode and mixed mode dryers offer advantages in terms of drying speed since the irradiation energy can be absorbed directly by the products rather than being transferred first to the air and then to the products (Kalogirou , 2013; Sodha and Chandra, 1994).

2.3 Pervaporation for species separation

Pervaporation is a membrane separation process whereby a liquid mixture is separated by partial vaporization using a membrane that is nonporous and permselective (Néel, 1991; Pangarkar and Ray, 2015). The species that is transported across the membrane has an affinity for the membrane, unlike other membrane separation processes, such as membrane dilation, where the membrane is not wetted by the species (Saravacos and Kostaropoulos, 2002). 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 et al., 2006). From the solution-diffusion theory, the mass transfer through the membrane occurs in a three-step process (Olsson et al., 2002):

- Selective sorption into the membrane on the feed side
- Selective diffusion through the membrane
- Desorption on the downstream side of the membrane into the vapour phase

The rate at which the separation occurs can be adjusted by controlling the driving force for mass transport across the membrane. 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. Traditional pervaporation enhances the driving force in one of two ways: 1) by applying a vacuum on or 2) sweeping a gas along the downstream side of the membrane (Néel, 1991; Pangarkar and Ray, 2015). The separated vapour molecules are then collected in cold traps downstream. Pervaporation is well established for separating ethanol/water mixtures but also has applications in the food industry for the separation of organic aroma compounds from juices such as apple, pineapple, grape and orange juice (Lipnizki et al., 1999; Olsson and Trägårdh, 1999; Pereira et al., 2005; Rajagopalan and Cheryan, 1995; Shepherd et al., 2002).

2.3.1 Solar Assisted Pervaporation (SAP) for water vapour separation

Solar Assisted Pervaporation (SAP) is the term that was given to the novel fruit juice preservation method presented in this research. Pervaporation theory applies to SAP since a hydrophilic permselective membrane is used to separate water vapour (i.e. the permeating species) from a liquid mixture (i.e. fruit juice). Sweep gas pervaporation principles are applied by forcing air along the downstream side of the membrane at a controlled air velocity. If the air is pre-heated in a solar collector, then the relative humidity of the air will decrease and the mass transfer driving force will further increase. Traditionally, pervaporation is a continuous process but in the case of SAP, water vapour removal is performed batchwise using pouches made of a hydrophilic permselective membrane.

2.4 Social implications of the research

Malnourishment is a serious problem in many developing countries. In Mozambique, for example, 25% of the population was considered undernourished in 2015 (FAO, 2015). At the same time, there is enough food grown in Mozambique to meet the nutritional requirements of the population but food spoilage rates remain high due to a lack of affordable and robust small-scale preservation technologies. Many developing countries face this food security, food spoilage and undernourishment dilemma and it is unclear if the situation is going to get better or worse in the coming years since many factors can influence the outcome. Three factors that play a role are poverty, economic growth and gender equality. By improving food security in Mozambique, this research aims to indirectly affect poverty alleviation, economic growth and gender equality in a positive way. Examples will be given in the subsequent paragraphs about the effects that could be achieved.

Improving quality of life while promoting economic growth

This research aims to improve the quality of life of people in developing countries while promoting economic growth. This is done by giving farmers the opportunity to add value to crops that would normally rot. Not only would this bring nourishment throughout the lean season to the farmers and their families, but it would also provide the farmers with a way to earn extra income by selling their dried products at local markets or through other distributors within the country. The extra income earned would remain at the farmer level to avoid the potential negative effects of corruption at the government level (Spector et al., 2005). Poverty would therefore be targeted through economic growth at the farmer level.

Improving gender equality as a result of economic growth

It is hoped that one outcome of the research by the end of the doctoral project is a positive effect on gender equality. Estimates show 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 developing countries are often disadvantaged because they have less access to technology due to cultural or financial restrictions (U.S. Government, 2012; Lokshin and Mroz, 2003). It is the intention of this project to promote the SAP technology to all farmers, thus allowing women to have the same opportunities as men.

A second benefit that could result is related to the link between gender equality and poverty reduction (Lokshin and Mroz, 2003). The hypothesis is that a positive effect on the economy could reduce poverty and in turn 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 and Mroz, 2003). Research also shows that the effect on gender differences varies depending on where the economic growth in concentrated. If the growth is targeted towards poor people rather than the rich, trends show that it is more likely that gender differences in households will decline in the long run (Lokshin and Mroz, 2003).

2.5 Environmental implications of the research

SAP is an eco-friendly drying method that promotes sustainable global development. The SAP process is driven solely by solar energy, which means there will never be a risk of fuel shortage, the environmental impact and carbon footprint are minimal and the operating cost is low. The technique allows for the utilisation of agricultural resources to be maximised, which could lead to improved food security and poverty alleviation. Greenhouse gas emissions would be minimal and limited to the initial transport of the drying equipment to the farm, the transportation of the pouches from the manufacturing site to the farms in Mozambique and the transportation of the dried products within the country. Since the water is evaporated on-site, excess water is not being transported. Refrigerated transport and storage is never needed, which allows for significant energy savings. There is a possibility that the pouches could also be re-used which would reduce the amount of waste entering into the communities. A local recycling system could also be put in place for collecting the used pouches so that the material could be recycled and re-used in a responsible way.

3. Aim and Objectives

The overall aim of this research is to develop a safe and practical fruit juice preservation technology that is suitable for rural and remote areas of developing countries. The overall aim can be broken down into a number of objectives, three of which will be discussed in this thesis:

- Investigate the drying time and influencing parameters under realistic drying conditions with model substances (Paper I)
- Evaluate the possible effects of internal mass transport on food safety
- Quantify the drying performance and decouple the effects of temperature, relative humidity and air velocity on drying flux (Paper II)

4. Methods and Approach

4.1 Theoretical approach

The SAP process is complex as it involves simultaneous heat and mass transfer inside, outside and through the membrane. Figure 1 illustrates the different modes of heat and mass transfer that could take place when drying a fruit juice or purée in a membrane pouch (Paper II). Table 1 defines the variables in the diagram.

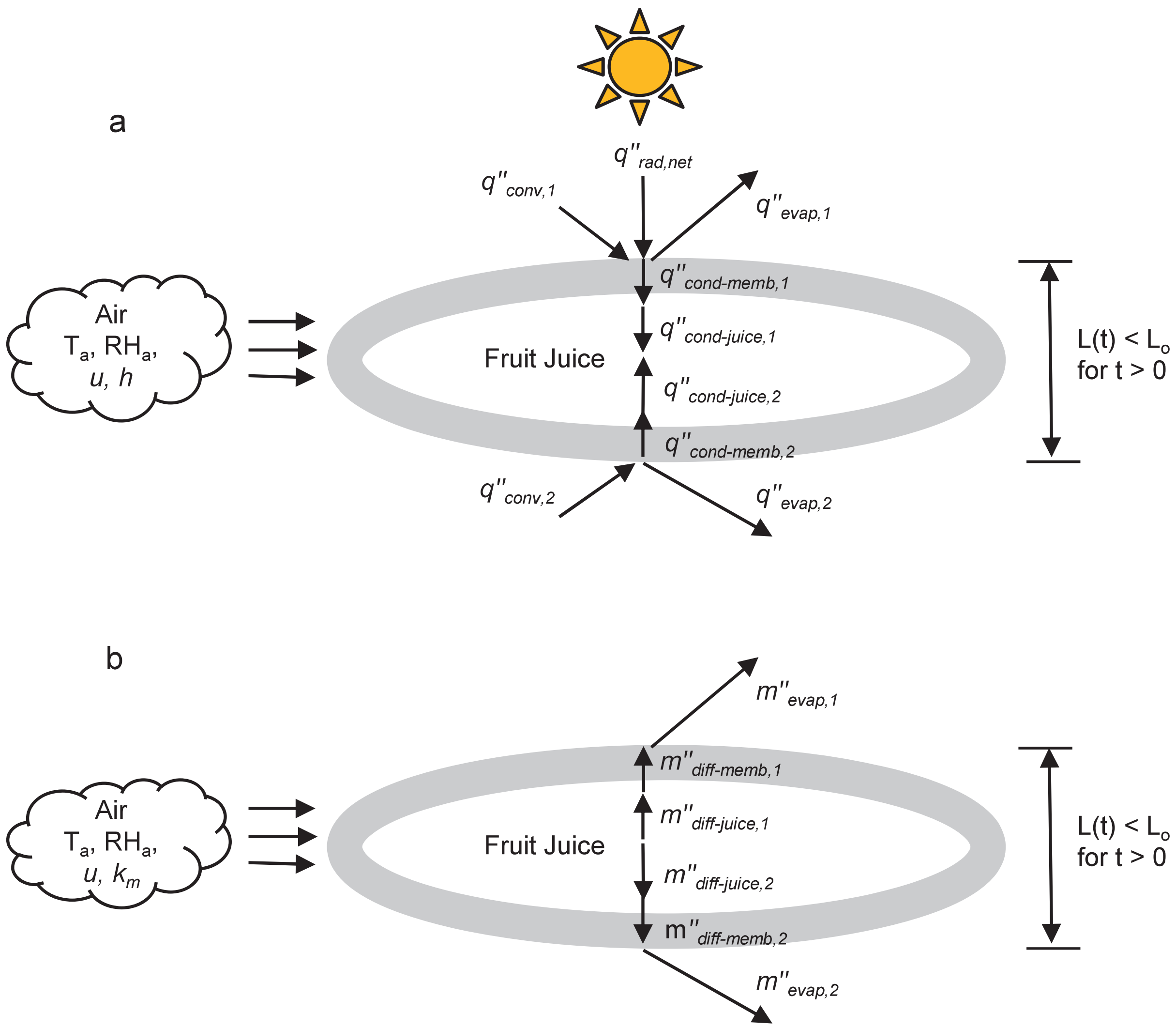


Figure 1
Energy and mass balances illustrating the modes of heat and mass transfer that could be present during the SAP process. The thickness of the membrane is not drawn to scale to be able to visualise the transport phenomena that apply to the membrane (Paper II).

Table 1: Definition of variables used in the theoretical models depicted in Figures 1 and 2 and Eqn 2. Note: SI units for mass flux are kg s^{-1} m^{-2} but kg h^{-1} m^{-2} are commonly used in the results.

Variable	Description	Units
$q''_{cond-juice,1}$	conduction heat transfer flux through the juice from the center to the top of the pouch	W m^{-2}
$q''_{cond-juice,2}$	conduction heat transfer flux through the juice from the center to the bottom of the pouch	W m^{-2}
$q''_{cond-memb,1}$	conduction heat transfer flux through the top membrane of the pouch	W m^{-2}
$q''_{cond-memb,2}$	conduction heat transfer flux through the bottom membrane of the pouch	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 memrane	W m^{-2}
$q''_{evap,1}$	heat flux corresponding to the latent heat of evaporation from the top of the pouch	W m^{-2}
$q''_{evap,2}$	heat flux corresponding to the latent heat of evaporation from the bottom of the pouch	W m^{-2}
$q''_{rad,net}$	net radiation transferred from the sun and surroundings to the top surface of the pouch	W m^{-2}
$L(t)$	thickness of the pouch as a function of time (t)	m
L_o	initial thickness of the pouch	m
t	drying time	s
T_a	temperature of the air	°C
$T_{a,K}$	temperature of the air	K
RH_a	relative humidity of the air	%
u	air velocity	m s^{-1}
h	convective heat transfer conefficient from the air to the surface of the open dish or pouch	W m^{-2} K^{-1}
$m''_{diff-memb,1}$	mass flux of water difussing through the top membrane	kg s^{-1} m^{-2}
$m''_{diff-memb,2}$	mass flux of water diffusing through the bottom membrane	kg s^{-1} m^{-2}
$m''_{diff-juice,1}$	mass flux of water diffusing through the juice from the center to the top	kg s^{-1} m^{-2}
$m''_{diff-juice,2}$	mass flux of water diffusing throught he juice from the center to the bottom	kg s^{-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}
k_m	apparent convective mass transfer coefficient	m s^{-1}
M_w	molecular weight of water	kg $kmol^{-1}$
R	universal gas constant	J $kmol^{-1}$ K^{-1}
$p_{w,sat}(T_s)$	saturation partial pressure of water vapour on the inner side of the membrane or at the surface of the open dish	Pa
$p_{w,a}(T_a)$	partial presure of water vapour in the air equal to the saturation partial pressure of water vapour at the air temperature multiplied by the relative humidity	Pa
T_s	surface temperature	°C
$T_{s,K}$	surface temperature	K
q''_{conv}	lumped convective heat transfer flux from the bulk air to the inside surface of the membrane (Figure 2)	W m^{-2}
q''_{evap}	lumped heat flux correspondng to the latent heat of evaporation (Figure 2)	W m^{-2}
m''_{evap}	lumped mass flux for mass transport from the inner side of the membrane to the bulk air (Figure 2 and Eqn 2)	kg s^{-1} m^{-2}

The model in Figure 1 was used as a starting point in the design of the experiments conducted in Paper II. Since there are many different types of heat and mass transfer occurring in the SAP process, it becomes difficult to try to optimise and understand any of the elements of the process without first isolating certain components and making certain assumptions. It was decided that the external heat and mass transfer phenomena and the heat and mass transfer through the membrane would be the first focus. By doing this, all of the conduction and diffusion terms related to the juice could be disregarded. By focusing on the surface phenomena, Figure 1 can be re-drawn as surface energy and mass balances. The resulting simplified model is shown in Figure 2. Since Paper II focused on simulating indirect solar drying, the radiation heat transfer term in Figure 1 can also be ignored.

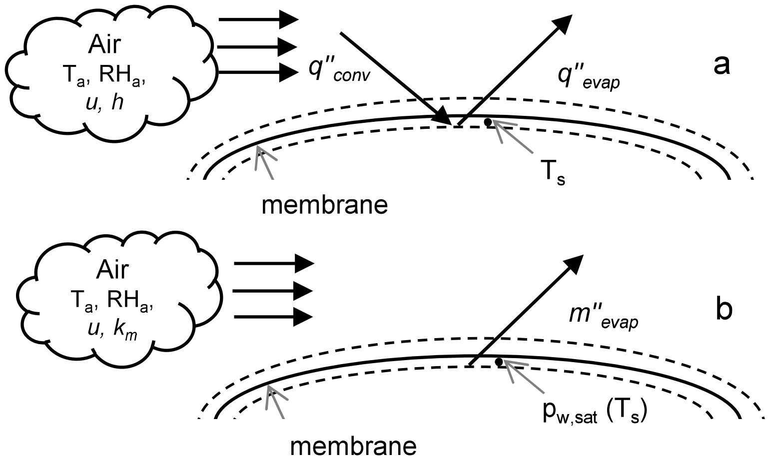


Figure 2
Surface energy and mass balances applied in this study to be able to isolate and investigate the heat and mass transport inside the membrane and in the external ambient environment. All radiation effects have been neglected assuming that the pouch is drying inside an indirect solar dryer and the net radiation exchange between the interior surface of the dryer and the bag is minimal due to the low temperature of the wall surface (Paper II).

The open dish and pouch drying processes were determined to be heat transfer or mass transfer limiting by using the following equation to calculate the apparent convective mass transfer coefficient (k_m):

Equation (2)

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

The assumptions for this model framework and additional explanations of the equations and variables can be found in Paper II.

4.2 Experimental approach

4.2.1 Materials

Two different membrane materials were used in this research. In Paper I, a black textile with a polymer coating (referred to in the remainder of the thesis as "supported membrane") was used to investigate the drying time and feasibility of the process. The same supported membrane was then used to study the effects of internal mass transport on food safety. In Paper II, a polymer membrane without a textile backing layer (i.e. "unsupported membrane") was used to perform a multifactorial analysis on the process to decouple the effects of temperature, relative humidity and wind speed on the drying flux. When performing this type of multifactorial analysis, it is preferable to use only a membrane layer to ensure that the resistance of the membrane itself, and not the support layer, is being measured. When the SAP technique will be implemented in reality, an opaque supported food-grade membrane will be preferred to improve the mechanical strength of the pouch and enhance the absorption of solar irradiation.

Details about the materials used in Papers I and II are given in the respective papers. For the internal mass transfer investigation, Golden Delicious apples purchased in Sweden were used (organic, 94021, Italy). The same apples that were tested with the convection dryer at Lund University were transported to Switzerland and used in the neutron radiography experiments. Bananas were purchased from a local supermarket in Lund (Chiquita). In Switzerland, Fairtrade bananas (Max Havelaar, Fairtrade Code 1539) were purchased at a local supermarket in Dubendorf.

4.2.2 Methods

Experimental setups

Four different experimental setups were used to obtain the results presented in this thesis. They are depicted in Figures 3 to 6 below.

Figure 3 shows the convection dryer that was used in Paper I and for the internal mass transfer investigation. It is referred to in the thesis either by "convection dryer" or "first generation indirect solar dryer without relative humidity control".

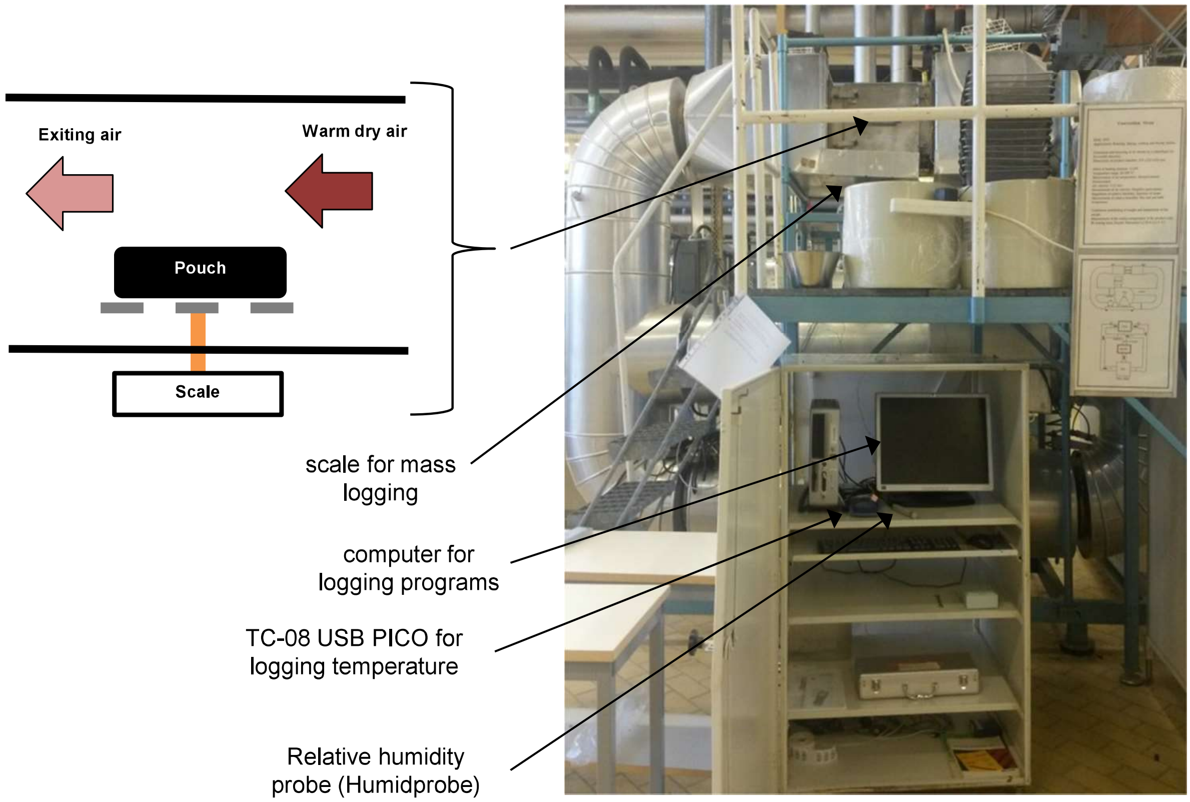


Figure 3
Convective dryer equipped with a scale that was connected to the computer for logging mass data. A USB TC-08 PICO logger was used to log the temperature in the dryer. A Humidprobe relative humidity probe was used to measure the temperature and relative humidity of the ambient air outside the dryer. The sample (e.g. pouch) is placed on a rack that is attached to a scale outside the dryer. This apparatus was used in Paper I and for the internal mass transfer experiments.

Figure 4 shows a schematic of the setup that was used in Paper I to test drying flux as a function of irradiance.

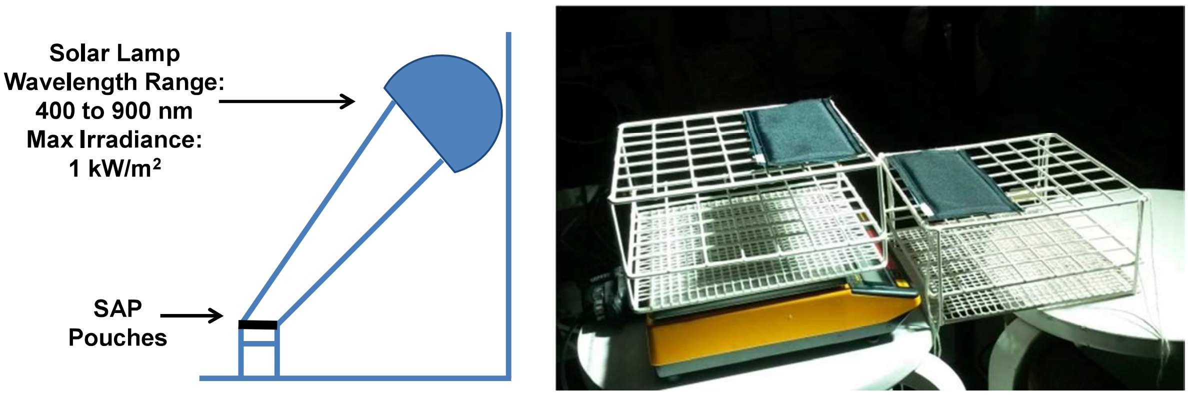


Figure 4
Left: Position of the SAP pouches in relation to the solar simulating lamp. Right: image of the pouches exposed to the radiation from the lamp. A scale was used (yellow object at the bottom of the image) to log the mass of one bag continuously.

A major part of this work has been the development of a reliable method with controlled relative humidity for experimentally measuring the drying performance of SAP pouches. Figure 5 shows the apparatus that was built to accomplish this. The method includes a climate-controlled cabinet that can control relative humidity, temperature and air velocity. In Paper II, the statistical repeatability of the method was confirmed. In the thesis, the apparatus is often referred to as "the second generation indirect solar dryer with relative humidity control".

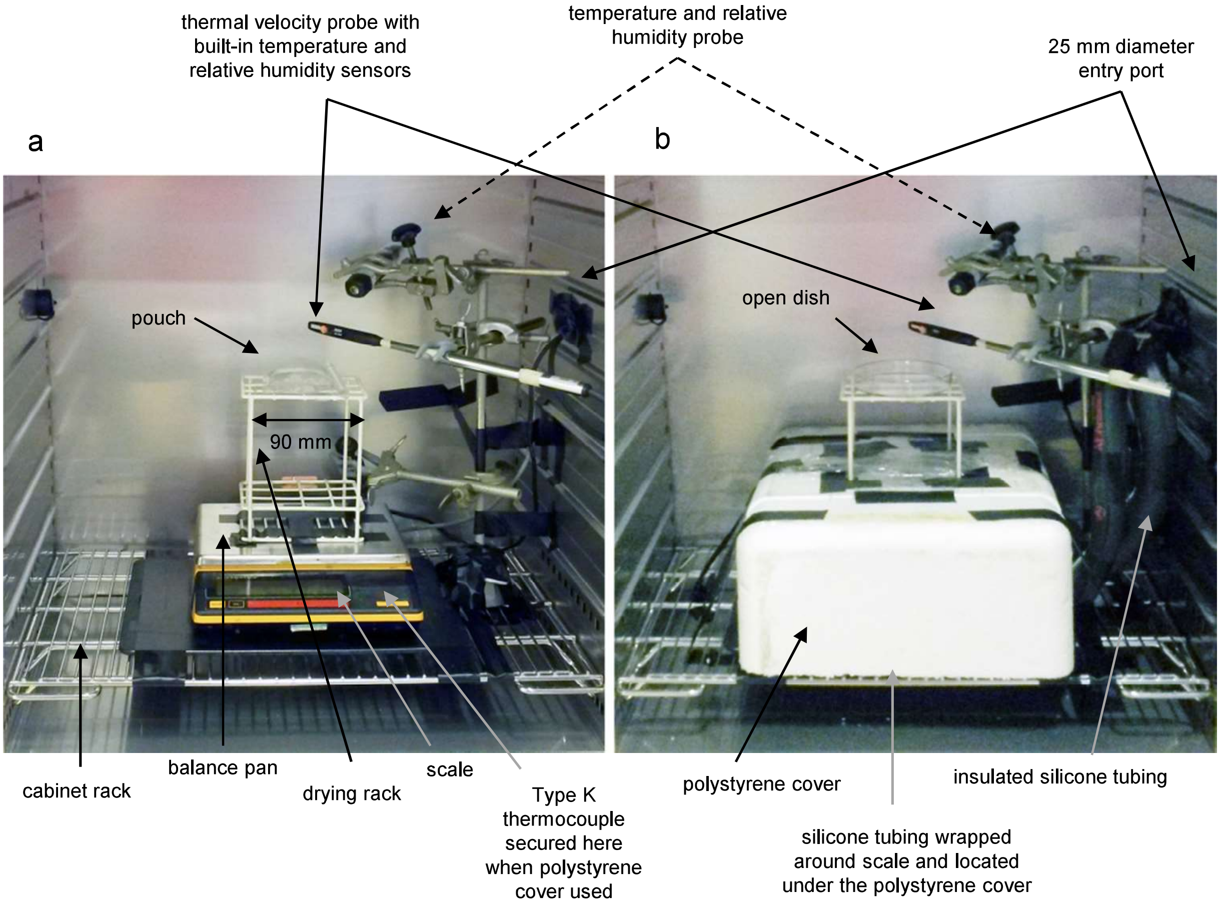


Figure 5
Experimental setup used to simulate an indirect solar dryer with relative humidity control: (a) without cooling system showing the position of the pouch and (b) with cooling system showing the position of the open dish (Paper II).

Neutron radiography experiments were conducted at Paul Scherrer Institute (PSI) in Villigen, Switzerland. The neutron source was SINQ (Swiss Spallation Neutron Source). It is a continuous source with a flux of 10^{14} neutrons cm^{-2} s^{-1}. The NEUTRA beamline was used for the experiments. It is a thermal neutron radiography station. The NEUTRA beamline has three possible sample positions. Position 2 was used for this work. The characteristics of the NEUTRA beamline at position 2 are given in Table 2. A schematic of where position 2 is located and how the pouches were secured on the sample stage is shown in Figure 6. Neutron radiography was used for both experiments.

Table 2
Characteristics of the NEUTRA beamline (Paul Scherrer Institute, Villigen, Switzerland) used for the neutron radiography experiments.

Characteristic	Value
Neutron energy	25 meV thermal Maxwellian spectrum
Neutron flux at sample position	>5 x 10^{6} neutrons cm^{-2} sec^{-1} mA^{-1} (p-current)
Maximum field of view	30 cm x 30 cm

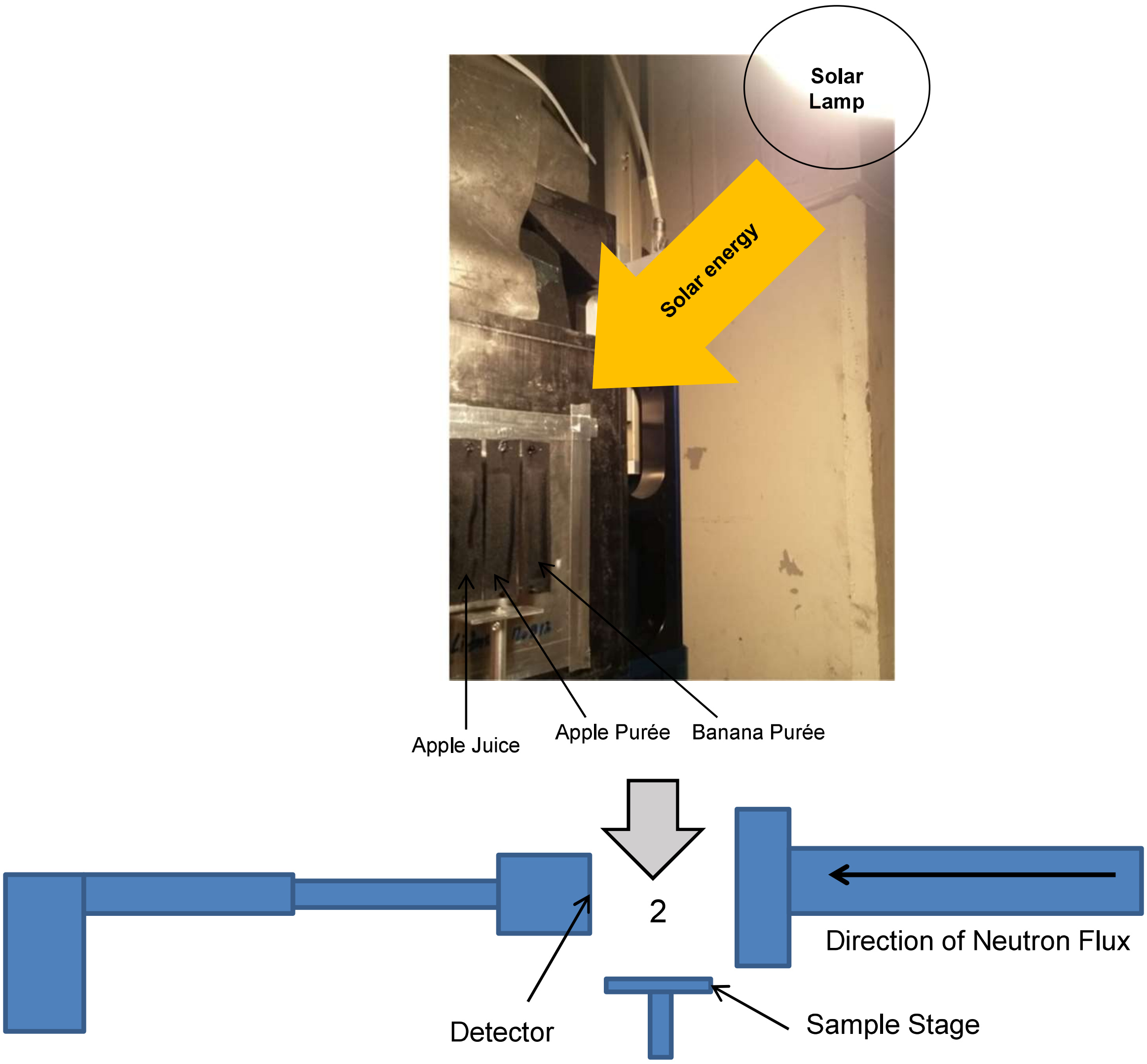


Figure 6
Cross-sectional view of the NEUTRA beamline and where “position 2” is located. Position 2 was the beamline position used for the experiments in this study. A solar lamp was used to heat the SAP pouches and provide the latent heat for evaporation. The pouches were fixed to an aluminum stand in a vertical orientation. The same setup was used for the D_2O experiment.

Experimental design

The experiments in Paper I were designed based on model food matrices that were to represent citrus fruit juices. The experiments in Paper II were designed in line with the requirements of a two-level multifactorial analysis. Details about the designs and methods can be found in Paper I and Paper II, respectively.

For the internal mass transfer investigation, apple and banana purées were chosen because of their fiber and starch contents, respectively. For the drying experiments, the same procedure was used as discussed in Paper I with the first generation indirect solar dryer simulator shown in Figure 3. For the neutron radiography experiments, it was not possible to access the beamline ahead of time and so the preparations beforehand focused on constructing pouches of suitable dimensions to be sure this could be done efficiently and rapidly on-site. Pouches could have a maximum thickness of 10 mm. In addition, a number of frames of aluminum were constructed beforehand based on the dimensions at position 2 in the beamline and knowing that the maximum field of view was 30 x 30 cm.

Drying performance assessment

The drying performance of the SAP process was assessed based on three criteria: 1) by expressing the pouch drying flux as a percentage of the open dish (or reference) drying flux, 2) by calculating and comparing the convective mass transfer coefficients and permeances for the open dish and pouch, and 3) by calculating a drying time for each set of drying conditions based on the drying fluxes obtained, accounting for the effects of the falling rate period that are present when a complex food matrix is used (Paper II).

Statistical analyses

Water activity, moisture content, and °Brix measurements were always performed in at least duplicate (Paper I). Each treatment combination in Paper II was also performed at least twice. In all cases, values are reported as averages ± standard deviation. One-way ANOVA and two sample t-tests assuming equal variances were performed in Excel to determine if there were statistically significant differences between two drying fluxes or between two apparent convective mass transfer coefficients. For the two-level factorial regression, a test statistic was calculated based on the mean square error of each *effect* and the mean square error of all of the treatments (Tambane, 2009). The following regression model was used to determine a single equation for drying flux as a function of temperature, relative humidity and air velocity (see Paper II for definitions and further details).

$$\bar{\boldsymbol{y}} = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + e$$

Equation (3)

4.3 Fieldwork and ethical considerations

Fieldwork for testing prototype membrane pouches was conducted in April 2015 and April-May 2016 with two farmers' associations in the province of Inhambane, Mozambique. The objectives of these fieldtrips were:

- To obtain feedback from the farmers with regards to the pouch design and how it is handled and filled, and
- To conduct interviews and workshops with the farmers to learn about their lifestyles, behaviours, needs and limitations to avoid introducing the technology too soon. The aim has been to design the technology for their needs rather than adapt their lifestyle to the technology. A method known as Participatory Rural Appraisal (PRA) was used to design the interviews and workshops. The results are not discussed but two papers that have been submitted based on the outcome of the PRA are mentioned in the list of related papers in the front matter of the thesis.

Ethical considerations have also been taken into account for the fieldwork. All participants remain anonymous when the data is reported to a third party outside the working group and all members of the farmers' associations are also given the option not to participate in the studies if they feel strongly against them. The manner in which questions are asked is also taken into consideration to try to avoid leading questions and obtaining biased data.

All testing with fruit juices and other foods is also taken very seriously. In May 2016, the farmers were allowed to experiment with the pouches for the first time. Extra effort was made to ensure the juice preparation area was as hygienic as possible and that the farmers were aware of the risks in participating in such a study.

In the coming 2.5 years, testing with the farmers will involve longer and more complicated studies and prototype assessments. An assessment on ethical considerations for these longer studies will need to be done to ensure that none of the participants is harmed physically or emotionally from the testing experience and that the experiments are also designed in an unbiased way.

5. Main Results and Discussion

5.1 Effect of influencing parameters on the drying flux and drying time under realistic conditions

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 irradiation affect the drying flux and drying time for a supported SAP pouch are presented in this section. Additional details about all of the experiments performed during this screening phase can be found in Paper I.

5.1.1 Effect of dry solids content on drying curves

Drying curves obtained with model solutions dried in supported SAP pouches in a convection oven at 40.9°C, 13.9% relative humidity and with 1.8 m/s air velocity are shown in Figure 7. The model solutions were lemon juice (10.6°Bx), Milli Q water with added sucrose (20.1°Bx) and lemon juice with added sucrose (27.1°Bx). Solutions with a higher initial °Brix dried in approximately the same amount of time as solutions with a lower initial °Brix (assuming the final desired moisture content was 0.25 kg water/kg dry solids since this corresponds to a final water activity of approximately 0.7 for orange juice (Iglesias and Chirife, 1982). The higher the initial °Brix of the solution, the less water that needed to be removed to achieve the final desired moisture content as can be seen in Figure 7. Since the drying times were approximately the same but different amounts of water were removed, the drying fluxes were not equal. The lemon juice solution with an initial °Brix of 10.6 had the fastest drying flux, followed by the 20.1°Bx solution and then the 27.1°Bx solution. The drying time to achieve a final moisture content of 0.25 kg water/kg dry solids was approximately 15 hours for all three solutions. This drying time could be achieved if a solar dryer was able to provide heated air at 41°C and 14% relative humidity for approximately eight hours per day. This would result in a total process time of two days which is reasonable for the end users in terms of production rate.

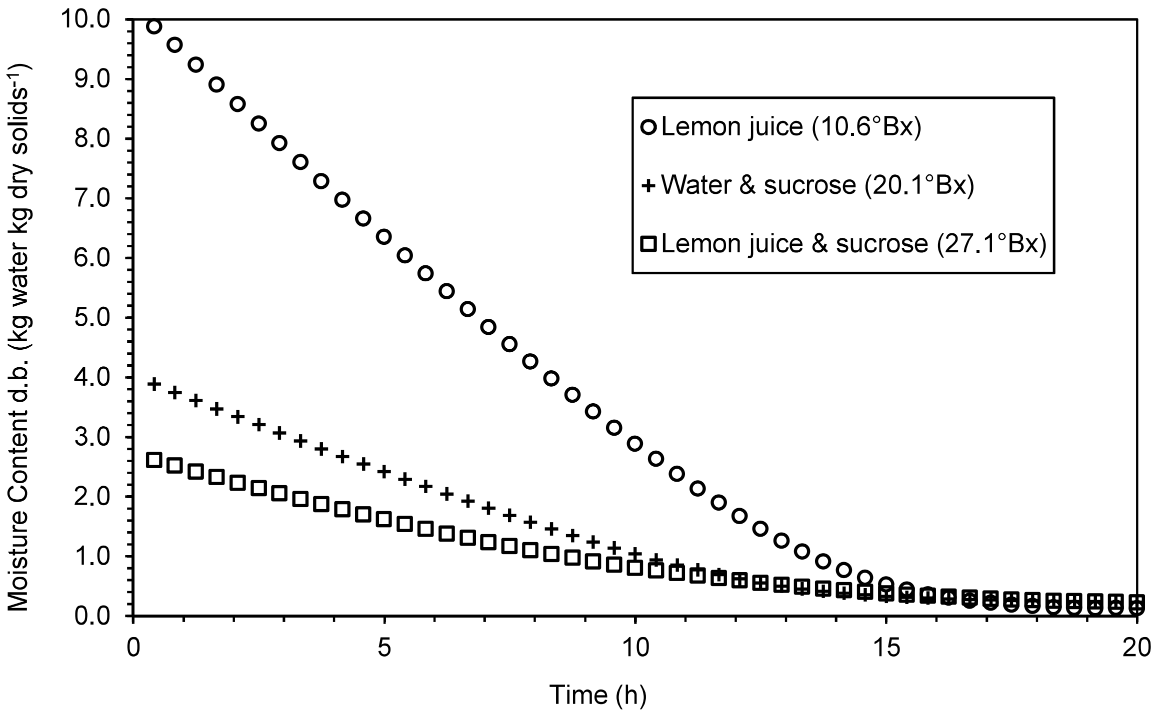


Figure 7
Drying curves for model solutions dried in supported SAP pouches in a convection oven with the following drying conditions: 40.9 ± 0.1°C, 13.9 ± 1.5% relative humidity, 1.8 ± 0.2 m/s air velocity.

5.1.2 Effect of increasing dry solids content on drying flux

Drying flux and change in dry matter content as a function of time are shown in Figure 8 for a lemon juice model solution (10.6°Bx) dried in a supported SAP pouch in a convection oven 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 at a high level for about 7 hours 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 8 what the cause is of the rapid decrease in drying flux. It could be related to a sudden decrease in the water activity of the fruit juice which would affect the driving force for mass transport. It could also be related to an increase in the viscosity of the juice due to the increase in dry matter content and loss of water, or a combination of both. An understanding of which of the two mechanisms is responsible for the decrease in drying flux is necessary to be able to optimise the SAP process since the goal is to maintain the highest drying flux possible for the longest possible period of time. A deeper look into the internal mass transfer phenomena will be part of the next phase of the research.

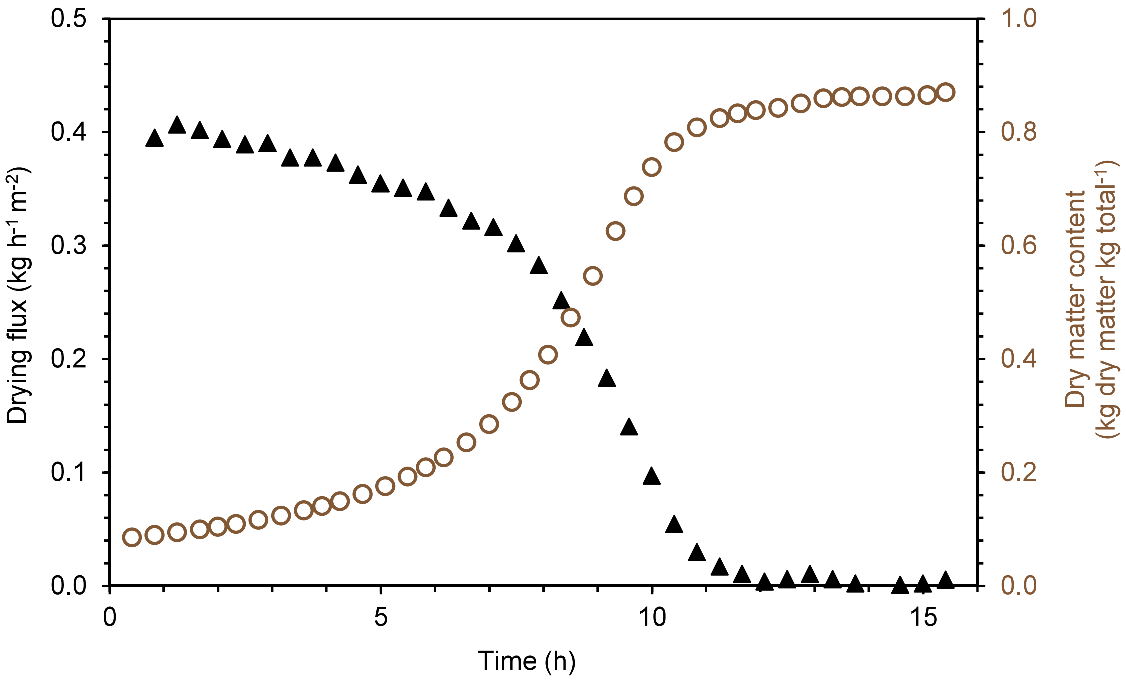


Figure 8
Drying flux and change in dry matter content as a function of time for lemon juice (10.6°Bx) dried in a convection oven with a supported SAP pouch with the following conditions:51.6 ± 0.1°C, 7.5 ± 0.5% RH, 1.8 ± 0.2 m/s air velocity.

5.1.3 Effect of irradiation on drying flux

A solar simulating lamp was used to obtain the results in Figure 9 for drying flux as a function of solar irradiation for lemon juice plus sucrose solutions (27.1°Bx). Drying flux was found to be a linear function of irradiation for a black, opaque supported SAP pouch positioned under the solar lamp in such a way that only the top of the pouch was exposed to the solar irradiation. 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 et al., 2003)), the irradiation values studied were in a reasonable range for daily average values.

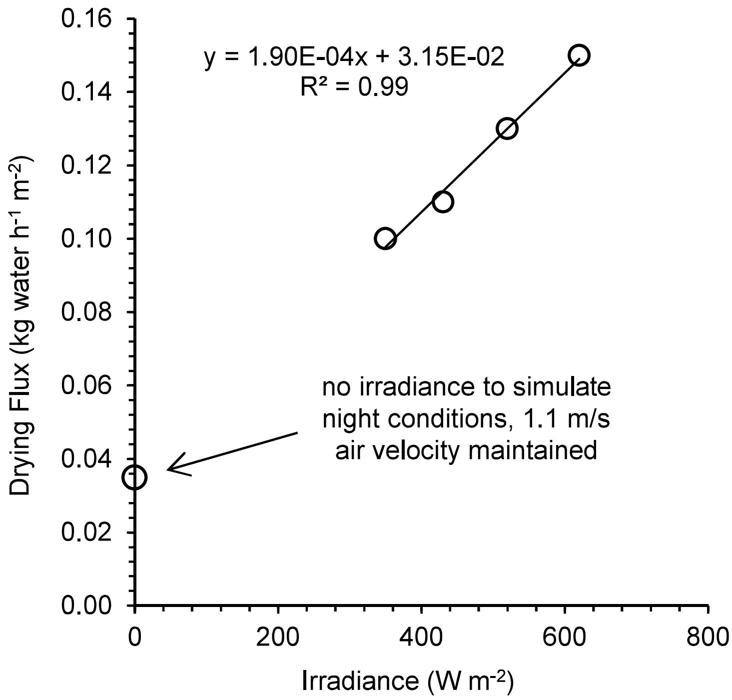


Figure 9
Drying flux as a function of irradiance for lemon juice + sucrose (27.1°Bx) solutions with ambient surrounding conditions (20.7 ± 0.1°C and 51.1 ± 1.3% RH) with 1.1 ± 0.2 m/s airflow (Paper I).

5.1.4 Limitations of open air sun drying

Solar irradiation can have a positive effect on the drying flux as was observed in Figure 10. It is possible, however, that the presence of ambient forced convective airflow reduces this positive effect. According to Figure 10, forced convective airflow has a positive effect on the evaporation flux when no solar irradiation is present. When a forced convective airflow is applied with direct solar radiation, however, there is a negative effect on drying flux. This can be explained by the air being able to convect away energy from the irradiated surface if the air temperature is less than the surface temperature on the pouch. This is commonly the case if the surface exposed to the radiation is black, which it was for the pouch used in these experiments. The result is that less energy is available for the latent heat of evaporation. In the experiments illustrated in 10, the pouch surface temperature was measured with and without air flowing over the pouches and the result was a surface temperature of 40°C without forced convective airflow and 25°C with forced convective airflow. Therefore, forced convective ambient temperature airflow applied with direct radiation has the potential to decrease the evaporation flux, prolong the drying time and increase the risk of spoilage during the drying process.

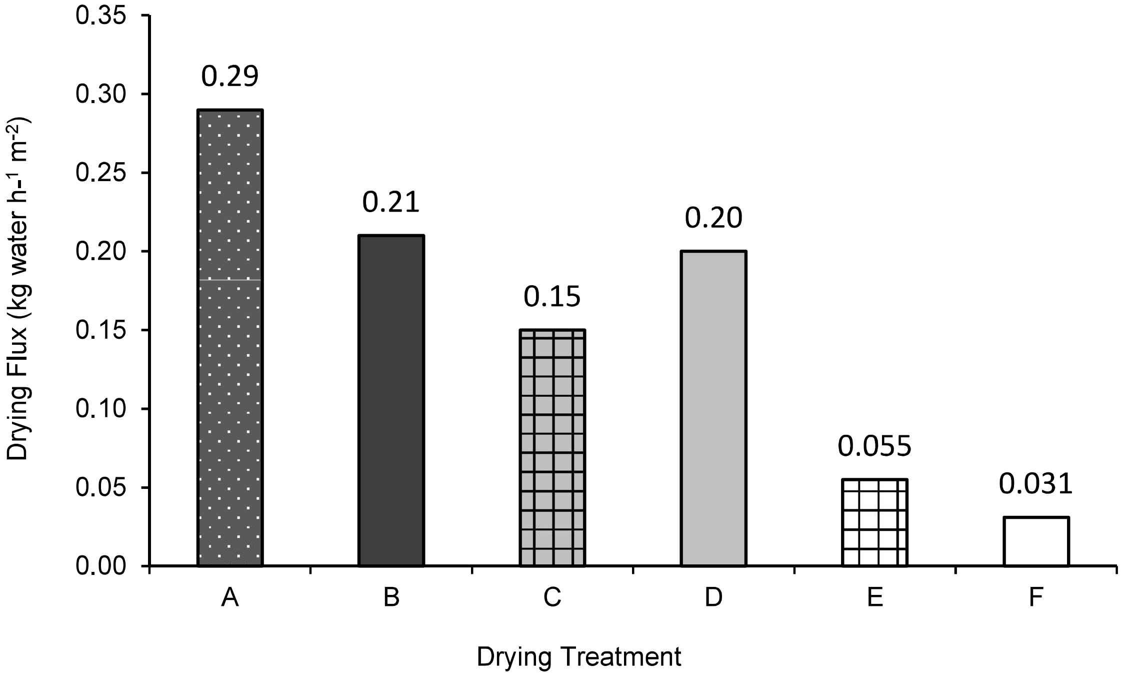


Figure 10
Comparison of drying fluxes in the constant rate drying period period for lemon juice plus sucrose solutions (27.1°Bx) dried with different drying treatments. A: no solar + convection (51.6°C, 7.5%RH, 1.8 m/s), B: no solar + convection (40.9°C, 13.9%RH, 1.8 m/s), C: solar (620 W/m^2) + convection (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).

This result motivates the use of a solar dryer. Since adequate drying fluxes can be achieved at both 40.9°C and 51.6°C (13.9% and 7.5% relative humidity, respectively) without direct irradiation, as shown in Figures 10, the option of using an indirect solar dryer is promising and has potential benefits over a direct solar dryer design. An indirect solar dryer is beneficial since the temperature inside the dryer is theoretically easier to control and there is no risk of photo-oxidation of the product. The drying conditions chosen for the experiments presented in section 5.3 were therefore based on what could be realistically achieved in an indirect solar dryer.

5.2 Evaluation of the possible effects of internal mass transport on food safety

The food safety aspects of the SAP process are one of the main focuses and challenges of this research. The SAP technique has the potential to create shelf-stable dried fruit products with water activities below 0.7 (Paper I). If some parts of the product have water activity above 0.7, this poses a food safety risk. A supported SAP pouch was used to investigate the possible effects of internal mass transfer on food safety.

5.2.1 Complex food matrices dried with SAP pouches

In order to assess the suitability of different fruits for the SAP process, drying trials were performed with a number of different types of fruits to determine if a water activity below 0.7 could be achieved without destroying the sensorial properties of the product (e.g. taste, aroma and texture). The aim was also to assess the homogeneity of the drying. The results from the experiments are shown in Figure 11. In this graph, the water activities for various fruits that were dried using SAP pouches are plotted in relation to the final moisture content dry basis achieved (note: sampling was from the middle of the pouch). This graph is a type of "product window" indicating suitable fruits and also drying end points.

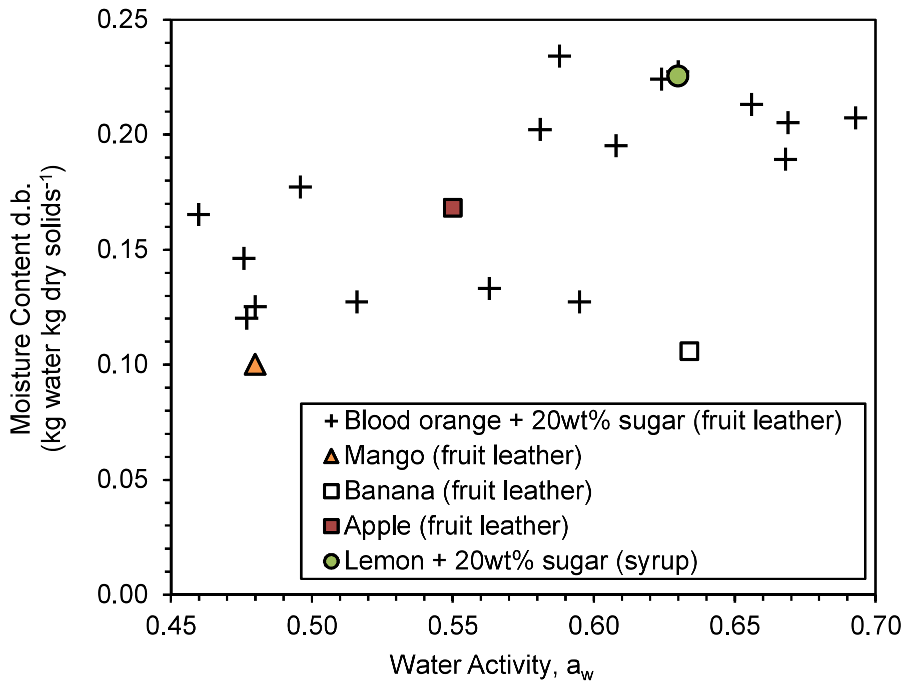


Figure 11
Moisture contents (dry basis) and water activities for different fruits dried with supported SAP pouches showing the various products that could be produced. In the legend, an indication of the texture and form of the final product is given (i.e. fruit leather or syrup).

From Figure 11 it appears that many types of fruits are compatible with SAP pouches. In order to confirm or reject this hypothesis, a visual assessment of the dried products is needed along with a more detailed quantitative look at the distribution of water activity or moisture content in the product during drying.

Figure 12 and 13 show images of banana and apple purée dried with supported SAP pouches. The banana purée formed a crust during drying, which may be related to the high starch content in banana versus 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 13a, 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. In Figure 13b, the final dried product from this experiment is shown. The darker and lighter shaded regions on the dried apple slab indicate that the final product is not completely homogeneous. The edges in particular are lighter and crispier. Moisture content and water activity measurements were taken after 14.8 hours and 16.4 hours of drying for the product shown in Figure 13b with the results shown in Table 3. It can be seen that the standard deviations for moisture content and water activity were very high compared to what was achieved when measuring the initial apple purée. The average value that is reported is an average of measurements that were taken from different locations in the sample, which means the standard deviation in this case represents the variation in moisture content and water activity in different locations of the dried product. It is clear from these results that inhomogeneous drying is a problem. The underlying cause of the problem, however, cannot be confirmed from these initial experiments.

Figure 12
Banana purée dried using a supported SAP pouch with a convection dryer simulating 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.

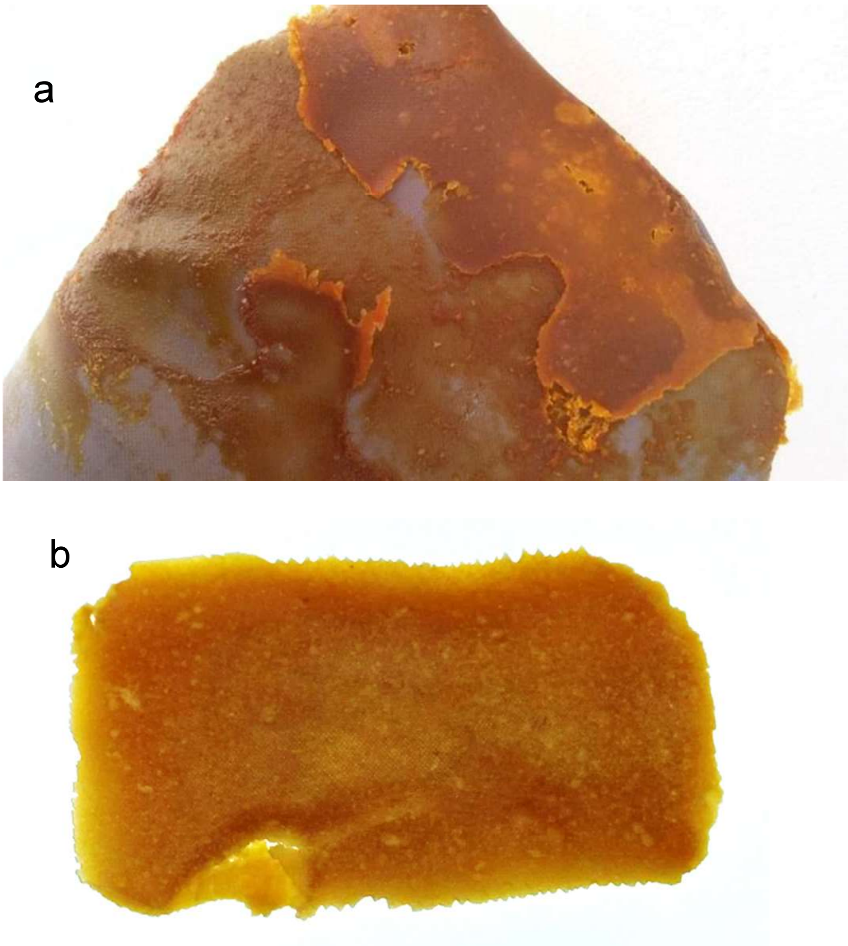


Figure 13
Apple purée dried using a supported SAP pouch with a convection dryer simulating an indirect solar dryer without relative humidity control. The dried form of the purée is more like a fruit “leather”. a: Sample removed after 10 hours of drying. b:Sample removed after 16.4 hours of drying. The 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 cases.

Table 3
Moisture content (wet basis), moisture content (dry basis) and water activity for the initial apple purée and two apple “leathers” produced using supported SAP pouches after 14.8 and 16.4 hours, respectively. The standard deviations indicate how well the water is distributed throughout the sample. 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. The apple leather after 16.4 hours drying is the same shown in Figure 13b (Paper I).

Sample	Moisture content w.b. (%)	Moisture content d.b. (kg water kg dry solids^{-1})	Water activity
Fresh apple purée (Ingrid Marie variety)	85.1 ± 0.0	5.71 ± 0.00	0.99 ± 0.00
Apple leather after 14.8 h drying	25.9 ± 5.1	0.350 ± 0.069	0.78 ± 0.13
Apple leather after 16.4 h drying	14.4 ± 4.3	0.168 ± 0.050	0.55 ± 0.04

5.2.2 Visualising and quantifying inhomogeneous drying

The pouches tested with banana and apple were black and opaque. This made it difficult to observe how the water was distributed inside the pouches during drying without opening the pouches. Neutron radiography was used to obtain a visual image of the mass transport phenomena taking place inside pouches during the drying process. Numerous setups were tried to determine which pouch orientation, pouch size and drying conditions would be optimal to investigate the homogeneous drying problem. Two in particular provided good information.

The first setup involved three narrow vertically oriented pouches each of which was filled with a different fruit juice or purée (see chapter 4 for details about the method). The results for an experiment performed with apple juice, apple purée and banana purée are shown in Figure 14. In this figure, the dark grey colour indicates where the water is located in the samples. The intensity of the darkness indicates the concentration of water at a specific location along its thickness.

Over the course of the 8 hour drying period, the three food matrices exhibit very different behaviours. Due to the vertical orientation of the pouches, gravity cannot be ignored and so the apple juice, being the least viscous of the three substances, collects at the bottom of the pouch as more and more water is evaporated. The banana purée loses the least amount of water of the three substances and the water loss seems to be primarily from the right side of the pouch. The apple purée exhibits behavior similar to the banana purée except that more water appears to have evaporated after 8 hours. In the apple purée and banana purée images at 8 hours, the most important observation to note is that there are local dark spots of varying sizes, which provides visual evidence that uneven drying occurs for viscous substances. Uneven drying may occur if a purée has not been sheared sufficiently. If it is inhomogeneous, local wet spots could develop from localized concentrations of fibers that 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 would need to be done to identify the actual mechanism(s) and their relative contributions to the inhomogeneity. In the second setup, D_2O (i.e. deuterium oxide or heavy water) was injected into a pouch filled with apple purée to observe whether convection or diffusion mass transfer was taking place internally. The results are shown in Figure 15. It can be seen that the D_2O concentration near the injection point decreases with drying time. The D_2O mass appears to spread out slowly and evenly towards the top and bottom of the pouch. The gray value at each pixel along a vertical line was plotted at different time steps (see Figure 15).

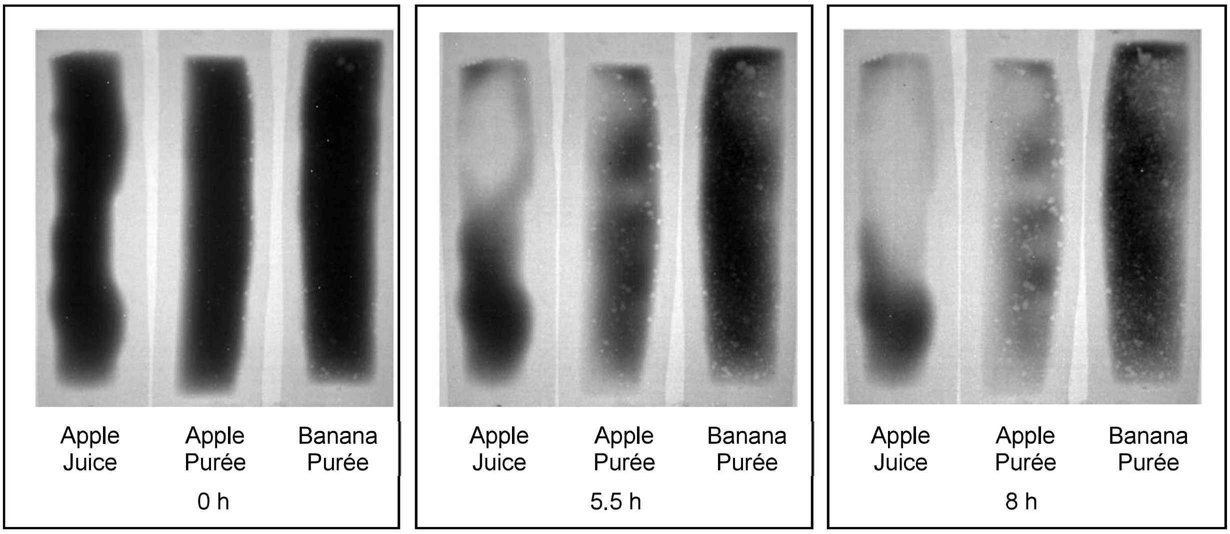


Figure 14
Neutron radiography images for the drying of vertical pouches with three different food matrics: apple juice, apple purée and banana purée. Each pouch had active surface area dimensions of 15 mm x 72 mm x 2 since there are two sides for drying. The dark colour indicates the presence of water molecules.

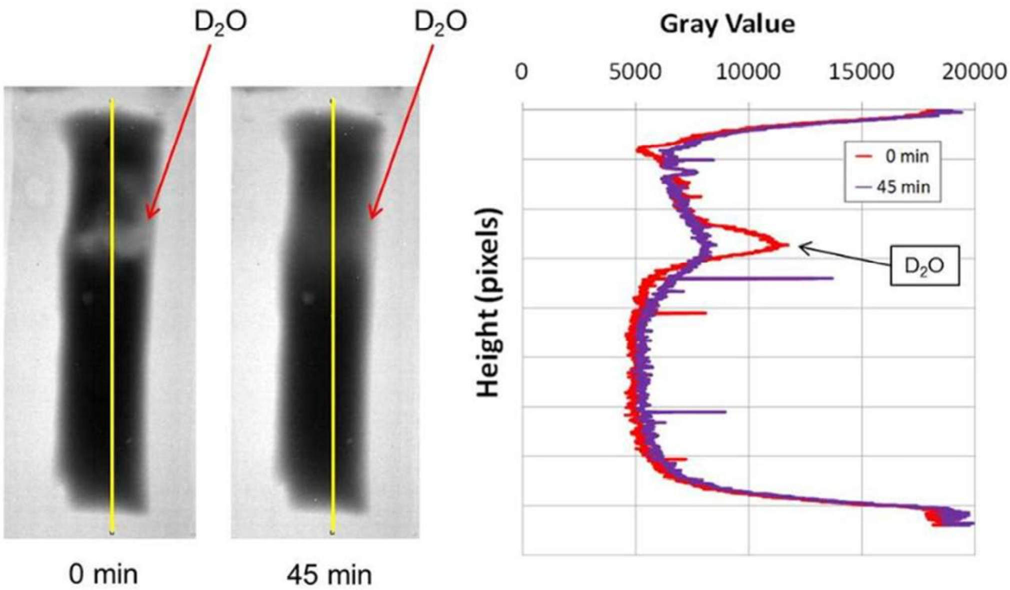


Figure 15
Neutron radiography images for a vertical pouch filled with apple purée (active surface area dimensions 15 mm x 75 mm x 2 since there are two sides for drying) that was injected with D_2O. The gray values along the yellow line were plotted at different time points to see how the D_2O peak changed.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

This was done to observe how the injected D_2O was being transported inside the pouch. At time zero, a peak was observed 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 most likely dominated by diffusion. 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 convective mass transfer inside the pouch. The D_2O experiment has not yet been performed with less viscous fruit juices to investigate this convection hypothesis but it is recommended to conduct this test in the future.

5.2.3 Compatibility of citrus fruits with SAP pouches

In contrast to fruits like apples and bananas that have significant amounts of fiber and/or starch, citrus fruits, when converted into juices, contain very little fiber on the order of less than 1wt% (Li et al., 2002). They also tend to have lower pH values, which is favourable from a microbiological point of view. Citrus fruits like tangerines and oranges ripen in massive quantities during certain peak periods of the year in many tropical countries and they are susceptible to spoilage as a result of their juicy and soft nature (Affognon et al., 2015). This makes them an ideal candidate for SAP.

Figure 16
Marmalade produced with a supported SAP pouch from clementine juice with 10wt% added sucrose.

To assess the suitability of citrus fruits with SAP pouches, solutions of lemon juice were tested to see if the drying behavior would be homogeneous or not. The results from the drying of a lemon juice solution with added sucrose (initial °Brix of 34.9) are shown in Table 4. It can be seen that the standard deviations are much lower compared to the case with apple purée in Table 4 which shows that drying is more homogeneous. Even after only 10 hours of drying when the water activity was still above 0.78, the lemon juice sample was homogenous (i.e. low standard deviations).

In addition to their preferable drying behavior, concentrated citrus juices are also easier to handle and can be removed from the pouch more easily than a dried fruit bar since the latter can stick to the membrane and damage it during the removal of the dried product. This means pouches used to dry citrus juices are likely to have a longer working life. The end product for a citrus juice is a more viscous and pasty substance compared to when a purée is dried. If sucrose is added before the drying process, a marmalade or syrup can also be produced (see Figure 16). From these initial tests, citrus fruits have shown to be the most promising and most compatible with the SAP technique due to their less-fibrous nature and ability to dry homogeneously.

Table 4

Moisture content (wet basis), moisture content (dry basis), water activity and °Brix for the initial lemon juice + sucrose solution and two concentrated solutions measured after 10 and 19 hours of drying inside supported SAP pouches. The standard deviations indicate how well the water is distributed throughout the sample. The drying conditions were 51.9°C ± 0.2°C, 9.0%RH ± 0.9%RH, and 1.8 m/s ± 0.2 m/s (Paper I).

Sample description	Moisture content w.b. (%)	Moisture content d.b. (kg water kg dry solids^{-1})	Water activity	°Bx
Before drying	64.4 ± 0.0	1.81 ± 0.00	0.98 ± 0.00	34.9 ± 0.2
After 10 h drying	27.1 ± 0.1	0.372 ± 0.001	0.78 ± 0.00	70.9 ± 0.1
After 19 h drying	18.4 ± 0.2	0.225 ± 0.002	0.63 ± 0.00	79.5 ± 0.2

5.3 Quantification of the drying performance and the effects of temperature, relative humidity and air velocity on the drying flux

In section 5.1, it was shown that a solar dryer has the potential to improve the SAP process in terms of drying time. 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 critical design criteria for optimizing the design of an indirect solar dryer specifically 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.

It is important to be able to describe the performance of a drying process either qualitatively or quantitatively. There are many ways to measure drying performance. This research has focused on a quantitative approach in which drying performance is assessed using three criteria described in chapter 4 and in Paper II. The first criterion and second criterion are discussed in the thesis. The third criterion, drying time, will not be discussed in detail in the thesis. A more in depth discussion about the third criterion, drying time, can be found in Paper II.

5.3.1 Relative drying performance of a SAP pouch by comparing pouch flux to a reference case

Drying fluxes were obtained experimentally in Paper II for the open dish and pouch using six different temperatures, two relative humidities and two air velocities. The results are reproduced from Paper II and shown in Table 5. These flux values were then used to express the pouch drying flux as a percentage of the open dish drying flux at the same drying conditions. The results of this analysis are shown in Figure 17. The results show that the pouch flux is 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. This is a notable result since the absolute values of the fluxes changed considerably over this temperature range, as can be seen in Table 5.

Table 5
Experimentally determined drying fluxes for the open dish and pouch reported as average ± standard deviation. Values with the same superscript letter in the same row or column are not significantly different from each other (significance level $p < 0.05$) (Paper II).

Air Velocity ($m\ s^{-1}$)	Air Relative Humidity (%)	Air Temperature (°C)	Average Drying Flux: Open Dish ($kg\ h^{-1}\ m^{-2}$)	Average Drying Flux: Pouch ($kg\ h^{-1}\ m^{-2}$)
0.15 ± 0.09	17.4 ± 2.0	29.8 ± 0.3	0.49 ± 0.01	0.40 ± 0.01
		34.7 ± 0.3	0.59 ± 0.01	0.48 ± 0.01
		39.6 ± 0.3	0.69 ± 0.01	0.53 ± 0.02
0.15 ± 0.09	38.2 ± 2.0	20.2 ± 0.3	0.28^{a} ± 0.01	0.22 ± 0.01
		29.8 ± 0.3	0.36 ± 0.01	0.29 ± 0.01
		34.7 ± 0.3	0.43 ± 0.01	0.34 ± 0.01
		39.6 ± 0.3	0.49 ± 0.01	0.38 ± 0.01
0.39 ± 0.12	17.4 ± 2.0	29.8 ± 0.3	0.57 ± 0.01	0.47 ± 0.02
		34.7 ± 0.3	0.67 ± 0.01	0.55 ± 0.01
		39.6 ± 0.3	0.78 ± 0.01	0.62 ± 0.02
		49.3 ± 0.3	1.07 ± 0.01	0.74 ± 0.01
		53.9 ± 0.3	1.22 ± 0.01	0.81 ± 0.02
0.39 ± 0.12	38.2 ± 2.0	20.2 ± 0.3	0.28^{ab} ± 0.02	0.25^{ab} ± 0.01
		29.8 ± 0.3	0.42 ± 0.01	0.35 ± 0.01
		34.7 ± 0.3	0.48^{c} ± 0.01	0.39 ± 0.01
		39.6 ± 0.3	0.56^{c} ± 0.03	0.45 ± 0.01
		49.3 ± 0.3	0.76 ± 0.02	0.52^{d} ± 0.01
		53.9 ± 0.3	0.89 ± 0.01	0.56^{d} ± 0.02

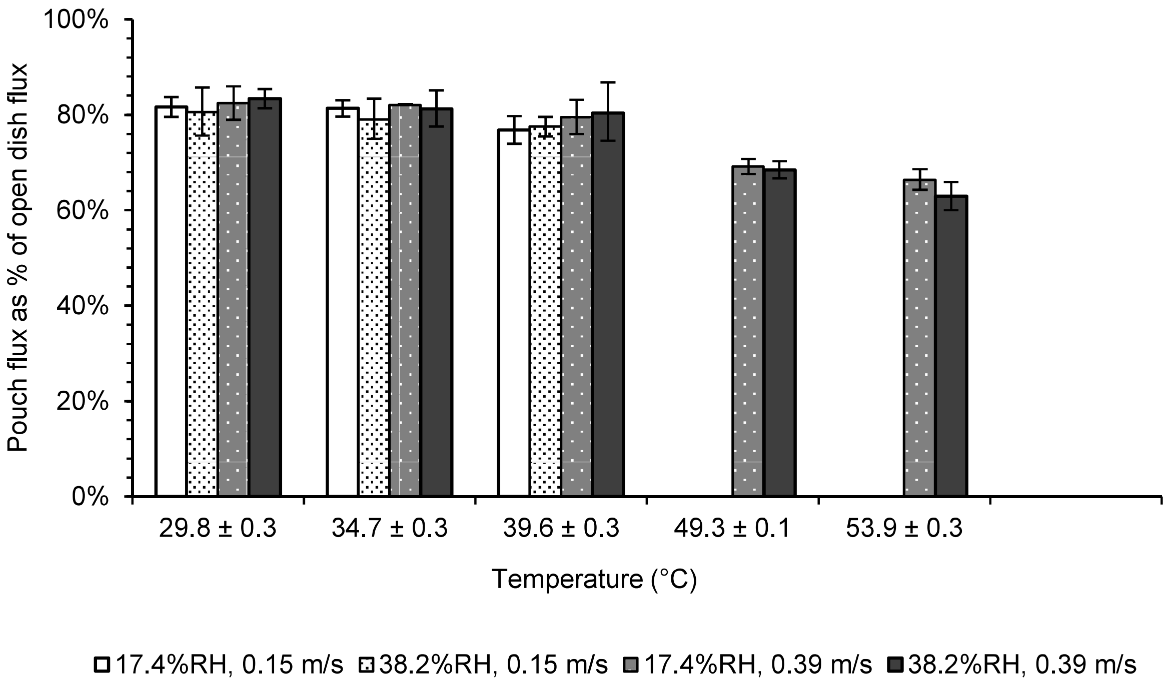


Figure 17
Pouch flux as a percentage (%) of its corresponding open dish flux with the same temperature, relative humidity and air velocity. The standard deviations for the relative humidities and air velocities are: 17.4% ± 2.0%, 38.2% ± 2.0%, 0.15 ± 0.09 m/s and 0.39 ± 0.12 m/s (Paper II).

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, it appears that the pouch flux could no longer increase by the same proportion as the open dish flux, with the relative performance of the pouch decreasing to approximately 66%. As will be shown in the next section, the open dish evaporation flux is limited by the heat transfer to the surface of the open dish whereas the pouch flux is limited by the rate of mass transfer through the membrane, within the operational limits tested in this experiment study (20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity). The results in Figure 17 further support this as they suggest that at higher temperatures, the energy available to the open dish is so great that the drying flux can increase by a substantial amount that is not matched by a substantial decrease in the membrane resistance for the pouch. In terms of performance, the conclusion is that the pouch performance remains at a constant level of 80% up to a certain temperature limit, above which it decreases according to how the convective heat transfer efficiency is improving for the open dish (i.e. for these operational limits: 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity).

5.3.2 Evaluation of the rate limiting phenomena

The apparent convective mass transfer coefficients (k_m) were calculated using equation (2) and the experimental drying fluxes shown in Table 5. The influence of temperature, relative humidity and air velocity on the convective mass transfer coefficient is illustrated graphically in Figure 18. The trends in this figure make it clear which transport phenomena are limiting the open dish evaporation flux and which are limiting the pouch evaporation flux. k_m for the pouch is not affected by temperature whereas k_m for the open dish is strongly dependent on temperature, especially at a higher air velocity of 0.39 m/s. This finding further supports the discussion in section 5.3.1 that claims that the open dish flux is strongly correlated to temperature. For both the open dish and pouch, the air velocity also has a statistically significant effect on k_m, with increasing air velocity resulting in higher k_m values. The statistical significance of these effects on k_m was confirmed in Paper II. In terms of what is limiting the evaporation process, for the open dish, the evaporation is heat transfer limited but also affected by the thickness of the boundary layer which seems to decrease with increasing air velocity. The pouch evaporation flux is not limited by heat transfer but instead by the rate at which water can pass through the membrane, or in other words, the membrane resistance. The thickness of the pouch boundary layer also seems to play a small role, with higher air velocities increasing both the convective mass transfer coefficient and the resulting drying flux.

Two main remarks can be made from these results. The first is related to the design of an indirect solar dryer. Since the rate limiting phenomena are different for the two containers, a solar dryer optimised for an open dish may not perform as well for a pouch, depending on the operating conditions. An indirect solar dryer for a SAP pouch operating within the ranges tested by this experiment (i.e. 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity) should allow for high air velocities and low air relative humidities. The temperature indirectly affects the drying flux since it affects the air relative humidity. It also reflects the energy content of the air. As long as the minimum energy required for the latent heat of evaporation is present in the air, the results mentioned above should apply. Therefore depending on the desired drying temperature, a calculation should be done to check if the latent heat requirements are met. If not, the pouch flux is not just limited by mass transfer but heat transfer as well.

A second remark relates to the nomenclature that has been used in this research. For the open dish case, the term "apparent convective mass transfer coefficient" has been used appropriately as it is referring to the convection mass transfer of water vapour from the open dish surface to the air. For the pouch, the term represents a lumped value corresponding to the sum of two mass transfer coefficients: the external convective mass transfer coefficient (similar to the open dish case) and the membrane mass transfer coefficient (assumed to be equal to the inverse of the membrane resistance). Since it is now known that the pouch drying flux is controlled mainly by the membrane resistance and not by the external convective mass transfer, it seems like a misnomer to refer to the membrane mass transfer coefficient as the convective mass transfer coefficient. No changes to the nomenclature will be made in this thesis but the use of a more appropriate term will be considered in future work.

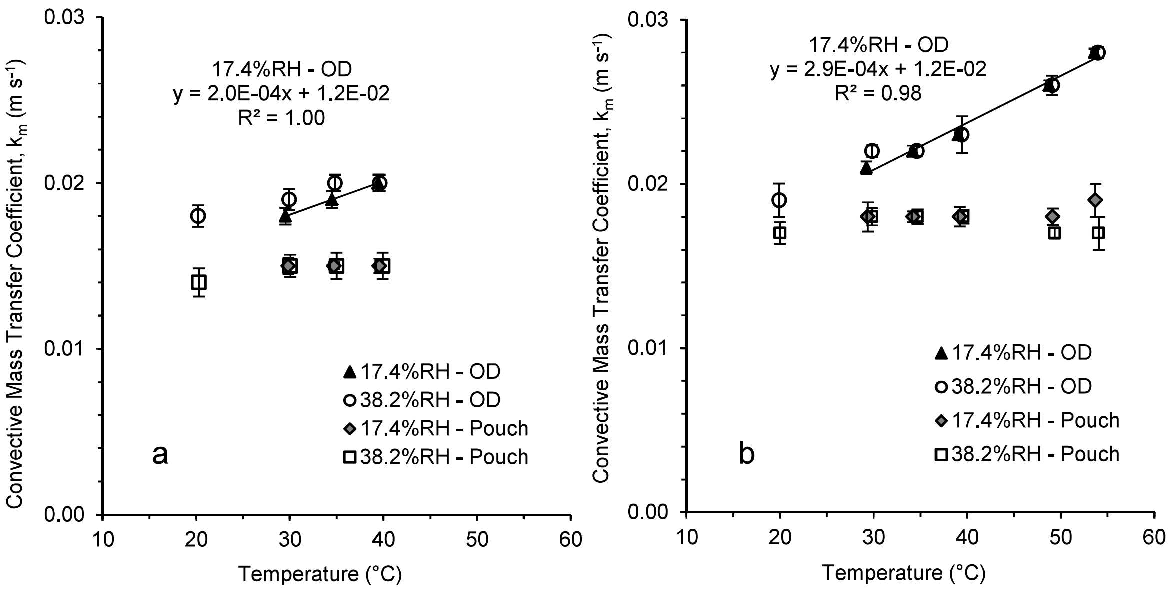


Figure 18
Convective mass transfer coefficient (k_m) as a function of temperature for the two relative humidities and two containers studied (OD = open dish). a: 0.15 ± 0.09 m/s, b: 0.39 ± 0.12 m/s (Paper II).

5.3.3 Coupling effects and driving forces

Coupling effects are seen everywhere in nature. Some examples are thermochemical, thermoelectric and photochemical. If coupling effects are present, they may be synergistic or inhibitory. In a drying process, multiple factors may influence the drying flux at the same time and it can be difficult to assess the relative importance of each factor and how the factors interact together unless a study is properly designed that allows for the factors to be “decoupled”. The experimental method that was developed as part of this research made it possible to conduct experiments where the temperature, relative humidity and air velocity could each be independently controlled. As a result, the coupling effects could be investigated and quantified.

Coupling effects were first investigated in this work by examining the slopes of two-dimensional plots with drying flux as a function of temperature for constant relative humidity and air velocity. The plots are presented in Figure 19 and the accompanying slopes in Table 6. Slopes can be compared between two data sets if one factor has been varied. If the trendlines for the two datasets are parallel (i.e. equal slopes), there is no coupling effect; if the trendlines diverge, there is a synergistic coupling effect; and if the trendlines converge there is an inhibitory coupling effect.

In Figures 19a and 19b, all trendlines show that drying flux increases with increasing temperature for a constant relative humidity. 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 20 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 slope are the same no matter what 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 20 for the two different relative humidities are different and diverging as temperature increases. The same effect can be seen in Fig 19a and 19b, and Table 6 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, 0.027 and 0.018 kg h^{-1} m^{-2} $°C^{-1}$, respectively. Without looking at Figure 20, one might conclude from Figure 19 that because the 17%RH and 38%RH trendlines

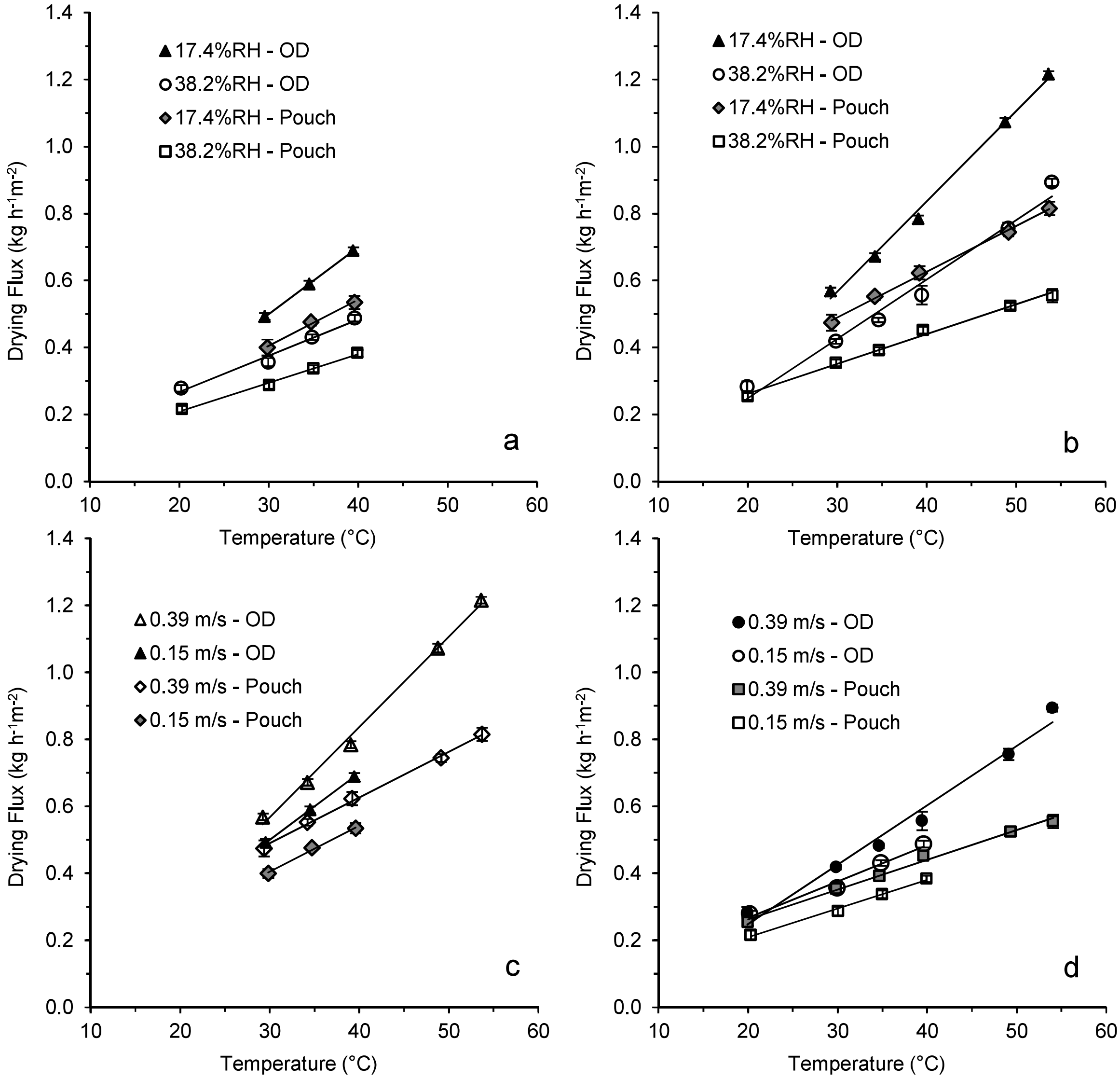


Figure 19
Drying flux as a function of temperature for the open dish (OD) and pouch for constant relative humidities (a and b) and constant air velocities (c and d). a: 0.15 ± 0.09 m/s, b: 0.39 ± 0.12 m/s, c: 17.4 ± 2.0%RH, d: 38.2 ± 2.0%RH (Paper II).

diverge for a given container, there must be a synergistic coupling effect between temperature and relative humidity. However, by then looking at Figure 20, it becomes apparent that the divergence observed in Figure 19 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.

The purpose of conducting this analysis with Δp as a function of temperature is to show that one needs to be cautious about making coupling effect conclusions 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 determine the temperature and air velocity. However, because relative humidity is a relative value, it is more appropriate to compare driving forces with Δp.

Table 6
Summary of the slopes, y-intercepts and R^2 values from the linear regressions performed on the data displayed in Figure 19 where the independent variable is temperature (Paper II).

Type of Container	Relative Humidity (%)	Air velocity ($m\ s^{-1}$)	Slope ($kg\ h^{-1}\ m^{-2}\ °C^{-1}$)	y-intercept ($kg\ h^{-1}\ m^{-2}$)	R^2
Open dish	17.4 ± 2.0	0.15 ± 0.09	0.020	-0.096	1.00
Open dish	17.4 ± 2.0	0.39 ± 0.12	0.027	-0.24	1.00
Open dish	38.2 ± 2.0	0.15 ± 0.09	0.011	0.050	0.98
Open dish	38.2 ± 2.0	0.39 ± 0.12	0.018	-0.11	0.98
Pouch	17.4 ± 2.0	0.15 ± 0.09	0.014	-0.0081	0.99
Pouch	17.4 ± 2.0	0.39 ± 0.12	0.014	0.080	1.00
Pouch	38.2 ± 2.0	0.15 ± 0.09	0.0085	0.039	0.99
Pouch	38.2 ± 2.0	0.39 ± 0.12	0.0089	0.085	0.99

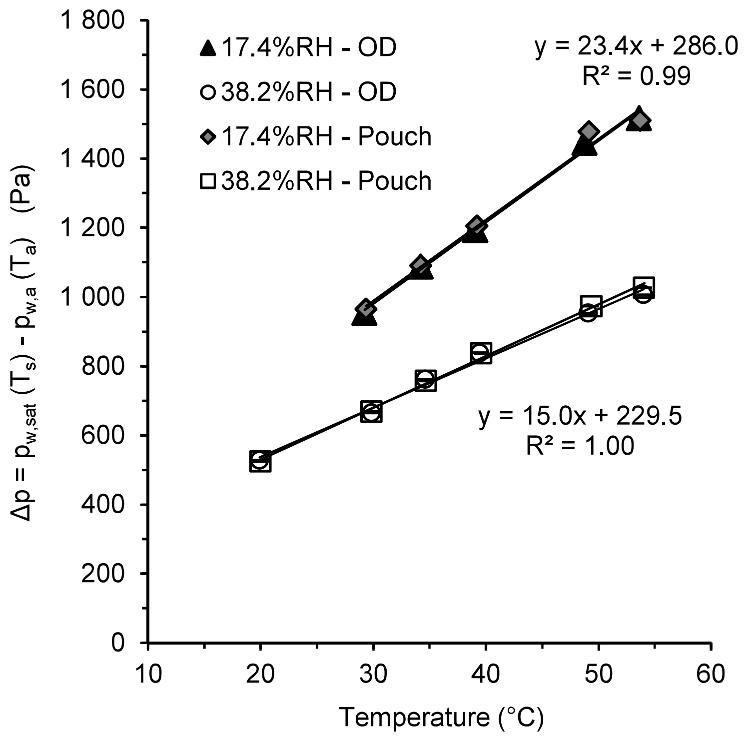


Figure 20
Δp (i.e. difference in water vapour partial pressure between the inner surface of the membrane and the bulk air) as a function of temperature for two relative humidities.

5.3.4 Two-level multifactorial analysis to confirm coupling effects and derive regression equations

A way to quantify coupling effects is by using a two-level multifactorial analysis. With this approach, a number of factors (or independent variables) are selected to be investigated and then each factor is assigned two values that have the categorical names *high* or *low*. In this research, three factors were selected (i.e. temperature, relative humidity and air velocity) which meant that there were eight different treatment possibilities. A summary of the drying fluxes for these eight treatments is shown in Table 7. The factor value and output value (i.e. drying flux) were then fitted to a regression model by first calculating the *effect* of each factor on its own as well as the interaction *effects* describing how two independent variables or factors created either a positive or negative effect on the output variable. The *effects* may or may not be significant so statistical testing was performed to confirm the significance. Full details of the approach and results are found in Paper II.

The result that will be focused on in this discussion is the regression model equation. The regression equation that was obtained for the pouch is shown in Table 8. The coefficient of determination is close to one which indicates that the model accounts for nearly 100% of the total variation between the independent variables and the output variable. To show how good the fit is, Table 9 shows how the predicted drying flux with the regression equation compares to the measured drying flux. As can be seen, the estimates by the model are excellent with no more than 2.2% error for the eight predictions made. This type of regression equation is very useful since it provides one equation for the output variable that can easily be used to predict drying fluxes as a function of three variables for cases not tested (note: the predictions should only be done with interpolated values not extrapolated values).

The next phase of the research will focus on developing mathematical models to optimise the drying process and so this regression model approach will be used when creating the models. Besides the benefit of output variable prediction, the second benefit is obtaining quantitative and statistically verified proof that a coupling effect exists. The coupling effects are represented by the interaction *effects* in the regression equation. For these experiments, the coupling effect between temperature and relative humidity was significant and could not be ignored. The coupling effect is represented by β_{12} in Table 8. This further supports the results in section 5.3.3. The difference, however, between relative humidity and Δp should be considered when interpreting β_{12}.

Table 7
Factor levels used for the eight treatments and the resulting drying fluxes (open dish and pouch) for each treatment. The *high* factors are coloured grey (Paper II).

Factor			Pouch average drying flux (kg h^{-1} m^{-2})
a Temperature (°C)	b Relative Humidity (%)	c Air Velocity (m s^{-1})	
29.8	17.4	0.15	0.40
39.6	17.4	0.15	0.53
29.8	38.2	0.15	0.29
29.8	17.4	0.39	0.47
39.6	38.2	0.15	0.38
39.6	17.4	0.39	0.62
29.8	38.2	0.39	0.35
39.6	38.2	0.39	0.45

Table 8
Coefficients with significance for the regression model (see equation (3)) obtained for SAP pouches dried within these operational limits: 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity (Paper II).

β_o	β_1	β_2	β_3	β_{12}	R^2
0.44	0.059	-0.069	0.036	-0.011	0.997

Table 9
Comparison of the experimental pouch drying fluxes with the pouch drying fluxes predicted using the regression model in equation (3) with the coefficients in Table 8.

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
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%

6. Conclusions

The overall aim of this research is to develop a safe and practical fruit preservation technology that is suitable for rural and remote areas of developing countries. This licentiate thesis presented the technology under development which has been termed Solar Assisted Pervaporation (SAP). Three objectives related to the overall aim were discussed in this thesis. The resulting outcome for each objective is presented below.

Investigate the drying time and influencing parameters under realistic drying conditions with model substances (Paper I)

Realistic drying times (i.e. a maximum of 2 to 3 days assuming 8 hours of active solar drying each day) were obtained from initial screening experiments using an indirect solar dryer simulator without relative humidity control. Typical drying behavior was observed with constant drying in the beginning followed by falling rate periods. Drying flux decreased with increasing °Brix in the starting juice. When the same type of membrane pouch was tested under a solar lamp, drying flux was found to increase linearly with increasing irradiation. Drying with the solar lamp was then tested with and without forced air convection. The presence of the forced convection reduced the drying flux since the cooler air passing over the pouches was able to convect heat away from the pouch surface thereby reducing the amount of energy available for the latent heat of evaporation. Drying without radiation with air conditions 40.9°C, 13.9% relative humidity and 51.6°C, 7.5% relative humidity showed comparable drying fluxes to drying with a solar simulating lamp with irradiation of 620 W/m^2 and no forced convection. These results indicate that a solar dryer can significantly improve the drying performance of the pouches and if an indirect solar dryer is used, the harmful effects of photo-oxidation can be avoided.

Evaluate the possible effects of internal mass transport on food safety

Additional tests with an indirect solar dryer simulator without relative humidity control showed that viscous, fibrous or starchy fruit purées experience uneven drying and in some cases develop a crust that prevents the middle of the purée from drying. Neutron radiography imaging was used to visualize the mass transport phenomena inside the pouch during drying. For the apple purée and banana purée, local wet spots were formed during drying whereas no such wet spots could be observed for the apple juice case. By injecting D_2O into a vertical pouch of apple purée, the mechanism by which the D_2O mixed with the remainder of the purée could be observed. The disappearance of the D_20 appeared to be by diffusion and so to confirm this, the gray values in the radiography image obtained were plotted as a function of height along the pouch. A noticeable peak was present at the D_2O injection site. By analyzing images at specific time intervals, it could be confirmed that the peak did not translate up or down but instead lessened in intensity at a gradual rate during the drying process. This indicates diffusion mass transfer was present for water vapour transported though the apple purée. It was concluded that viscous purées and juices/ purées with high amounts of fiber or starch introduce complications into the system and increase the food safety risk. Due to these food safety risks and the fact that tangerines and oranges are widely available in Mozambique and also have high spoilage rates, it was decided that the focus would remain on citrus juices.

Quantify the drying performance and decouple the effects of temperature, relative humidity & air velocity on drying flux (Paper II)

Since SAP is a complex process involving simultaneous heat and mass transfer from two sides of a pouch that shrinks while it dries, a method was needed to be able to isolate different heat and mass transfer modes and decouple the various independent variables. A climate-controlled cabinet was used to construct an apparatus and develop a statistically repeatable method for measuring the drying flux of water from a container (i.e. open dish or SAP pouch). The method was used to assess the drying performance of the pouch at different temperatures, relative humidities and air velocities. A two-level factorial analysis was used to decouple the effects of the three input variables. An interaction effect between temperature and relative humidity was significant. The rate limiting step for evaporation for the open dish was found to be the convective heat transfer from the air to the surface of the dish. For the pouch, it was found to be the membrane resistance. The drying flux for both containers was positively influenced by air velocity. These results imply that an indirect solar dryer designed for SAP pouches within the operational limits tested in this study (20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity) should focus on (1) establishing large differences in the water vapour partial pressure between the inner surface of the membrane and the air, and (2) a high and controllable air velocity, assuming that the energy content of the air meets the requirements for the latent heat of evaporation.

The following overall conclusions can be made by comparing the outcomes of each objective:

- Homogeneous drying is strongly dependent on the type of fruit and its composition. If a juice or purée is viscous (e.g. due to a high fiber or starch content), there will likely be a strong effect on the diffusion of water inside the product to the inner surface of the membrane.
- Since the lumped apparent convective mass transfer coefficient of water from the inner surface of the membrane to the bulk air surrounding the pouch is not dependent on temperature over the range of conditions studied (i.e. 20.2°C to 53.9°C, 17% to 38% relative humidity, 0.15 to 0.39 m/s air velocity) but instead dependent on (1) the water vapour partial pressure difference between the inside of the membrane and the bulk air (Δp) and (2) air velocity, the mass flux of a SAP pouch could be controlled by regulating Δp and air velocity in an indirect solar dryer.
- The presence of crust formation and uneven drying in the fruit juice/ purée suggests that the mass flux of water in the juice/purée is rate limiting, or in other words, the rate at which the water is diffusing to the inner surface of the membrane is less than the rate at which the water is able to diffuse through the membrane into the bulk air. If the mass flux of water diffusing through the membrane could be reduced in a controlled way, this may prevent or slow down the onset of crust formation.
- It can therefore be hypothesized from these results that crust formation and uneven drying could potentially be controlled by using an indirect solar dryer and regulating the Δp and air velocity. If Δp is reduced (e.g. by increasing the relative humidity), this would reduce the mass flux of water vapour through the membrane to the bulk air. If the air velocity is reduced, this would lower the lumped apparent convective mass transfer coefficient k_m and also reduce the mass flux through the membrane to the bulk air. By reducing this mass flux and preventing crust formation, it is possible that the overall drying time could actually be reduced since the drying flux would be decreasing at a slower rate than if a crust was present. Even if the drying time is not less but still comparable, the end result would be a safer and higher quality final dried product.

7. Recommendations and Next Steps

This licentiate thesis is part of a doctoral research project that will continue for two and a half more years. The overall aim of the research will remain the same during the next phase of the project. The first three objectives have been addressed in this thesis and so a new set of objectives for the next phase are needed.

The main recommendation that has come out of the thesis is to investigate if it is possible to control the evenness of the drying and the crust formation by regulating the relative humidity and air velocity of an indirect solar dryer. To confirm this, experiments with higher air velocities and actual fruit samples are recommended.

Other possible objectives to explore are:

- Evaluate if solution-diffusion theory from sweep gas pervaporation can be applied to SAP.
- Quantify drying performance with the experimental method developed in this study for real food matrices.
- Apply a two-level factorial design to a four factor model for inputs of temperature, relative humidity, air velocity and irradiance.
- Decouple the effects of water activity and viscosity on the drying flux in the falling rate period. Identify if the falling rate periods are due to a decrease in driving force, a decrease in the diffusivity of water in the fruit, or a combination of both.
- Develop a mathematical model to optimise the process based on the controllable parameters of the solar dryer and the intrinsic properties of the food matrix. Investigate delaying crust formation by using this model.
- Conduct a risk assessment on the juice making and drying processes to identify the critical control points and if additional heat treatments are required. Apply food safety risk modelling to the SAP process to be able to predict the risks associated with different treatment options.

In addition, it is aimed to complete the following multi-disciplinary objectives with the help of other institutions:

- Optimise the design of the membrane pouch
- Optimise the design of the solar collector
- Test optimised pouch & solar collector designs with farmers associations in Mozambique through a Participatory Rural Appraisal approach

Acknowledgements

I would first like to acknowledge the Swedish Research Council for providing the funding for this doctoral project (VR grant number Dr.n. 2013-6290).

Thank you to all of my friends, family and colleagues who have been there to support me throughout the first half of the PhD. Your words of encouragement motivate me in ways that I can't explain in words.

Also a very big thank you to

- Dan Johansson from the Department of Food Technology for all of the help with ordering the equipment and your continuous help in the lab.
- Henrik Davidsson and Ricardo Bernardo from Energy and Building Design, Lund University for helping us with the experiments in Paper I. The solar lamp really saved us!
- Pia Otte for your hard work and dedication to this project. You bring a wonderful and new perspective to our work.
- Lucas Tivana (my supervisor from Eduardo Mondlane University in Maputo, Mozambique) and Anabela Chambule for taking care of me in Mozambique and making me feel like a part of your family.
- Petr Dejmek (former supervisor) for always double checking that I know what I am talking about. I enjoy the intellectual challenge.
- Ingegerd Sjöholm (supervisor) for always coming to every meeting with a smile and a bunch of energy. You have a great ability to motivate people.
- Marilyn Rayner (supervisor) for always having my back. Thanks for all the great talks and bringing my energy level up when it starts to sink.
- Thijs Defraeye and Dominique Derome from Empa and Peter Vontobel from Paul Scherrer Institue (PSI) for giving me the opportunity to include neutron radiography and topography in my research. I hope we can continue to work together in the future.
- Smart Textiles, Textilhögskolan in Borås and Swerea IVF for the assistance with identifying, obtaining and testing suitable fabrics and membrane films.
- Paula Leckius and the Mediatryck team for being so calm and efficient when the deadline was near. You are all amazing!

References

Affognon, H., Mutungi, C., Sanginga, P. and Borgemeister, C. (2015). Unpacking Postharvest Losses in Sub-Saharan Africa: A Meta-Analysis. *World Development*, 66, pp. 49-68.

Food and Agriculture Organization of the United Nations (2011). Global Food Losses and Food Waste – Extent, causes and prevention. [online] Rome. Available at: http://www.fao.org/ [Accessed 25 Jan 2017].

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

Food and Agriculture Organization of the United Nations (2015). The State of Food Insecurity in the World. [online] Rome. Avaialbe at: http://www.fao.org/ [Accessed 15 Mar 2017].

Iglesias, H.A. and Chirife, J. (1982). *Handbook of Food Isotherms: Water Sorption Parameters for Food and Food Components*. New York: Academic Press, pp. 150-151.

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. Oxford: Elsevier Inc., pp. 397-430.

Li, B.W., Andrews, K.W. and Pehrsson, P.R. (2002). Individual Sugars, Soluble, and Insoluble Dietary Fiber Contents of 70 High Consumption Foods. *Journal of Food Composition and Analysis*, 15, pp. 715-723.

Lindner, E., Gyurcsanya, R.E. and Buck, R.P. (2006). Membranes in Electroanalytical Chemistry: Membrane-Based Chemical and Biosensors. In: P. Somasundaran, ed., *Encyclopedia of Surface and Colloid Science*, 2nd ed. , vol 5, New York: Taylr and Francis Group, pp.

Lipnizki, F., Field, R.W. and Ten, P.-K. (1999). Pervaporation-based hybrid process: a review of process design, applications and economics. *Journal of Membrane Science*, 153, pp. 183-210.

Loksin, M. and Mroz, T.A. (2003). Gender and Poverty: A life cycle approach to the analysis of the differences in gender outcomes, Report # WPS3153, October 1 2003

Magaia, T. (2015). *Chemical Analysis to promote the use of Wild Fruits from Mozambique*. PhD. Lund University.

Néel J. (1991). Introduction to Pervaporation, In: R.Y.M. Huang, ed., *Pervaporation membrane separation processes*, Amsterdam: Elsevier, pp. 1-109.

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

Olsson, J. and 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, pp. 107-115.

Olsson, J., Trägårdh, G. and 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), pp. 1199-1223.

Pangarkar, V.G. and 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., Boca Raton: CRC Press.

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

Rajagopalan, N. and Cheryan, M. (1995). Pervaporation of grape juice aroma. *Journal of Membrane Science*, 104, pp. 243-250.

Saravacos G.D., and Kostaropoulos, A.E. (2002). *Handbook of Food Processing Equipment*, New York: Kluwer Academic/Plenum Publishers.

Shepherd, A., Habert, A.C. and Borges, C.P. (2002). Hollow fibre modules for orange juice aroma recovery using pervaporation. *Desalination*, 148, pp. 111-114.

Singh, R.P. and Heldman, D.R. (2014). *Introduction to Food Engineering*. San Diego: Academic Presss, pp. 675-708.

Sodha, M.S. and Chandra, R. (1994). Solar Drying Systems and Their Testing Procedures: A Review. *Energy Conversion and Management*, 35(3), pp. 219-267.

Tamhane, A.C. (2009). *Statistical Analysis of Designed Experiments: Theory and Applications*. Hoboken: John Wiley & Sons, pp. 256-299.

USDA (2011). Feed the Future Mozambique FY 2011-2015 MultiYear Strategy. [online] Available: www.feedthefuture.gov [Accessed 5 Feb 2017].

U.S. Government (2012). Feed the Future- Mozambique Fact Sheet [online] U.S. Gov. Global Hunger & Food Security Initiative. Available at: https://www.feedthefuture.gov/ [Accessed 26 Nov 2016].