Technology
Arts Sciences
TH Köln

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

FACULTADES DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA

PROGRAMAS MULTIDISCIPLINARIOS DE POSGRADO EN CIENCIAS AMBIENTALES

AND

TH KÖLN - UNIVERSITY OF APPLIED SCIENCES

INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS

PARTICIPATIVE DEVELOPMENT OF A SUSTAINABLE VANILLA POD DRYER FOR SMALL SCALE VANILLA PRODUCERS IN THE HUASTECA POTOSINA, MEXICO

THESIS TO OBTAIN THE DEGREE OF

MAESTRÍA EN CIENCIAS AMBIENTALES

DEGREE AWARDED BY UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

AND

MASTER OF SCIENCE

NATURAL RESOURCES MANAGEMENT AND DEVELOPMENT

DEGREE AWARDED BY TH KÖLN – UNIVERSITY OF APPLIED SCIENCES

PRESENTS:

CLEMENS GERHARD BRAUER

CO-DIRECTOR OF THESIS PMPCA

PROF. DR. HUMBERTO REYES HERNÁNDEZ

CO-DIRECTOR OF THESIS ITT

PROF. DR. RAMCHANDRA BHANDARI

ASSESSOR:

DIPL.-VOLKSW. STEFFEN ROLKE

COLOGNE, GERMANY 11.09.2017

Technology
Arts Sciences
TH Köln

PROYECTO CO-FINANCIADO POR:

ITT

PROYECTO REALIZADO EN:

ITT

PMPCA

FACULTAD DE CIENCIAS SOCIALES Y HUMANIDADES

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

CON EL APOYO DE:

CONSEJO NACIONAL DE CIENCIA Y TECNOLOGÍA (CONACYT)

CENTERS FOR NATURAL RESOURCES AND DEVELOPMENT (CNRD)

LA MAESTRÍA EN CIENCIAS AMBIENTALES RECIBE APOYO A TRAVÉS DEL PROGRAMA NACIONAL DE POSGRADOS

(PNPC - CONACYT)

Technology
Arts Sciences
TH Köln

Erklärung / *Declaración*

Name / *Nombre*: Clemens Gerhard Brauer

Matrikel-Nr. / *N° de matricula*: 11110462 (TH Köln), 255961 (UASLP)

Ich versichere wahrheitsgemäß, dass ich die vorliegende Masterarbeit selbstständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten und nicht veröffentlichten Schriften entnommen sind, sind als solche kenntlich gemacht.
Aseguro que yo redacté la presente tesis de maestría independientemente y no use referencias ni medios auxiliares a parte de los indicados. Todas las partes, que están referidas a escritos o a textos publicados o no publicados son reconocidas como tales.

Die Arbeit ist in gleicher oder ähnlicher Form noch nicht als Prüfungsarbeit eingereicht worden.
Hasta la fecha, un trabajo como éste o similar no ha sido entregado como trabajo de tesis.

Köln, den /*el* 11.09.2017
Unterschrift / *Firma*: ______________

Ich erkläre mich mit einer späteren Veröffentlichung meiner Masterarbeit sowohl auszugsweise, als auch Gesamtwerk in der Institutsreihe oder zu Darstellungszwecken im Rahmen der Öffentlichkeitsarbeit des Institutes einverstanden.
Estoy de acuerdo con una publicación posterior de mi tesis de maestría en forma completa o parcial por las instituciones con la intención de exponerlos en el contexto del trabajo investigatición de las mismas.

Unterschrift / Firma: __________________

Technology Arts Sciences
TH Köln

Master Thesis:

Participative Development of a Sustainable Vanilla Pod Dryer for Small Scale Vanilla Producers in the Huasteca Potosina, Mexico

Author: Clemens Gerhard Brauer

Co-Director (UASLP): Prof. Dr. Humberto Reyes Hernández

Co-Director (ITT): Prof. Dr. Ing. Ramchandra Bhandari

Assessor: Dipl. Volksw. Steffen Rolke

Acknowledgements

I thank my parents Gabriela and Hans-Jochen for not only their mental support during my studies. Without you, these studies would have been much more complicated.

I am extremely grateful to my girlfriend Jasmin Lechuzita for her comments, her grammar-check-skills, making lunch and for her talent in calming me down in hours of stress.

Muchas gracias to my fellow ENREM students, Cecilia, Daniela, Alina, Santiago, Dimitri and all the others who helped me out with translations, information that I almost missed, notes of field trips, or just for drinking a beer with me when I needed one.

Einen fetten Dank to my brothers Markus and Jörg and my friends Shumba, Jens and Murz for visiting me in Mexico and bringing a little piece of home.

I thank my co-directors Prof. Dr. Humberto Reyes Hernández and Prof. Dr. Ing. Ramchandra Bhandari, as well as my assessor Dipl.-Volksw. Steffen Rolke for their ideas, advice and solar irradiation data.

I cordially thank Ms. Karina Lizbeth Trinidad for all her help in organising the workshops and being my intermediary in the contact with the vanilla producers.

I say tlaskamati miak to the vanilla producers who participated in the project for their patience, enthusiasm, explanations, suggestions, criticism, and jokes: Doña Viky, Maestra Cándida, Don Jacobo, Don Emilo, Don Fernando, Don Benito, Los Perfectos and all the others.

Many thanks also to Prof. Dr. Javier Fortanelli Martínez, Ing. Jean, Prof. Dr. Marcos Algarra Siller of the UASLP Faculty of Engineering, Prof. Dr. Alfonso Lastras Martínez, and Maestra Luz María Nieto Caraveo for supporting me with advice, instruments and recommendation letters.

I say thank you very much also to Prof. Dr. Matthias Hochgürtel, M.Sc. Eva Rausch and Dipl. Ing. Marcus Schief of the Faculty of Applied Natural Sciences of the TH Köln, for the HPLC analysis.

Contents

List of Figures

List of Tables

Glossary

Definitions and Abbreviations

Centro de acopio: English: Supply Centre – Location where vanilla pods are collected and cured

LPG: Liquid propane gas

MXN: Mexican Peso

Vanilla growers: Spanish: Productores de vainilla - persons who cultivate and harvest vanilla and sell the ripe green pods to the "centro de acopio"

Vanilla producers: Spanish: Beneficiadores de vainilla - persons working in the "centro de acopio" and in charge of the vanilla curing process. This also includes vanilla growers curing their own vanilla

Vanilla drying: The process of reducing the vanilla pods' humidity moisture content from the initial ca. 0.83 to the ca. 0.35 of the product.

Vanilla curing: The process of turning the ripe green vanilla pods into a flavourful marketable product. This includes drying (insolation) as well as killing, sweating and conditioning.

Nahuatl: One of the many indigenous languages spoken in Mexico. It was spoken by the Aztecs and still is in many regions, including parts of the Huasteca Potosina.

Normal: In a three-dimensional space, the normal of a surface is a line planted in a right angle on it.

Symbols

A	:	surface [m^2]
β	:	tilt angle
C	:	heat capacity [kJ/kg K]
db	:	dry base
δ	:	declination angle
Δ	:	change
E	:	efficient irradiation [Wh/m^2]
E	:	emissivity
f	:	free moisture content
f_c	:	free moisture at the critical moisture content
G_{sc}	:	solar constant (1367 W/m)
γ	:	azimuth angle
h_c	:	convective heat flow coefficient [W/m2K]
h_r	:	radiation heat flow coefficient [W/m2K]
I	:	irradiation [Wh/m^2]
I_{on}	:	normal irradiation outside the atmosphere [Wh/m^2]
I_{df}	:	diffuse irradiation [Wh/m^2]
I_{dr}	:	direct irradiation [Wh/m^2]

λ_s	:	latent heat of evaporation
L_{loc}	:	local meridian
L_{st}	:	standard meridian (for local time)
m	:	total mass of product [kg]
m_1	:	initial total mass of product [kg]
m_w	:	mass of water in the product [kg]
m_d	:	mass of dry matter in the product [kg]
m_e	:	evaporated mass [kg]
mA	:	drying factor m multiplied with the surface of the drying good A
μ	:	efficiency
v	:	drying rate
v_c	:	drying rate in the constant period
v_f	:	drying rate in the falling period
φ	:	latitude angle
ω	:	hour angle
q	:	heat flow [W]
Q	:	heat quantity [J][Wh]
Q_e	:	heat quantity for evaporation [J][Wh]
Q_{heat}	:	heat quantity for heating [J][Wh]
σ	:	Stefan-Boltzmann-Constant $=5.6697 \times 10{-}8$ W/m^2 K^4
t	:	Time of Drying [h]
t_c	:	Time of Drying in the constant rate period [h]
t_f	:	Time of Drying in the falling rate period [h]
T	:	Temperature [°C]
T_d	:	dry bulb temperature [°C]
T_w	:	wet bulb temperature [°C]
Θ	:	incidence angle
wb	:	wet base
x	:	decimal moisture content wet basis (wb)
X	:	decimal moisture content dry basis (db)
X_1	:	initial moisture
X_c	:	critical moisture content
X_e	:	equilibrium moisture content

Abstract

In this thesis, a solar dryer for vanilla pods was developed for the vanilla producers in the Huasteca Potosina. The development and usage of such a dryer promised a faster and more efficient drying process. The sun-drying of vanilla pods is a very important part in the traditional Mexican vanilla curing process as in this step the vanillin, which is the most important component of the vanilla's aroma, develops.

Traditional sun-drying results in marketable high-quality vanilla, and the vanilla producers highly identify with that technique. However, sun-drying has some disadvantages, such as low drying rates and discharge because of mould or disintegration of pods.

The challenge in the development of the solar dryer was to eliminate these disadvantages while respecting the local traditions and living conditions of the rural community to which the vanilla producers belong. It is necessary respect these prerequisites in order to assure the sustainability and persistence of the project. As key tool for finding an appropriate technology, interactive participation was identified.

In participatory workshops with the vanilla producers, the traditional vanilla curing process was analysed, and the basic constructional and functional parameters for a vanilla pod dryer were defined.

To prove the applicability of solar drying under these prerequisites and circumstances, two models of solar dryers were constructed and tested in cooperation with the vanilla producers. One model was constructed according to the principle of indirect drying, the other one was a direct dryer model. Three batches of vanilla were dried in the test-run in March 2017, one in the direct model, one in the indirect model, and one in the open sun as reference.

With the results of this test run and the feedback of the vanilla producers, a direct solar vanilla pod dryer was developed.

At the end of the process, the designed solar dryer was assessed by the principles of sustainable development. Four basic dimensions were considered in this assessment.

The assessment of technical sustainability included the measurement of vanilla quality and the drying rate. Also, the vanilla producers' perception of drying performance and vanilla quality was assessed in a questionnaire.

The assessment of economic sustainability compared the costs of the designed solar vanilla dryer with the benefits by avoided quality losses and less costs for manpower and energy.

For the social sustainability, the concepts of interactive participation, endogenous development, appropriate technology, as well as intercultural and inter-disciplinary learning were taken into account. The assessment was performed with a questionnaire.

Last but not least, the environmental aspects of sustainability were assessed. In an eco-balance sheet, the greenhouse gas emissions occurring during the construction of the solar dryer were compared to the greenhouse gas emissions that would occur using a LPG, under the same prerequisites.

Key words: Vanilla, Solar Energy, Drying, Sustainability, Participatory Processes

Zusammenfassung

Im Rahmen dieser Master Thesis wurde ein Solartrockner für Vanilleschoten entwickelt. Das Projekt wurde in Zusammenarbeit mit den Vanilleproduzenten in der Huasteca Potisona in Mexiko durchgeführt. Die Entwicklung und Nutzung eines solchen Trockners vor Ort verspricht einen schnelleren und effizienteren Trocknungsprozess. Das Trocknen der Vanilleschoten in der Sonne ist ein sehr wichtiger Teil des traditionellen mexikanischen Trocknungsprozesses, da hierbei das Vanillin, als wichtigster Bestandteil der Vanille, entsteht.

Durch das traditionelle Trocknen in der Sonne entsteht Vanille von hoher Qualität die eine hohe Nachfrage erzielt. Zudem identifizieren sich die Vanilleproduzenten sehr stark mit diesem traditionellen Prozess. Jedoch hat der traditionelle Trocknungsprozess auch Nachteile – wie langsame Trocknungsraten und hohe Verluste durch Schimmel oder dem Zerfallen der Schoten.

Die Herausforderung in der Entwicklung eines Solartrockners war die Eliminierung dieser Nachteile ohne die lokalen Traditionen und Lebensumstände der ländlichen Bevölkerung, zu der die Vanilleproduzenten zählen, aus den Augen zu verlieren. Um die Nachhaltigkeit und das Fortbestehen dieses Projektes zu garantieren ist es enorm wichtig diese Voraussetzungen zu respektieren. Als Schlüssel zur Findung einer adäquaten Technologie wurde die interaktive Partizipation ausgewählt.

Aus diesem Grund wurden in interaktiven Workshops mit den Vanilleproduzenten der traditionelle Trocknungsprozess analysiert und die grundlegenden bautechnischen und funktionellen Parameter für den Vanilletrockner definiert.

Um die Anwendbarkeit des Vanilletrockners unter diesen Voraussetzungen zu überprüfen, wurden zwei Modelle von Solartrocknern mit den Vanilleproduzenten gebaut und getestet. Es handelte sich hierbei um einen indirekten Solartrockner und einen direkten Solartrockner. Mit jedem dieser Modelle wurde im März 2017 je eine Charge Vanille getrocknet. Eine weitere Charge wurde zum Vergleich nach dem traditionellen Trocknungsprozess behandelt.

Anhand der objektiven Ergebnisse dieses Testlaufes und dem subjektiven Feedback der Produzenten wurde die finale Version eines Vanilletrockners entwickelt.

Am Ende des Prozesses wurde dieser Vanilletrockner anhand der Prinzipien der Nachhaltigen Entwicklung bewertet. Hier wurden vier grundlegende Dimensionen betrachtet.

Die technische Nachhaltigkeit beinhaltet die Messung der Vanillequalität und der Trocknungsrate durch objektive Analysen aber auch durch Befragungen der Vanilleproduzenten. Die wirtschaftliche Nachhaltigkeit wurde mittels eines Kostenvergleichs durchgeführt indem die Kosten des Vanilletrockners mit den Vorteilen durch reduzierte Qualitätsverluste und den gesunkenen Kosten für Arbeitskraft und Elektrizität verglichen wurden. Um die soziale Nachhaltigkeit zu messen wurden die Konzepte der interaktiven Teilnahme, des endogenen Entwicklungsprozesses, der angemessenen Technologie und des interkulturellen und interdisziplinären Lernens anhand von Fragebögen betrachtet. Am Ende wurden die ökologischen Aspekte bewertet. In einer Umweltbilanz wurden die während des Baus des Solartrockners entstehenden Treibhausgase mit den Treibhausgasen, welche mit der Nutzung eines LPG-Trockners unter gleichen Voraussetzungen entstünden, verglichen.

Schlüsselwörter: Vanille, Solarenergie, Trocknung, Nachhaltigkeit, partizipatorische Prozesse

Resumen

En esta tesis de maestría fue desarrollado un secador solar de vainas de vainilla para los productores de la Huasteca Potosina. El desarrollo y uso de dicho dispositivo y su uso promete un rápido y eficiente proceso de secado. El secado solar de las vainas de vainilla es una parte muy importante del tradicional proceso de curado mexicano. La vainillina, la cual es el componente importante del aroma de la vainilla, se produce en esta etapa.

El secado tradicional de vainilla resulta en un producto de alta calidad, y los productores de se identifican altamente con esta técnica. Sin embargo, el secado solar tiene algunas desventajas, como las bajas tasas de secado debido al clima húmedo durante la temporada de vainilla y las pérdidas bebido a la desintegración de las vainas por moho.

El reto en el desarrollo del secador solar fue eliminar esas desventajas respecto a las tradiciones locales y las condiciones de vida de la comunidad rural a la cual pertenecen los productores de vainilla. Esto es necesario asegurar la sostenibilidad y la persistencia del proyecto como una herramienta clave para encontrar una tecnología y una participación interactiva.

En talleres participativos con los productores, el proceso tradicional de curado de la vainilla fue analizado, así como fueron definidos los parámetros básicos de funcionalidad y construcción.

Para probar la aplicabilidad del secador solar, bajo las circunstancias dadas, dos modelos del secador solar fueron construidos y evaluados en cooperación con los productores de vainilla. Por lo cual, tres lotes de vainilla fueron secados en una ronda de prueba en marzo de 2017, uno en cada modelo y directamente al sol.

Con los resultados de esta evaluación y la retroalimentación de los productores de vainilla el secador solar fue desarrollado.

Al final del proceso, el secador solar diseñado fue evaluado por los principios de sostenibilidad y desarrollo, las cuatro consideraciones básicas fueron consideradas en esta evaluación.

La evaluación de la sostenibilidad técnica incluyó la evaluación de la calidad de la vainilla y la tasa de secado. La evaluación de la sostenibilidad económica comparó los costos del diseño del secador solar con los beneficios por evitar la pérdida de calidad del producto y la disminución de los costos de recurso humano y energía. En cuanto a la sostenibilidad social, los conceptos de participación interactiva, desarrollo endógeno, tecnología adecuada, así como el aprendizaje intercultural e interdisciplinario fue tomado en cuenta. Mediante cuestionarios se realizó esta evaluación.

Por último, pero no menos importante, los aspectos medioambientales de sostenibilidad fueron evaluados. En una hoja de cálculo las emisiones de Co2 que se emitieron durante la construcción del secador fueron comparadas con las emisiones de efecto invernadero, lo que puede resultar del secado de la misma cantidad de vainilla con LPG.

Palabras clave: Vainilla, Energía solar, Secado, Sostenibilidad, Procesos participativo.

1 Introduction

When, in 1985, the Coca-Cola Company introduced “New Coke” with artificial vanilla flavour, an economic crisis in Madagascar was caused as the world market price for vanilla sunk drastically. The crisis lasted until the original Coca-Cola recipe was reintroduced and Coca-Cola started buying vanilla again (Azeez 2008). In vanilla producing countries, vanilla is an important cash-crop for the rural population, because of its high value In the year 2000, 20,000 vanilla growers and 5,000 producers were working in this sector in Madagascar, and still vanilla is one the most important sources of income for the country (De La Cruz Medina et al. 2009).

The global demand for natural vanilla rose significantly in the 1980ies, which led to a growing production worldwide – also in Mexico, where vanilla originally comes from (De La Cruz Medina et al. 2009). Today, only a small share of worldwide vanilla sales comes from Mexico, but about 95% of the national production is for export. In the Totonac region in the state of Veracruz, vanilla growing is the most important agricultural activity. But in other Mexican regions, vanilla is grown and cured as well, e.g. in the state of San Luis Potosí (De La Cruz Medina et al. 2009; Odoux 2011).

The tropical region in the southeast of this state is called the Huasteca Potosina. It is one of the poorest regions of Mexico and characterized by its indigenous population and traditions (Trinidad García 2014). Alongside saffron and cardamom, vanilla is one of the most expensive spices in the world (Parthasarathy et al. 2008). Thus, it offers one of the few opportunities for local farmers to generate a noteworthy income as supplement for subsistence farming or the production of commodities such as maize and oranges, for which they receive low prizes. Therefore, the production is supported by various governmental and non-governmental projects, seeking to make the local vanilla production more efficient and competitive.

The vanilla plantations in the Huasteca Potosina region are carried out by small-scale growers. The freshly harvested green vanilla pods are sold to a community-organised “centro de acopio” (Spanish for supply centre) after the harvest where they are cured the traditional way by drying them in the sun. This guarantees an artisanal character of their products and makes them marketable to a relatively high price.

Because of the humid and cloudy weather in this particular region, this process takes up to three months as the drying process stops when there is no direct sunshine. This delay provokes a high demand of labour for the on-going observation and reallocation, a long duration of the process, and much discard because of fungus occurring due to humidity and contact to human skin during the process.

Open sun drying is a very old way of conserving or upgrade food. During the trend for renewable energies, solar drying techniques got into the focus of scientific research. In 1976 Everitt and Stanley developed the first solar dryer to avoid problems of open solar drying, such as debris and animals (Kumar et al. 2016). Since then, a large variety of solar dryers were developed and continuously improved. They offer the possibility to control drying conditions and therefore are currently in use for a vast variety of different crops (Chel, Kaushik 2011; GIZ 2011). A solar dryer could also reduce the difficulties of the vanilla producers in Tamazunchale.

In order to introduce a solar dryer for the traditional vanilla production in the Huasteca Potosina, it is essential to adapt it perfectly to the climate of the region, the special characteristics of the vanilla curing process and the living conditions of the people who are supposed to use it (Pearce 2012).

2 Frame of Reference

In this chapter, the theoretical fundaments for this master thesis will be explained. Since the approach of the thesis is multi-disciplinary, various different topics are of importance. These are technical background, socio-scientific theories and the environmental, social, economic, and technical aspects of sustainability.

2.1 Study Area

The Huasteca Potosina is a region in the eastern part of central Mexico. It is mainly populated by indigenous people and counts as one of the poorest regions of the country. The most important economic sector is agriculture (Trinidad García 2014). For the introduction of a vanilla pod dryer one particular area of this region was chosen, namely: Tamazunchale.

Figure 1: Location of Tamazunchale in Mexcio (Encyclopedia Britannica 2012)

Tamazunchale is a city and municipality in the Huasteca Potosina, located in the south-western part of the state of San Luis Potosí (Figure 1). The municipality has about 97,000 inhabitants with 25,000 living in the city of Tamazunchale (INAFED 2016). The climate of this region is tropical with heavy rainfalls throughout the year, which cease slightly in winter. The average rainfall per year is more than 2,000 mm. The annual mean temperature is around 25 °C, with up to 30 °C in June and about 20 °C in January. This means that during the drying season of the vanilla in the cooler winter, the weather is rather humid with a lot of rain and little sunshine (http://de.climate-data.org). The coordination of the contemplated location is: Latitude = 21.243746, Longitude = -98.777049.

2.2 Project Partner

The Sociedad de Productores de Vainilla Tlilixochitl S.P.R. de R.L. (Tlilixochitl) is a cooperative founded in January 2014 in Tamazunchale. Its main activities are the curing, marketing and sale of the vanilla pods harvested by the vanilla growers of the community. The cooperative's goal is to enable the vanilla growers to profit from their product to the full extent. Before the foundation of Tlilixochitl, market access, and transport capacities were limited as the growers only could sell their product to middlemen, who themselves resold them to local "centros de acopio", as there was limited collaboration. Because of the vanilla growers' precarious financial situation and the lack of alternatives, those middlemen could dictate the prices and had a very high profit margin, while the vanilla growers only profited to a very small extent from their hard work.

Today, Tlilixochitl is the strongest regional vanilla processing organization. It is formed by 150 vanilla growers and 22 other associates. In the vanilla season 2016/17, the vanilla harvest was almost 3.5 tons of green pods. The curing process is artisanal and follows the traditional Mexican curing methods. In addition to selling whole cured pods, they also produce vanilla extract. They own a commercial brand called "Pacqui", the Nahuatl word for joy. A great share of the vanilla produced in Mexico is exported to the USA. Currently, the "Sociedad de Productores de Vainilla Tlilixochitl" is listed by the USDA as certified organic business for vanilla.

The vanilla growers associated to Tlilixochitl sell their green vanilla to the cooperative. Then, the actual vanilla curing in Tlilixochitl's "centro de acopio" is done by workers, who are hired and paid on a daily basis. 50 % of the profits of the vanilla are disbursed to the vanilla growers in relation to the amount of raw vanilla they contributed to the total production. The rest remains within the cooperative for reinvestment. The working chairwoman of Tlilixochitl is Ms. Cándida Morales Santos on a voluntary base.

The vanilla agriculture and production performed by Tlilixochitl in Tamazunchale already are subject to investigation of students of the Universidad Autónoma de San Luis Potosí (UASLP), hence reliable structures to work with can be found (Trinidad García 2014).

2.3 Vanilla – More than Just a Bean

In this chapter, a broad overview will be given. It will deal with its biological features, and its past, present and future as a spice and cash crop. Additionally, a description of the traditional manufacturing methods in Mexico will be given as these are a crucial factor in the emergence of the vanillas' aroma.

2.3.1 Biology

Figure 2: Green Vanilla Pods (Vanilla Review 2008)

Vanilla (bot.: Vanilla planifolia) belongs to the family of orchids and is the only member of the family bearing fruits. As a fleshy, herbaceous perennial vine (Charles 2013), it grows in warm and humid climates, climbs host trees and profits from the shade they provide (Damirón Velázquez 1994). Vanilla blooms once a year over a period of two months. Each plant has 20 or more flowers. To obtain a vanilla pod, the flowers have to be pollinated. Naturally this is done by insects and humming birds. At the beginning of the 19th century, French vanilla producers developed an artificial pollination, transferring pollen from one plant to another. In 1875, they introduced this technique in Mexico, where it is now common, as it increases the number of pods per plant ten-fold (Odoux 2011). Vanilla pods (Figure 2) are pendulous, narrowly cylindrical, faintly three-angled, and variable. They are about 20 cm long (Charles 2013). There are other vanilla varieties like: vanilla tahitensis, vanilla pompona or vanilla odorata. They have a less important role in the worldwide vanilla production and are not cultivated in Mexico (Damirón Velázquez 1994; Odoux 2011).

2.3.2 History and Current Role as Spice and Cash Crop

Vanilla was used long before the arrival of the Spanish conquerors to prepare food and drinks. It was harvested and used by the Totonac people in Veracruz and later by the Aztecs. Vanilla is considered as one of the fruits the Aztecs were paid as tribute by various neighbouring cultures (Damirón Velázquez 1994). It was first mentioned in an historical text in the 15th century. The Spanish officer Bernal Díaz, who came to Mexico with Hernando Cortes, first described a drink of cocoa seed and ground vanilla pods consumed by the Aztec king Moctezuma. The Spanish conquerors later used vanilla to flavour chocolate and marketed and commercialised the fruit to Europe. While the Spanish people soon preferred cinnamon over vanilla for flavouring their chocolate, the French population continued to favour vanilla. In France, vanilla soon was used to flavour other things, such as ice cream or sweets, or as a perfume. Thus, vanilla was then increasingly cultivated in the tropical French colonies such as La Réunion and Madagascar (Correll 1953). This was only possible because of the invention of the hand-pollination, as natural pollinators for vanilla do not exist outside Mexico. The well-known term *bourbon vanilla* refers to the old name of the island La Réunion (Ile Bourbon) and today is only used for vanilla from Madagascar, La Réunion, the Comoros, Seychelles, or Mauritius (Odoux 2011).

Even though vanilla is native to Central America, it is now grown in many countries all over the world. The by far biggest amounts of produced and traded vanilla come from Indonesia and Madagascar while Mexico plays an unimportant role in vanilla production (Charles 2013; De La Cruz Medina et al. 2009; www.worldatlas.com 2017).

The vanilla production in Mexico decreased significantly during the second half of the 20th century. Reasons for this decrease were falling prices, due to a worldwide production growth, the invention of synthetic vanillin in 1974, and the affection of vanilla production areas by the oil industry. Still, Mexico and Madagascar are considered to produce the best quality vanilla (Azeez 2008). Within Mexico, most of the vanilla comes from the state of Veracruz, where the Totonac still play a big role a big role in the production (Odoux 2011).

The most important vanilla importers are the USA, France and Germany (De La Cruz Medina et al. 2009) and the world's largest customer is the Coca-Cola Cooperation (Azeez 2008).

Today natural vanilla flavour from vanilla planifolia is one of the most expensive flavours. It is used in food (60%), cosmetics (33%), and aromatherapy (7%) (Sreedhar et al. 2009). Vanilla is also said to have various favourable impacts on the human body (Charles 2013).

2.3.3 Traditional Vanilla Curing in Mexico

The mature green vanilla pods do not have any specific smell or taste directly after the harvest, but develop their characteristic aroma during the curing process (Roling et al. 2001). The curing processes in the various vanilla production regions of the world share the basic steps, but differ in some details. Aside destemming the vanilla pods and sorting them by their size, the vanilla curing process consists of "killing", "sweating", "insolation", and "conditioning" (Dignum et al. 2002; Pérez Silva et al. 2011).

2.3.3.1 "Killing, Scalding or Wilting"

The first step in processing the vanilla pods is called "killing". This has nothing to do with the act of taking somebody's life, but derives from the word kiln, a kind of oven (Hernández Hernández 2014).

The killing, which is also called scalding (Dignum et al. 2002), blanching (Van Dyk et al. 2010) or marchitamiento (Spanish for withering) (Hernández Hernández 2014), basically means the introduction of heat. This can be done in different ways (Arana 1944; De La Cruz Medina et al. 2009). In Mexico and Indonesia, killing in the sun is the most common practice. In Mexico, killing in a traditional brick-oven is common as well (De La Cruz Medina et al. 2009; Hernández Hernández 2014; Odoux 2011). In Madagascar, the Comoros and La Réunion vanilla pods are scalded by dipping them into hot water for a few seconds (Arana 1944; De La Cruz Medina et al. 2009; Odoux 2011).

During the killing, germs are eliminated through heat and the pods change their colour from bright green into a dark brown (Hernández Hernández 2014). The killing also has a crucial part in the curing of vanilla pods as it stops biological maturing processes and destroys the cell structure of the pod. Thus, the vanilla's enzymes can mix with their substrates (Van Dyk et al. 2010; Odoux 2011), mostly glucosylated phenols (Brillouet et al. 2010).

2.3.3.2 Successive Insolation and "Sweating"

After the killing, the pattern of insolation and sweating begins. The vanilla pods, still hot from the killing, are wrapped into blankets to conserve the heat (Hernández Hernández 2014) and in some cases are even sealed air-tight (Correll 1953). The time for this initial sweating lasts from 18 to 48 hours (De La Cruz Medina et al. 2009; Hernández Hernández 2014).

In the days following, the vanilla pods are insolated and left to sweat in a repeating pattern. They are put into the sun until reaching a temperature of 50 to 55°C, and then again wrapped in blankets to sweat overnight. This process is repeated various times depending on the pods size. For the biggest Grade I vanilla pods, up to 24 repetitions are needed (Hernández Hernández 2014; De La Cruz Medina et al. 2009; Correll 1953). Alternatively, the vanilla pods are cured in an oven. Yet, there are different, faster drying methods, but these result in an inferior quality (De La Cruz Medina et al. 2009; Correll 1953) or are not used on a large scale because of their high costs (Odoux 2011).

If it becomes obvious that the vanilla pods might not reach the desired temperature to carry out the sweating, they are put onto shelves in a closed but vented room. The same is done on cloudy or rainy days. On the shelves, the vanilla pod rest until the next day which is sunny enough for insolation (Hernández Hernández 2014).

2.3.3.3 Conditioning

After the vanilla pods have reached the desired moisture content of 0.38 for classes 1 and 2, 0.30 for class 3, and 0.25 for class 4 (Odoux 2011), the final step, the “conditioning” follows. The conditioning consists of letting the pods rest in boxes for another 30 to 45 days in order to develop their full aroma (Hernández Hernández 2014; Arana 1944; De La Cruz Medina et al. 2009). Due to the specific climatic conditions, the traditional Mexican curing process can last up to six months(Damirón Velázquez 1994; Van Dyk et al. 2010; Pérez Silva et al. 2011; De La Cruz Medina et al. 2009). In this step it is important that they do not lose too much moisture (Odoux 2011).

2.3.4 The development of the vanilla’s aroma

The most important component of the vanilla´s aroma is vanillin. The chemical and enzymatic processes involved in the synthesis of vanillin are not fully investigated, yet.

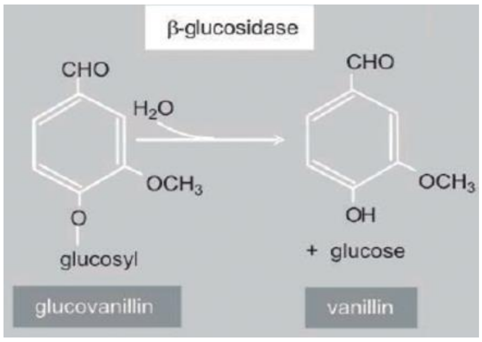

Figure 3: Hydrolysis of glucovanillin to vanillin (Brillouet et al. 2010)

Brillouet et al. (2010) and Van Dyk et al. (2010), for example, emphasize the enzymatic processes. According to them, the glucosylated phenols inside the vanilla pods are hydrolysed to sugars and aromatic phenols by an enzyme called β-glucosidase during the curing process. The by far most important of these phenols is vanillin, which is a result of the hydrolysis of glucovanillin (Figure 3). Those phenols are partly further oxidised into other cyclic or polycyclic polymers which not only have an influence on the vanilla pod’s taste but also are responsible for the development of a brown colour during the curing process (Brillouet et al. 2010) (Van Dyk et al. 2010).

Other authors point out that during the killing or scalding β-glucosidase is deactivated (Azeez 2008; Dignum et al. 2002). Dignum et al. (2002) suggest that there is a specific β-glucosidase for the hydrolysis of glucovanillin. Pérez Silva et al. (2011) came to a similar conclusion when they found out that some glycosylated phenols are hydrolysed during the curing process. Roling et al. (2001) revealed that green vanilla pods carry thermotolerant and thermophilic bacilli which survive killing/scalding. Some of these bacilli possess enzymatic activities (proteases, hemicellulases, cellulases, and β - glucosidases), which could also play a part in the vanilla curing process and the development of vanillin (Roling et al. 2001).

2.3.5 Quality Factors of Vanilla Pods

The quality of cured vanilla pods depends of many factors. In Mexico, vanilla pods are divided into five quality categories based on their size, vanillin content, aroma, and physical appearance. These categories are: “Extra”, “Superior”, “Buena”, “Mediana”, and “Ordinaria”. Physical quality characteristics are the desired humidity content, a chocolate brown colour, oiliness, flexibility, freedom of skin defects and a large size. These factors have an influence on the pod’s aroma. (De La Cruz Medina et al. 2009).

Other factors, which influence the vanilla's aroma, are maturity, and region of origin, microbial communities on the pods, as well as curing methods. (Karthik Kumar 2013; Pérez Silva et al. 2011; Van Dyk et al. 2010, 2010; Arana 1944; Correll 1953; De La Cruz Medina et al. 2009; Dignum et al. 2002).

The share of vanillin in all organic volatile compounds is 50 % in Bourbon vanilla and 30 % in the Mexican variety. However, the vanillin is not the only component responsible for the vanilla's taste. More than a hundred volatile compounds have been found, including aromatic carbonyls, aromatic alcohols, aromatic acids, aromatic esters, phenols and phenol ethers, aliphatic alcohols, carbonyls, acids, esters and lactones (Azeez 2008). Because of this multiplicity there is no direct correlation between high vanillin content and a favourable aroma (Odoux 2011). Vanilla from different origins has different characteristic aromas. Bourbon vanilla has a higher vanillin content (up to 2.9 %) than Mexican vanilla (up to 1.8 %). However, both of them are considered as high quality (Azeez 2008).

2.4 Drying with Renewable Energies

In this chapter, the most important issues of drying with renewable energies will be explained. This includes the basic principles that help to control and monitor the drying process, as well as theory and examples for the capture of solar energy for drying purposes.

2.4.1 Basic Principles of Drying Food

Drying is the removal of moisture of a solid or nearly solid material by evaporation. Drying involves both heat and mass transfer (Esther Magdalene Sharon et al. 2016). In convective drying, the heat required for evaporating moisture from the drying product is supplied by the external medium, which is usually air. It takes place in two steps, first the transport of moisture from the product's interior to the surface and then the evaporation from the surface into the drying medium (Esther Magdalene Sharon et al. 2016).

Drying of agricultural products is the oldest method for preserving food. A secure level of moisture content slows down the activity of enzymes, bacteria, yeasts, and moulds (Janjai, Bala 2012). This is very important as a prolonged availability of agricultural products contributes to food security. Drying also has other positive effects such as a better transportability, manageability, and marketability, which also result in an improvement of the producers' living conditions (Richardson et al. 2002; Tiwari et al. 2016a). However, drying is one of the most labour- and energy consuming tasks in the food and agricultural processing industries (Wilhelm et al. 2004).

In the process of drying, it is necessary not to damage the product by overheating or any influences that could impair its quality (Richardson et al. 2002)..

2.4.1.1 Basic Terms

- In drying applications, the *relative humidity* is the relative ratio of water vapor in the air to the air's water vapor absorption capacity. The lower the relative humidity, the more water from the drying good the air can absorb. The relative humidity of the drying air can be decreased by raising the air's water vapor absorption capacity or by removing moisture. The first can be achieved by increasing temperature or decreasing air pressure, the latter by an increased air flow (Mujumdar, Devahastin 2000).
- The *dry bulb temperature* represents the actual air temperature. In contrast, *the wet bulb temperature* is the temperature that occurs in a liquid affected by a rapid airstream with a relative humidity below 100%. The evaporation of the liquid decreases its temperature. The wet bulb temperature is a function of the air's relative humidity, temperature, and pressure, as well as the liquid's latent heat of evaporation (Mujumdar, Devahastin 2000).

2.4.1.2 Moisture Content

The moisture content of any material can be expressed in two ways: the moisture content wet basis (wb) and the moisture content dry basis (db). The moisture content (wb) is the mass of water in relation to the total mass of a product. The moisture content (db) is the mass of water in relation to the dry mass of the product. If the mass of water is higher that the dry mass, it is higher than 1. Both can be expressed either as decimal or as percentage (Wilhelm et al. 2004)

$$x = \frac{m_w}{m_d + w} = \frac{m_w}{m_t} \quad (1)$$

$$X = \frac{m_w}{m_d} \quad (2)$$

Wet and dry basis moisture content can easily be transformed into the other, respectively

$$x = \frac{X}{1+X} \tag{3}$$

$$X = \frac{x}{1-x} \tag{4}$$

Where:

x is the decimal moisture content wet basis (wb)

X is the decimal moisture content dry basis (db)

m_w is the mass of water in the product

m_d is the mass of dry matter in the product

All Equations are taken from Wilhelm et al. (2004)

2.4.1.3 Equilibrium Moisture Content

During the drying process, the moisture content of the product decreases until the equilibrium moisture content is reached. This means that no moisture exchange with the ambiance can take place anymore. The equilibrium depends on the environment's relative humidity and temperature. The total moisture content minus the equilibrium moisture content gives the free moisture content. This is the amount of moisture that can be removed under the recent conditions during the drying process.

$$f = X - X_e \tag{5}$$

Where:

f is the free moisture content

X is the current moisture content

X_e is the equilibrium moisture content

An empirical analysis resulted in the following equation for the equilibrium moisture content of vanilla (Kamaruddin, Kamaruddin 2007; Nelwan 7/17/2017):

$$X_e = -1.20875 + 2.47(T_d - T_w) - 0.0993(T_d - T_w)^2 \tag{6}$$

Where:

T_d is the dry bulb temperature

T_w is the wet bulb temperature

2.4.1.4 Drying Rate, Time of Drying, and Critical Moisture Content

The drying rate defines the velocity of the drying process. It depends on various drying conditions like velocity, humidity and temperature of airflow or external heat, and factors concerning the drying good, such as its surface, equilibrium moisture content, or instantaneous moisture content (Lewis 1921).

The drying rate is not always constant. One can distinguish a constant rate period and one or two falling-rate periods. In the constant rate period, the drying rate remains constant. In the falling-rate period, the drying rate is proportional to the free moisture. It starts at certain moisture content, called the critical moisture content (Richardson et al. 2002).

The drying rate *v* is the derivative of the moisture content with respect to the time *t (Richardson et al. 2002)*.

$$v = \frac{dX}{dt} \tag{7}$$

During the constant rate period, the drying rate can be expressed a little simpler by defining it as the difference of moisture content divided by the timespan (Richardson et al. 2002).

$$v = \frac{\Delta X}{\Delta t} \tag{8}$$

In the constant rate period, the time of drying t_c is (Richardson et al. 2002):

$$t_c = \frac{X_1 - X_c}{\mathrm{v_c}} \tag{9}$$

or

$$t_c = \frac{X_1 - X_c}{mA * f_c} \tag{10}$$

Where:

X_1 is the initial moisture content

X_c is the critical moisture content

mA is the factor m multiplied with the surface of the drying good A

f_c is the free moisture at the critical moisture content f_c: $f_c = X_c - X_e$

In the falling rate period, the time of dying t_f is (Richardson et al. 2002):

$$t_f = \frac{1}{mA} \ln\left(\frac{f_c}{f}\right) \tag{11}$$

2.4.1.5 Water Activity

The water activity is the ratio of the vapour pressure of a food, compared to condensed water under the same stable conditions. It determines the affinity of the moisture of a food to evaporate. The water activity is used to measure the likeliness of food to spoil. The reduction of the water activity through drying is responsible for the preservative effect (FDA 1984). A water activity below 0.65 is considered safe (Odoux 2011).

Jiménez et al. (2013) found out that the water activity of vanilla pods at a moisture content of 0.77 (wb) is 0.986 and 0.834 at a moisture content of 0.25 (wb). Odoux (2011) published similar numbers. However, both agree in the fact that marketable vanilla with a moisture content between 0.18 and 0.38 still has a water activity far above the safe value which prevents spoilage (Odoux 2011; Jiménez et al. 2013).

2.4.2 Renewable Energies

Unlike carbon based fossil energies or nuclear energy, renewable energies are considered to be regenerative and thus non-depletable. Using renewable energies means exploiting directly or indirectly the energy of the sun, planetary movements or the earth's interior heat sources (Eltrop 2013).

Renewable energies are favourable for sustainable energy supply for several reasons. At first, renewable energies are considered to be cleaner than fossil energies as no greenhouse gases or other harmful substances emerge as a result of combustion. This argument is valid, notwithstanding other adverse effects of renewable energy applications are possible, such as flooding of valleys for hydropower, disturbances for migratory birds by the wings of wind turbines, or usage of farmland for biofuels (Eltrop 2013; Andersen 2013; Koizumi 2015). At second, renewable energies are perfectly suitable for decentralized energy solutions, using regional resources and offering power and benefit to local stakeholders. At last, there is a large variety of applications of how to harness renewable energies. That is why it can be considered as available anywhere and anytime (Eltrop 2013).

The majority of renewable energy applications directly or indirectly take advantage of the sun's energy (Eltrop 2013):

- Solar energy can be used directly by generating electricity through solar photovoltaics (PV) or heat through solarthermics.
- The energy of the sun also can be exploited indirectly by using hydro- and wind energy, as the hydraulic cycle and wind are a result of sun energy. Hydro power applications convert the kinetic energy of a water stream into mechanic or electric energy. Wind power does the same with the movement of air masses.
- The growth of biomass also depends on the sun's energy. Biomass can be used as combustible - directly or after being fermented to biogas. Biomass can produce heat or mechanical energy by using an engine.
- Other sources of renewable energies are the rising and falling of the sea-level as a result of the tides (tidal energy) or the heat in the earth's interior (geothermal energy).

2.4.3 Advantages of Drying with Renewable Energies

Improvement in the agricultural sector leads to a rapidly growing energy demand in developing countries. While a more productive and modern production of food and cash crops contributes to food security and livelihood in those countries, the choice of suitable energy sources is crucial for a sustainable development in this sector. Fossil and electrical energy sources contribute to anthropogenic global warming and are subject to depletion and price fluctuation (Kumar, Bhattacharya 2005; GIZ 2011).

Solar energy is abundantly available in tropical and subtropical regions. Hence, it makes sense to use it for those drying purposes which need a high amount of energy for heating. Solar drying in contrast to sun drying includes the usage of a solar drying device which captures the solar energy and protects the product from any unwanted influences. With natural convection dryers, no electrical or fossil energy is needed (Janjai, Bala 2012). By combining traditional and industrial methods, solar drying offers significant improvements to the drying process without causing high investment or operational costs (GIZ 2011).

A combination with other energy sources is possible, either to force convection, or to secure the drying capabilities on days without sufficient sun. Complementary energy sources can be electricity or combustibles. The system then is partly renewable, but already reduces energy consumption to a minimum. The employment of photovoltaics and biofuel ensures the complete supply by renewable energies (Okoroigwe, Ndu 2015; Mustayen et al. 2014; GIZ 2011; Weiss, Buchinger 2003).

2.4.4 Sun Drying

The most traditional way of drying in tropical and subtropical regions is sun drying which means putting the product into the open sun on not or hardly elaborated surfaces until it has dried. In sun drying the product, it receives heat from the surrounding air through convection and from the sun by absorption. The air flow necessary for moisture removal is caused by natural convection or wind (Kumar, Bhattacharya 2005). Figure 4 shows the mass and energy flows during sun drying.

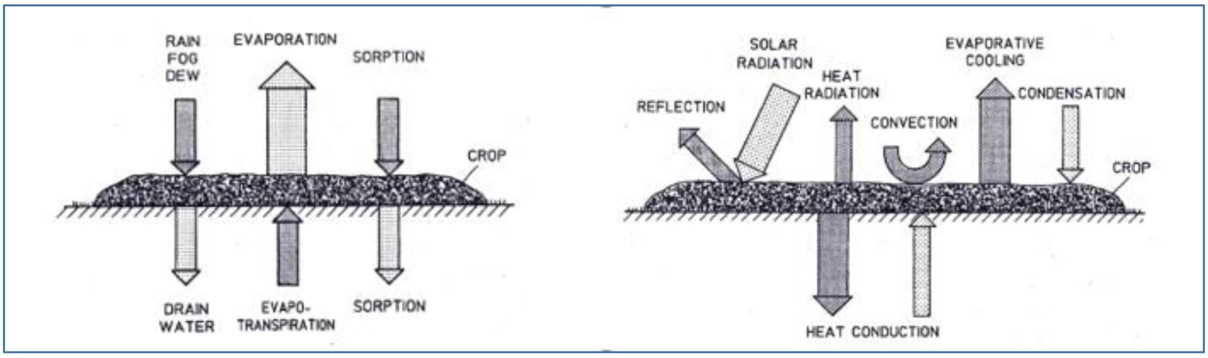

Figure 4: Mass Flow (left) and Heat Flow (right) Influencing Sun Drying (Kumar, Bhattacharya 2005)

This process is very common in developing counties, as it is inexpensive, but the product is exposed to rain, dust, and other contaminations, e.g. by insects, birds, and other animals (Janjai, Bala 2012; GIZ 2011). Furthermore, external drying parameters such as heat input, moisture contents, temperature, drying air flow rate, etc. cannot be controlled which results in extended drying times, incomplete or over drying (Kumar et al. 2016). Under certain (cold or wet) climatic conditions, the equilibrium moisture content can be too high for preserving the food, and even a rewetting of the product is possible, especially at night.

With suitable drying technologies, product quality can be improved, drying accelerated, and losses can be reduced by protecting the drying product and controlling drying conditions (Janjai, Bala 2012; Kumar et al. 2016). Currently, the price differences between high and low-quality products usually still are too low to justify an investment in improved drying technologies (Janjai, Bala 2012), but recently product quality of dried agricultural products has become of growing importance (Timoumi et al. 2004).

2.4.5 Solar Drying

Solar drying in contrast to sun drying includes the usage of a solar drying device which captures the solar energy and protects the product from any unwanted influences. In the case of natural convection dryers, no electrical or fossil energy is needed (Janjai, Bala 2012)

Advantages of solar drying over sun drying are (Weiss, Buchinger 2003):

- The higher temperature, movement of the air, and lower humidity increases the rate of drying.
- Food is locked in the dryer and therefore protected from dust, insects, birds and animals.
- The higher temperature deters insects and the faster drying rate reduces the risk of spoilage by microorganisms.
- The higher drying rate also gives a higher throughput of food and hence a smaller drying area (roughly 1/3 of the area needed for sun drying).
- The dryers are water proof and the food does therefore not need to be moved when it rains.
- Dryers can be constructed from locally available materials and are relatively low cost.
- More complete drying allows longer storage

To be able to compete with conventional dehydration processes, solar dryers must provide the equivalent performance. Capacity, labour input, the quality of the final product, the total drying costs, and reliability are also important factors (Weiss, Buchinger 2003). Weiss, Buchinger (2003)further suggest that “a backup heating system should be installed to ensure drying during the critical periods when the weather is bad”.

Reasons, why solar drying has not replaced sun drying on a larger scale, are (Weiss, Buchinger 2003):

- High costs or lack of funds
- Complicated technology and lack of training
- Solar dryers often are not designed to last and to harmonize with local traditions
- Low monetary incentives for investment in improved product quality

2.4.6 Basic Principles of Solar Thermal Energy

After describing the basic aspects of drying, an introduction of the basic principles of solar thermal energy will follow

2.4.6.1 Available Solar Radiation

The solar energy reaching the earth is represented by the solar constant (G_{sc}) of 1367 W/m^2. Nevertheless, the irradiation on the surface is less, due to the changing angle of incidence θ as well as cloudiness and other disturbances (Duffie, Beckman 2013).

Two different kinds of solar radiation must be differentiated. Direct radiation reaches the earth without having been deflected in the atmosphere. Diffuse radiation in contrary has been deflected and therefore has another direction than the direct radiation.

The angle of incidence θ on a surface is the angle between the radiation vector and the surface's normal vector (Figure 5) (Wagner 2010).

The relation between the angle of incidence and the effective solar irradiation *E* is (Wagner 2010):

$$E = I\ A\ cos\theta \qquad (12)$$

Where:

I is the Irradiation

A is the surface

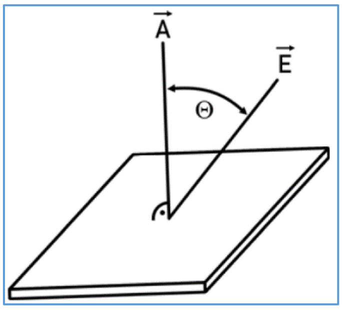

Figure 5: Angle of Incidence of Sun Light (Wagner 2010)

The angle of incidence θ is a result of the following angles (Duffie, Beckman 2013):

- The latitude *φ,* i.e. the angle of the solar incidence at solar noon at equinox in relation to the surface's normal.
- The tilt *β*, i.e. the angle of the surface relatively to the horizontal
- The surface azimuth angle *γ*, i.e. the angle between the normal of the surface
- The hourly angle *ω*, i.e. the angle between the solar radiation and the meridian caused by the earth's rotation
- The declination *δ*, i.e. the angle at solar noon between the normal of a surface on the equator and the solar radiation

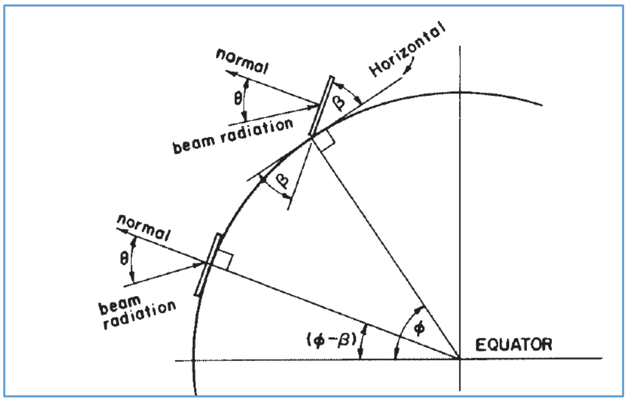

Figure 6: Section of earth showing β, θ, φ, and φ – β for a south-facing surface (Duffie, Beckman 2013)

One of the most important factors for the choice of a location for a solar dryer is the latitude. The higher the latitude, the higher the irradiation angle. By tilting the surface of a solar collector, this disadvantage can partly be compensated. In Figure 6 it is shown that the difference between latitude and tilt *(φ – β)* is the same in both cases. This only applies for the northern hemisphere. In the southern hemisphere, the term must be *(φ + β)* (Duffie, Beckman 2013; Wagner 2010).

For a tilted solar collector facing south directly the solar inclination can be calculated with the following Equation (Duffie, Beckman 2013):

$$\cos\theta = \cos\,(\varphi - \beta)\cos\delta\cos\omega + \sin(\varphi - \beta)\sin\varphi \qquad (13)$$

The solar inclination for a horizontal surface is:

$$cos\theta_z = \cos(\varphi)\,cos\delta\,\cos\omega + \sin(\varphi)\,sin\delta \qquad (14)$$

Of those angles, ω and δ are changing during the day and throughout the year, respectively and can be approximated with the following Equations (Duffie, Beckman 2013).

$$\omega = 0 + 15°(hrs - 12) \qquad (15)$$

$$\delta = 23.45\,\sin\left(360\frac{284 + n}{365}\right) \qquad (16)$$

Where:

n is the number of the day starting with 1 at the 1st of January

When the longitude of the location is different from the reference median for the local time, the standard time has to be corrected to the local time. The difference in minutes is calculated as follows (Duffie, Beckman 2013):

$$Solar\ time\ -\ standard\ time\ =\ 4(L_{st} - L_{loc})\ +\ E \qquad (17)$$

$$E\ =\ 229.2(0.000075\ +\ 0.001868\,cosB\ -\ 0.032077\,sinB - \ 0.014615\,cos\,2B - \ 0.04089\,sin\,2B) \qquad (18)$$

$$B\ =\ (n\ -\ 1)\frac{360}{365} \qquad (19)$$

Where:

L_{st} is the standard meridian for the local time zone, L_{loc} is the longitude of the location in question, and longitudes are in degrees west, that is, $0° < L < 360°$ (Duffie, Beckman 2013)

Not only the angle of solar radiation influences the effective solar irradiation, but also the losses in the atmosphere. Those losses depend on the air masses that the sunrays have to pass. The higher the inclination, the longer is its way through the atmosphere. Topography, cloudiness, relative humidity of the air, as well as air pollution have an influence on the effective solar irradiation, as well (Duffie, Beckman 2013).

The solar irradiation data base Meteonorm offers hourly irradiation data for every location in the world and considers diffuse and direct irradiation, all the above-mentioned influences, as well as tilt and azimuth of the solar collector. Therefore, data will be derived from this data base in this thesis. Hourly irradiation data offers the integrated solar irradiation for one hour each. The reference time indicates the end of the interval (Remund et al. 2017).

Two types of irradiation can be distinguished. Direct irradiation I_{dr} comes from the sun in a direct line without any scattering by the atmosphere. Diffuse irradiation I_{df} is scattered by obstacles in the atmosphere, e.g. clouds and therefore has changed direction. It does not have a uniform direction and thus cannot be concentrated. The sum of diffuse and direct radiation is the global irradiation I.

In this thesis I always is the irradiation with the unit Wh/m^2

$$I = I_{dr} + I_{df} \tag{20}$$

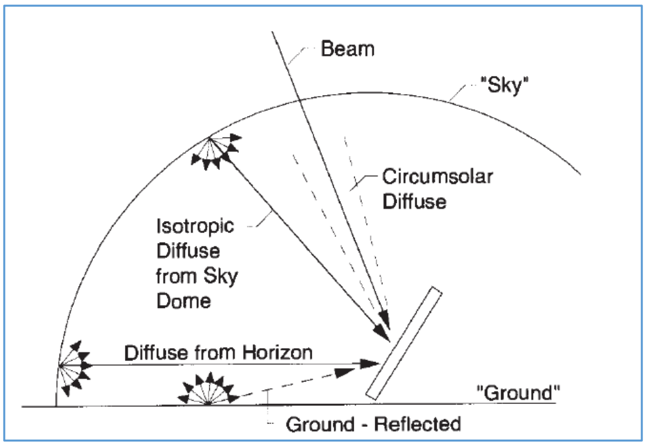

Figure 7: Beam (direct), diffuse, and ground-reflected radiation on a tilted surface (Duffie, Beckman 2013)

The share of diffuse radiation depends on many factors like clouds, air pollution cloudiness. There are three different sources of diffuse irradiation:

- circumsolar diffuse irradiation results in forward scattering and comes from a similar angle as the direct radiation,
- isotropic diffuse radiation shines from the entire sky dome uniformly, and
- horizon brightening comes from the horizon and is especially relevant on clear sky days.

With the Perez model, all three types can be calculated. Another source of irradiation aside direct and diffuse radiation is the radiation reflected from the ground. (Duffie, Beckman 2013; Perez et al. 1988).

2.4.6.2 Absorption, Heat Transfer, and Efficiency

When solar radiation strikes on a solid body, it can be either reflected, transmitted or absorbed. The factors for reflectivity ρ, transmittance τ, and absorptivity α indicate the ratio of the total irradiation that is reflected, transmitted or absorbed, respectively. The sum of those factors always equals 1, due to the law of conservation of energy. Only a perfectly black body absorbs the complete radiation, that it is irradiated with (Tiwari et al. 2016a; Duffie, Beckman 2013).

The transmitted radiation will pass the body and thereby is refracted in most cases. The reflected radiation will be send back with an emergent angle equal to its incident angle. The absorbed radiation $I \times \alpha$ will directly contribute to the absorbing body's enthalpy. In the application of solar drying, this can result in an increase of temperature or in evaporation of water (Duffie, Beckman 2013):

$$Q = A\,I\,\alpha \tag{21}$$

$$\Delta T = \frac{Q}{m\,C} \tag{22}$$

$$m_e = \frac{Q}{\lambda_s} \tag{23}$$

$$Q = q\,t \tag{24}$$

Where:

q is the heat flow

Q is the heat flow

t is the time

A is the collector surface

ΔT is the temperature change

m is the mass

m_e is the mass evaporated

C is the heat capacity

λ_s is the latent heat of evaporation (λ_s *=2393.6 kJ/kg at 45°C (Ogheneruona, Yusuf 2011))*

A body that has heated up due to absorption of radiation will start to emit radiation itself. According to the Stefan-Boltzmann-equation, the radiation towards the sky is (Duffie, Beckman 2013):

$$q = A\,\sigma\,\varepsilon\,(\mathrm{T} - T_{sky})^4 \tag{25}$$

The heat flow radiation from a body *1* to a body *2* is:

$$q = A_1\,h_r\,(T_2 - T_1) \tag{26}$$

If both bodies are parallel surfaces,

$$q = \frac{A\,\sigma\,(T_2^4 - T_1^4)}{\frac{1}{\varepsilon_1} - \frac{1}{\varepsilon_2} - 1} \tag{27}$$

Where:

T is the temperature

σ is the Stefan-Boltzmann-Constant σ

h_r is the radiation heat flow coefficient

For the convective heat flow between two bodies in direct contact with each other, the Equation is (Tiwari et al. 2016a):

$$\mathrm{Q} = \mathrm{h}_c\,\mathrm{A}\,\Delta\mathrm{T} \tag{28}$$

Where:

h_c is the convective heat flow coefficient

The efficiency of a solar dryer is the amount of energy used for heating up the product and evaporating water divided by the solar irradiation on the dryer (Bolea et al. 2012; Musembi et al. 2016).

$$\eta_c = \frac{Q_{heat} + Q_e}{\mathrm{I}\,A} \tag{29}$$

2.4.7 Types of Solar Dryers

Different products with different moisture contents and heat tolerances require different drying conditions. For these and other reasons, such as climatic conditions, a large number of dryer types exist. Primarily, solar dryers can be divided into direct, indirect and mixed mode dryers. A special case are hybrid dryers. Another important criterion for classification of solar dryers is whether convection works naturally or is forced by e.g. a ventilator (Kumar et al. 2016). Solar dryers, where the air flow is forced by means of external energy, e.g. electricity, are active dryers. Solar dryers that use natural convection only, and/or wind, are passive dryers (Tiwari et al. 2016b). For all dryer types there are various designs (Kumar et al. 2016; Janjai, Bala 2012). All of the solar dryer types presented in the following chapters, are thin layer dryers, which means, that the layers of product have a thickness of maximal 20 cm (Esther Magdalene Sharon et al. 2016).

2.4.7.1 Direct Solar Dryers

Solar dryers are the most commonly used drying devices for agricultural and food products. They consist of a box or another enclosure, and a transparent cover (Kumar et al. 2016). The product is placed on trays made of perforated material or mesh to allow the airflow to pass directly. The part of solar radiation that passes that cover directly hits the product inside the dryer.

A share of this irradiation is absorbed by the interior material of the dryer and its content. This leads to a temperature increase and evaporation of the moisture contained in the product (Kumar et al. 2016; Tiwari et al. 2016b; Weiss, Buchinger 2003). In some cases, an additional heat absorber e.g. a black metal plate is placed at the bottom (Mohamed Akoy, EL- Amin Omda et al. 2006; Ogheneruona, Yusuf 2011). The re-emitted heat cannot pass the transparent cover and is trapped inside the dryer which heats up the air inside the dryer (greenhouse effect). A direct dryer has air inlets at the bottom and outlets at the top for cold and hot air, respectively. This allows the air flow to remove the moisture from the dryer (Tiwari et al. 2016b).

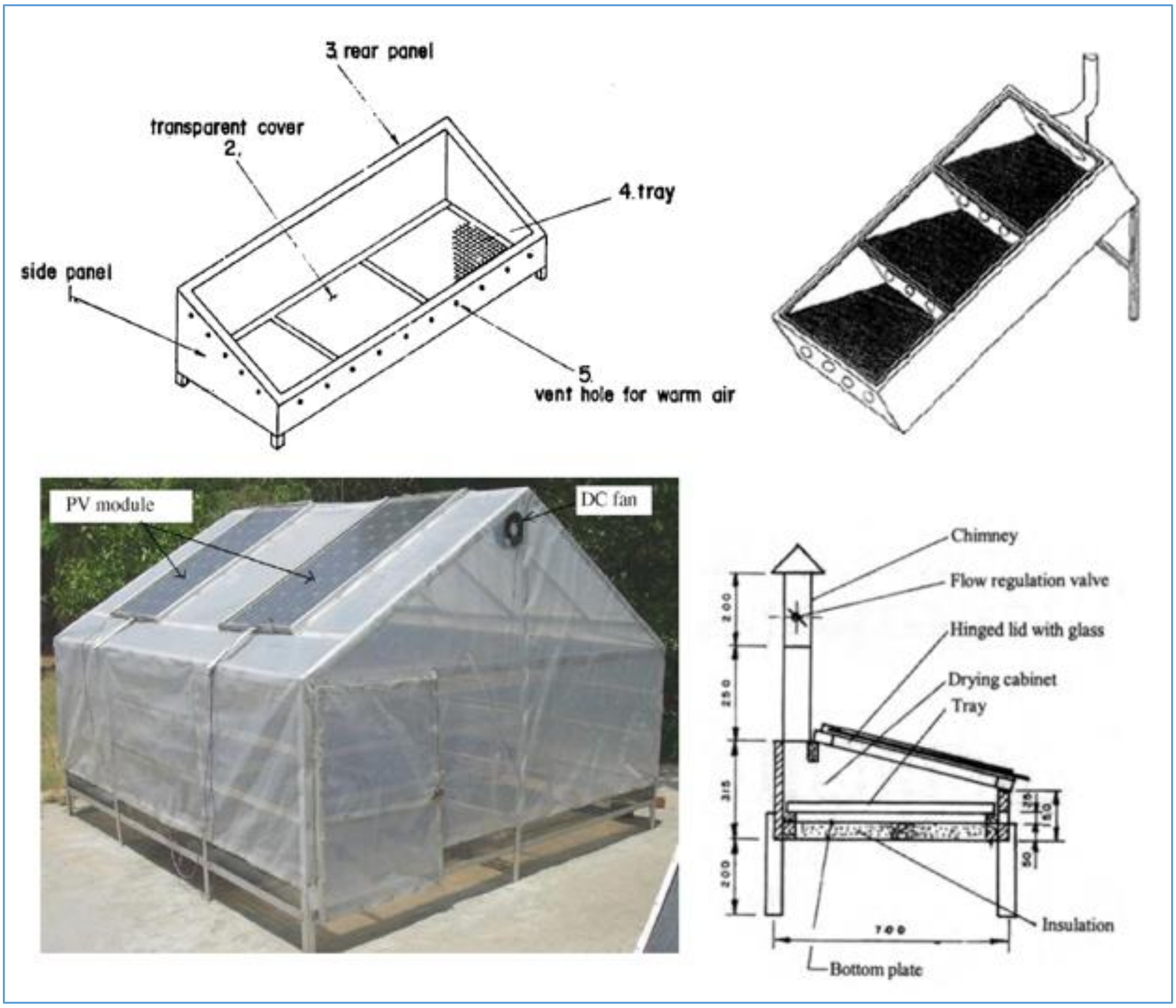

Figure 8: Solar Box Dryer (top-left) (Patranon 1984),Direct Solar Cabinet Dryer with Chimney (top-right) (Janjai, Bala 2012), Greenhouse Dryer (bottom-left) (Tiwari et al. 2016b), Improved Solar Box Dryer with Chimney (bottom-right) (Kumar, Bhattacharya 2005)

There are different structural shapes for direct dryers (

Figure 8). All of the following types of dryers can be designed either as active or passive dryer (Kumar et al. 2016).

- A solar box dryer consists of a simple box with and inclined transparent cover and holes for ventilation. A thin layer of product is placed on a tray and directly impinged by the solar irradiation. The disadvantages of such box dryers are for example: low drying rates, little capacity and quality loss due to an exposition to direct sunlight. Some direct box dryers have a chimney or a fan to improve ventilation (Kumar et al. 2016; Gewali, Bhandari 2005; Mustayen et al. 2014).
- A direct solar cabinet dryer is similar to the box dryer, but has various layers of trays and thus has a higher capacity (Gewali, Bhandari 2005).
- A solar greenhouse dryer is bigger than a direct box dryer. It is shaped like an ordinary greenhouse for planting fruits or vegetables and covered with transparent plastic sheets. A fan is used for the evacuation of moist air. The product is placed on shelves inside the dryer (Barnwal, Tiwari 2008; Tiwari et al. 2016b).

Mohamed Akoy, EL- Amin Omda et al. (2006) and Ogheneruona, Yusuf (2011) present two very similar direct solar cabinet dryers for mango slices and cassava. The dryers are based on a model that was introduced by Ampratwum (1998) for dates. Both authors built a prototype with a solar collector surface of about 1 m^2. The prototype consists of a metal cabinet with a glass on the top and an inclination of 15 ° or 5 ° respectively, corresponding to the location's latitude. The bottom consists of a galvanized metal sheet above a layer of insulating glass wool. The metal sheet was painted black and served as absorber. The dryers could be opened from the back side and were able carry two stacked trays for the drying good. The interior was lined with aluminium foil in order to concentrate the irradiation to the absorber. Figure 9 shows the drawing of the dryer presented by Mohamed Akoy, EL- Amin Omda et al. (2006).

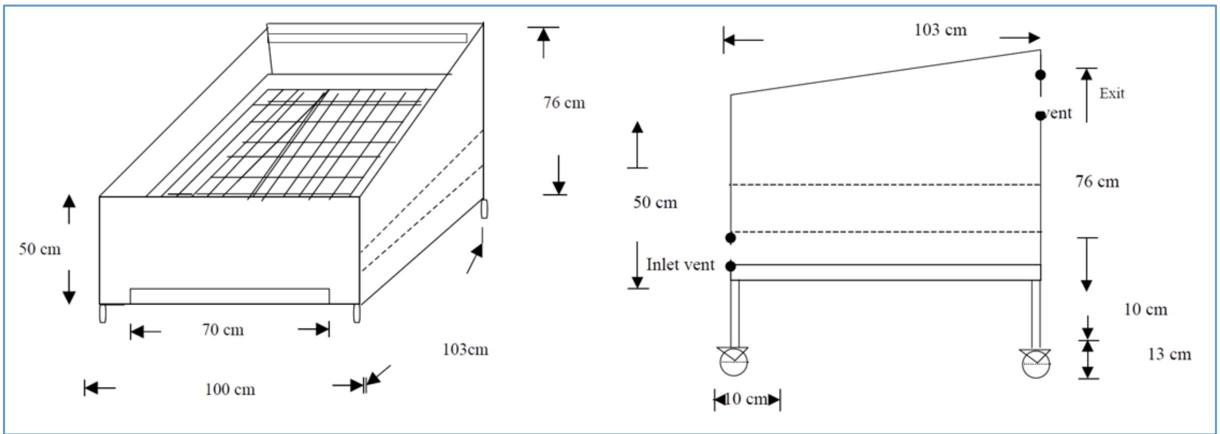

Figure 9: Direct Solar Cabinet Dryer for Mango Slices (Mohamed Akoy, EL- Amin Omda et al. 2006)

2.4.7.2 Indirect Solar Dryers

Indirect solar drying is a well-approved and often applied technology (Romero et al. 2013). In contrast to direct solar drying, the drying goods are not exposed to direct sunlight. Indirect solar dryers usually are designed as solar cabinet dryers. They consist of a solar collector and a cabinet. In the usually inclined solar collector, ambient air is heated up. The collector consists of two layers, a transparent top cover and a heat absorber at the bottom. The heat absorber usually is made of metal and/or is painted black to increase absorption. The cabinet has several trays which are permeable to air. On those trays, the product is put to dry. The hot air rises by natural convection and flows from the collector through the cabinet and through all trays, where it heats up the product and evaporates its moisture content. Because of the better air flow in indirect dryers, moisture is removed faster from the dryer. In some designs, natural convection is supported or replaced by forced convection from a blower or fan in order to increase its efficiency (Kumar et al. 2016; Kumar, Bhattacharya 2005; Mustayen et al. 2014).

Indirect solar dryers offer a more efficient utilisation of solar irradiation, higher controllability of drying parameters, and a better protection from negative influences than drying in direct sunlight (GIZ 2011).

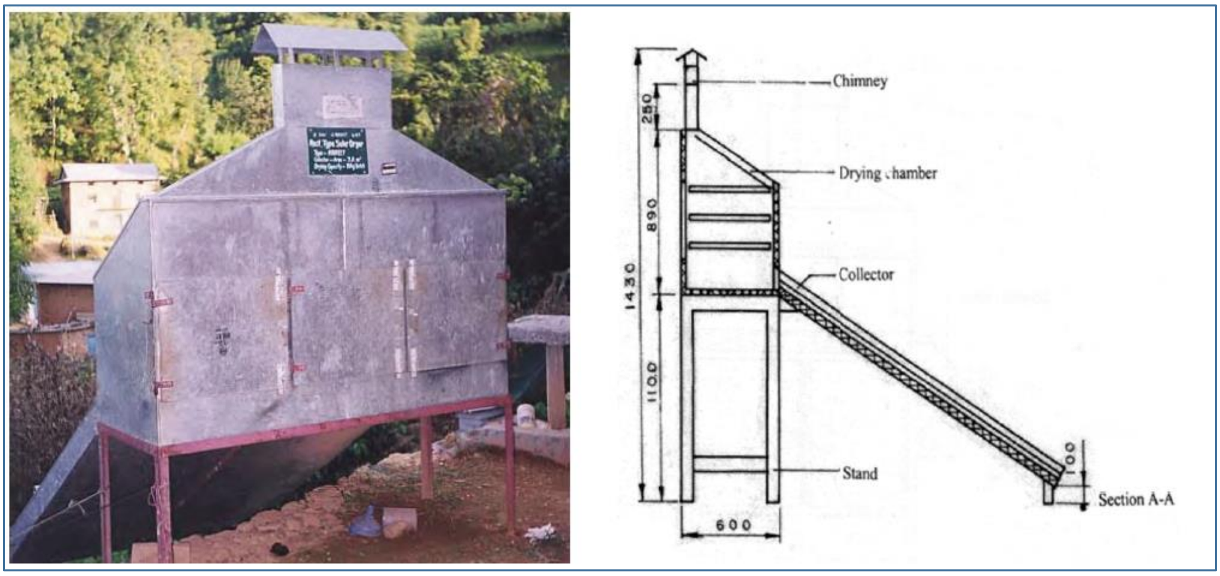

Figure 10: A Solar Cabinet Dryer (Bhandari et al. 2017)

2.4.7.3 Mixed Mode Dryers

Mixed mode and hybrid solar dryers combine different drying techniques. In mixed mode dryers both direct and indirect drying methods are applied (Mustayen et al. 2014).

A widely used design of such a dryer is a cabinet dryer that possesses a transparent cabinet cover as well as a separate solar collector. This can be active or passive (Janjai, Bala 2012).

Another common design is a solar tunnel dryer which combines one or more solar absorbers and a number of trays to place the product in a horizontal tunnel with a transparent cover. A fan provides a horizontal air flow. The product is exposed to the heat from the airflow. The airflow on one side is heated up while passing the absorbers, but also directly from the sun beams. Solar tunnel dryers offer a very effective moisture extraction and therefore reduce losses caused by spoilage or mould to a minimum (Kumar, Bhattacharya 2005; Weiss, Buchinger 2003; Bhandari et al. 2017).

2.4.7.4 Hybrid Solar Dryers

Hybrid solar dryers offer a combination of solar energy with another source of energy such as electricity, biomass, propane, wood, or any other locally available fuel. This auxiliary energy source can be used for pre-heating or for assuring the heat supply in times of insufficient solar irradiation. All types of solar dryers below can be supplemented by an auxiliary heat source (Kumar et al. 2016).

2.4.7.5 Concentrated Solar Power

Concentrated solar power involves the concentration of solar radiation through the use of mirrors and includes simple self-made solar cookers (Muthusivagami et al. 2010) as well as commercial high-tech solar power plants (Barlev et al. 2011). In very rare cases, concentrated solar power can be used for drying by concentrating solar irradiation by means of a parabolic mirror in a drying chamber (Lalage et al. 2010).

2.4.8 Solar Drying of Vanilla Pods

Besides the traditional drying process, there are various methods for drying vanilla pods. These require electric or fossil energy, such as coal stoves (Kamaruddin, Kamaruddin 2007), heat pump dryers, tunnel dryers (Van Dyk et al. 2010; Odoux 2011), and more. But there are also vanilla dryers, that work with renewable energies.

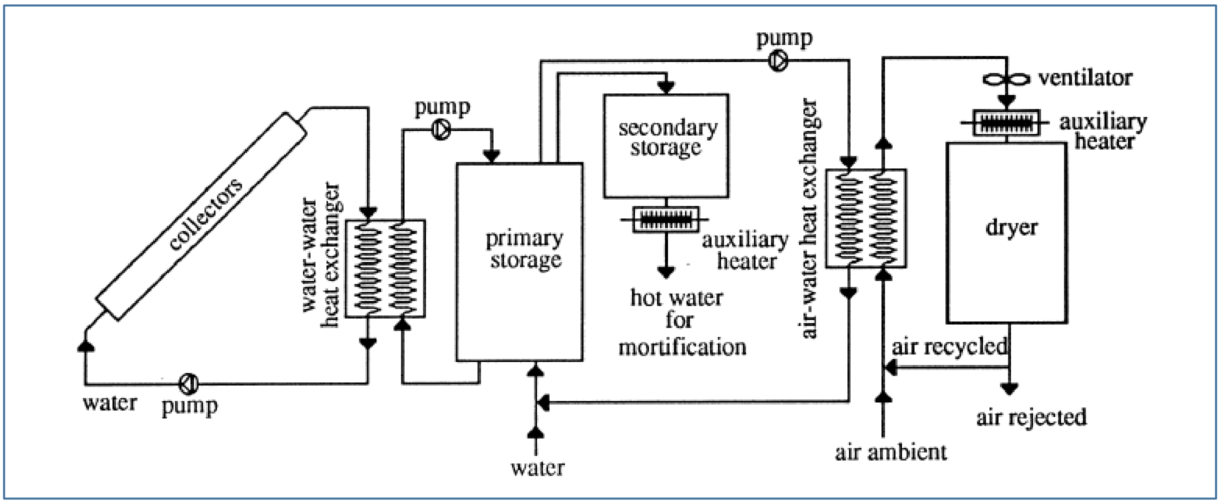

Figure 11: Solar Water and Air Heater for Vanilla Killing and Drying (Ratobison et al. 1998)

Ratobison et al. (1998) designed and simulated a solar water and air heater for both vanilla killing and drying (Figure 11). They provided easy-to-use Equations in order to make system sizing possible for vanilla producers without proper thermodynamic knowledge, even though the process itself is described as rather complicated. The emphasis of this analysis clearly was placed on the energy and mass flow for heat provision instead of the material properties, thermal behaviour, and quality aspects of the vanilla pods.

Kamaruddin, Kamaruddin (2007) designed and constructed a solar greenhouse effect dryer used in Indonesia (Figure 12). This dryer is equipped with a drying chamber, a coal oven, and an electric blower. The coal oven was used to maintain the drying temperature at night and the electric blower for providing a constant air flow. In two test runs they dried vanilla with an initial moisture content of 0.826 (wb). Coal was fired with a heating rate 0f 6.1 kW. The blower provided an average drying air flow rate of 0.6 kg/s. Further parameters and results are shown in Table 1. From these experiments, they concluded a constant drying rate of 0.0944 1/hr (db) until the critical moisture content of 1.59 (db). The vanilla quality resulting was grade 1A of the export quality standard with a vanillin content of 2.36 %.

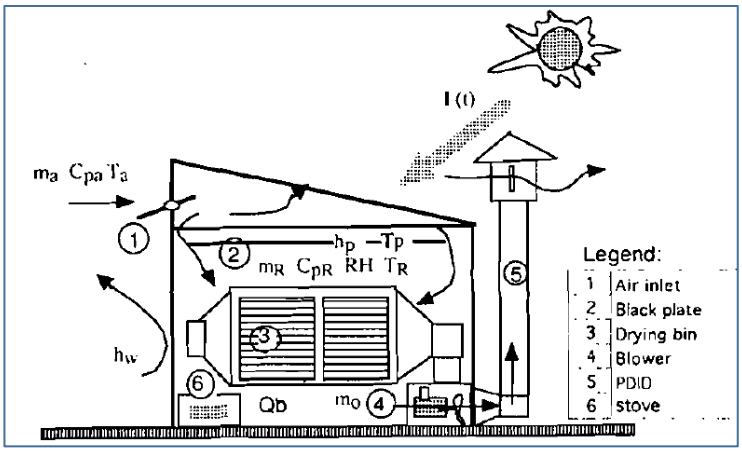

Figure 12: Solar Greenhouse Effect Dryer for Vanilla (Kamaruddin, Kamaruddin 2007)

Another design for sustainable vanilla pod drying is an indirect solar dryer described by Romero et al. (2013). They show that solar power already is used to dry vanilla pods in Cancún, Mexico (Figure 13). The main research topic here was the validation of a simulation model by measurement. The dryer presented was designed for a load of 50 kg of vanilla, but during their experiment only 1.6 kg where dried. This took about one month. The vanilla was dried according to the traditional way, which supposedly included heating and sweating. There is no information given about the vanilla temperature. The temperature inside the cabinet was between 45 °C and 50 °C. It is questionable if the vanilla pods reached this temperature, too. The most important data of this experiment is displayed in Table 1. Considering that the experiment was carried out with only a small fraction of the dryer's capacity and in the hottest of the three vanilla curing months (from January until March), it can be doubted if this dryer fulfils the temperature requirements of traditional vanilla curing. Table 2 shows the monthly averaged insolation in Cancún.

Figure 13: Indirect Solar Dryer for Vanilla (Romero et al. 2013)

Experiment	**1**	**2**
Mass of Vanilla [kg]	46.6	52.4
Final Moisture Content (wb)	0.379	0.378
Avg. Insolation [W/m2]	516	444
Avg. Temperature [°C]	43.3	44.4
Avg. Relative Humidity [%]	34.9	34.2
Drying Time [hrs]	49.0	53.3

Table 1: Parameters and Results of Vanilla Drying in Solar Greenhouse Effect Dryer (Kamaruddin, Kamaruddin 2007)

Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/m^2/day)

Lat 21.017 Lon -86.931	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	4.26	5.23	6.08	6.82	6.86	6.39	6.78	6.54	5.77	5.13	4.47	3.97	5.69

Table 2: Solar radiation data for Cancún (NASA 2017)

The quality of the vanilla from this dryer was not examined, this was left to further research.

Busono (2000) mentions that in Indonesia, solar tunnel dryers are used for drying various agricultural products, including vanilla. No further information is given on this concept.

2.4.9 Solar power application in the Huasteca Potosina

Investigations in Cuatlamayán – a community in the Huasteca Potosina have shown that the solar radiation is sufficient to justify the application of photovoltaic power (Flores Hernández 2011). However, the solar radiation in Tamazunchale (Table 3) is significantly lower than in Cuatlamayán

(Table 4), and a lot lower than in Cancún, where a solar cabinet dryer successfully was applied for the drying of vanilla pods (Romero et al. 2013; NASA 2017).

Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/m²/day)

Lat 21.244 Lon -98.777	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	3.54	4.32	5.12	5.67	6.07	5.85	5.52	5.70	4.68	4.38	3.95	3.40	4.85

Table 3:Solar Radiation Data for Tamazunchale (NASA 2017)

Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/m²/day)

Lat 21.703 Lon -99.303	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	4.04	4.92	5.86	6.28	6.44	6.03	5.64	5.76	4.71	4.58	4.34	3.82	5.20

Table 4: Solar radiation data for Cuatlamayán (NASA 2017)

2.5 Sustainable Development and Design

This subchapter gives an overview of theories and ideas in in sustainable development and design which are suitable in this thesis.

2.5.1 Development

There is a vast amount of varying development theories – each based on different ideologies, place and time of origin. This means that these theories are collections of visions about the best way to establish a desirable change in a society at a certain point in time. A large number of these development theories, which have emerged since the 19th century, focus on the development of a region (economically, socially or sustainably). Out of these approaches, regional science as a discipline emerged in the 1950s. This discipline “had strong economics basis and a focus on what firms did in regions and how their performance influenced a range of economic indicators: employment, profit, GDP and growth” (McCall 2010). From simplistic and schematic models in the beginning, the models have become more sophisticated, accurate and closer to reality. They were also influenced by changes in the society, namely globalization, technologization, transport and modern infrastructures. The core elements of these models were place and growth (in terms of economic development). Traditional development theories were usually based on neo-classical economic theory, i.e. the exogenous growth theory (Solow-Swan model) (Antonescu 5/9/2012; Nijkamp, Capello 2009; Cai et al. 2014).

2.5.2 Sustainable Development

The most acknowledged concept of sustainable development is given in the so called Brundtland Report of 1987: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WECD 1987). Sustainability includes three dimensions. These are economy, environment and society. This means that the definition of sustainable practices needs to involve these three dimensions. Thus, development has to be economically viable, there has to be a low environmental impact, and it has to respect social structures and necessities (Wu, Wu 2012). Dependent on ideology and political preferences one dimension can be considered more important than the others. Sustainability approaches that allow counterbalancing of one dimension for another, are called weak sustainability. A sustainability approach that defines the resilience of natural resources and ecosystem services as boundary for all actions and does not allow such balances, is called strong sustainability (Rogall 2002; Wu, Wu 2012). Wu, Wu (2012) further point out that the concept of sustainable development is not limited to those three dimensions.

2.5.3 Principles of Sustainable Design

Sustainable design, also called design for environment or green design, is a concept that extends the usual objectives of a design process, such as performance, reliability, and cost, by the aspects of sustainability (Kabongo 2013). Stelzer (2006) describes the consideration of these aspects as the “ultimate criteria of design”. Sustainable design requires the acknowledgement of the importance of environment protection by the corporate sector and its integration into companies’ strategies (Kabongo 2013). Its most important principles are a closed material loops, as well as the development of durable and repairable products

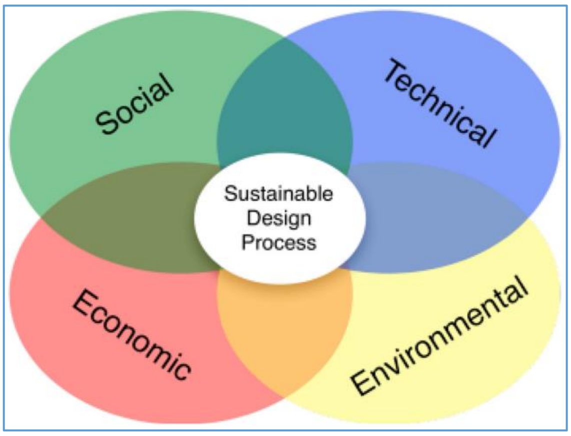

Figure 14: The four dimensions of sustainability (Nagel et al. 2012)

(Behrendt et al. 1997; Tonkinwise 2008). Through the assessment of mass and energy flows in their commercial activities, enhanced efficiency, impulses for creativity and innovation, and the anticipation of environmental legislations and market developments, sustainable design can turn into a serious competitive advantage (Kabongo 2013; Issa, Isaias 2015). It is a holistic approach, as its main principles risk-analysis, measurement of efficiency, technical development and decision-making encompass a variety of different stakeholders and disciplines (Kabongo 2013). Issa, Isaias (2015) states, that sustainable design does not only include environmental and economic, but also social aspects, such as global profit and equity. They emphasize the importance of participation in order to "take into account the opinions and perspectives of potential users to assist with the design" (Issa, Isaias 2015).

According to Nagel et al. (2012), social, technical, economic, and environmental contexts must synergize in a sustainable design process. This introduces a fourth dimension to the concept of sustainability (Figure 14).

Nagel et al. (2012) define these four dimensions of sustainable design as follows:

- ***Environmental Sustainability*** means the reduction of negative impacts or even the creation of favourable effects on the environment. Efficient use of material and energy is important throughout the entire life cycle "including manufacturing, assembly, distribution, use, and end-of-life recycle/reuse/recovery/disposal".
- ***Social Sustainability*** includes the long-term effects of a design on individuals, communities, regions, and cultures. This design has to respect local traditions, hierarchies and networks.
- ***Economic Sustainability*** deals with economic factors, including "standard of living, employment, as well as short-term and long-term costs and benefits". Here not only monetary costs must be considered, but also environmental and social.
- ***Technical Sustainability*** includes material selection, efficient use of material, recycling, recyclability, and "maintenance and functioning capabilities that meet the objective for which a product is designed". Technical sustainability also implies a focus on the design's durability and the application of appropriate technologies.

2.5.4 Appropriate Technology / Design for the other 90 Percent

Appropriate technology emerged in the 1960ies as an answer to the problems of technical aid. Technical aid in rural areas of developing countries often failed because the applied technologies often require qualifications not available in the community, are too capital-intensive, and/or are based on imported goods, which withdraw rare foreign currencies from those countries.

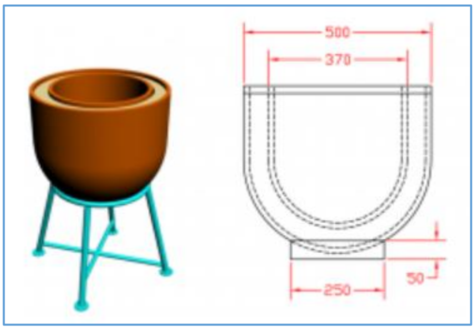

Figure 15: Zeer Pot Fridge Developed by Practical Action. It consists of one earthenware pot set inside another, with a layer of wet sand in between. As the moisture evaporates it cools the inner pot, keeping up to 12kg of fruit and vegetables fresher for longer (Practical Action).

Also, technical aid often ignores local conditions. This happens for example, when small scale community-owned poly-cultural farming is replaced by the introduction of highly mechanized mono-agricultural machinery, when people are dislocated and the landscape is changed for large hydro dams, when smoke-less stoves are promoted in areas where the smoke of cooking fires is used to fight mosquitoes and thereby malaria, or when solar-cookers are introduced in regions where traditionally the meals are taken in the late evening (Zelenika, Pearce 2011).

E. F. Schumacher is the pioneer of the appropriate technology movement (Nelson 2012). In his book “Small is Beautiful. A Study of Economics as if People Mattered” (German Title: “Die Rückkehr zum Menschlichen Maß”) he criticisees the strong technological discrepancies between urban and rural communities in developing countries. He also introduced the concept of “Intermediate Technology”, which should facilitate an more humane and eco-friendly production, taking into account the living conditions in poor rural communities (“production for the masses instead of mass-production”) (Schumacher 1983). Based on his ideas the “Intermediate Technology Development Grout (ITDG)” was founded, (renamed into “Practical Action” in 2005) being one of many organizations forming the Appropriate Technology movement (Nelson 2012; Practical Action). In Figure 15 an example for an appropriate technology by technical action is displayed (Practical Action).

Appropriate technology plays a role in sustainable development, as its includes smart and sustainable technical innovations that combine theoretical know-how and traditional knowledge (Zelenika, Pearce 2011). It is “demand-led innovation of technologies that are elegant, low energy, economical and designed to match the purpose and needs of those that use it” (Zelenika, Pearce 2011). Those non-complex, small scale technologies are based on regionally available resources and fitted into the environmental, cultural, economic, and educational conditions of their target group. Often, there are open-source (Pearce 2012). The goal of appropriate technology is the improvement of living conditions by the support of existing industries by innovation, rather than the introduction of new ones. Today, appropriate technology also focusses on vulnerability to climate change.

Sianipar et al. (2013) describes appropriate technology as an important tool in community empowerment. Empowerment, according to him, is the highest stage of development, giving the recipients the opportunity to independently develop themselves even further (Table 5). To reach this goal, a high level pf appropriateness is necessary, not only in the implemented technology itself, but also in the methods of implementation (Sianipar et al. 2013).

The concept of appropriate technology notwithstanding is subject to barriers and criticism of from different sides. Menck (1973) states that appropriate technology must not consist of the application of outdated techniques or even of outdated machinery from industrial countries. He also indicates, that appropriate technologies target small and medium scale entrepreneurs, among whom “one finds little inclination to venture into long-term productive investments”. Additionally, appropriate technologies usually are labour-intensive, which, alongside the small size of their users, are not competitive on the world market (Menck 1973).

Development	Outsiders **give** hoe to local people. The hoe will be used to develop the farming activities.
Sustainable Development	Outsiders give hoe to local people and teach them how to use and **maintain** it with better method. The use and maintenance of hoe with better method will sustain the development of farming activities.
Empowerment	Outsiders **give** hoe to local people, teach them how to use and **maintain** it with better method, and also teach them how to **make** it by themself, adjusting the function based on required conditions. These efforts will sustain the sustainable development, empower local people. When the outsiders leave them, local people will maintain the sustainable development by themself.

Table 5: Stages of Logic of Appropriate Technologies (Sianipar et al. 2013)

Zelenika, Pearce (2011) identified several barriers for appropriate technology. For example, appropriate technology has the stigma of being inferior, or of second-class technology, holding back real innovation.

The target group for appropriate design are the poorest communities in the world that do not tend to spend the little money they have too easily on new technologies. Therefore, appropriate technology projects often are first funded by donation, in order to establish trust in the aid organizations and their promoted technologies, especially in their robustness. This external funding which does not evolve from the within community itself can result in a lack of identification and thus continuity

In the last decades, many organizations dedicated to appropriate technology had to stop their activities or lost important funds (Nelson 2012; Polak 2010). According to Polak (2010) this was because of the high costs of appropriate technology projects and their dependence on donations. He is the founder of the "Design for the Other 90 Percent" approach. This approach is similar to appropriate technology but more focussed on market-led solutions with a strong emphasis on the technology's affordability. Instead of technology transfer funded by grants and donations in order to fight technical inequality, this approach seeks to empower and capacitate local producers and consumers. Its goal is the exploration of new markets and a more effective and efficient use of poor people's assets (Nelson 2012).

2.5.5 Participation and Participatory Design

Participatory processes are characterised by the inclusion of local communities to the projects of development that are dedicated to them. However, there are many different interpretations of the term participation in projects of rural development, especially concerning the level of influence that is conceded to the stakeholders (Bass et al. 1995)..

The level of participation is dependent on the stakeholder's interest in the activity, the formation of local groups, their degree of control over decisions, their powers to act, and to take effective responsibility, as well as the application of participatory methods and the creation of an institutional environment that facilitates participation (Bass et al. 1995; Brendel 2002). A multidisciplinary approach which includes a bandwidth of different methods also is important for a functioning participation (Bass et al. 1995; Norgaard 1989).

Often, governments, companies or organisations claim or are convinced that their project or policy-making is participatory, while the stakeholders involved do not feel like having given the opportunity to properly participate. This can be a serious threat for the success of projects or policies (Bass et al. 1995).

Bass et al. (1995) promote participation in all stages of a project, which are information gathering, analysis, decision-making, implementation, capacity-building, monitoring and evaluation. This corresponds to types 5 to 7 in Table 6. For them, participation is an important aspect for the sustainability of a project, because outsiders cannot always identify the priorities of stakeholders and the best ways to meet them. Additionally, centralized decision making often is impracticable, inefficient, vulnerable to corruption, "and at the same time taking responsibilities away". In contrast, a high level of participation is crucial to develop a commitment to the project and its success within the community.

Other authors agree with Bass et al. (1995) in the necessity of (inter)active participation. Altieri, Nicholls (2005) highlights the deep understanding of indigenous and rural communities about their natural environment, which is the result of a long learning process, and is of high importance for the efficiency of conservation activities and sustainable livelihood improvements.

Typology	Characteristics of Each Type
1. *Manipulative Participation*	Participation is simply a pretence, with 'people's' representatives on official boards but who are unelected and have no power.
2. *Passive Participation*	People participate by being told what has been decided or has already happened. It involves unilateral announcements by an administration or project management without any listening to people's responses. The information being shared belongs only to external professionals.
3. *Participation by Consultation*	People participate by being consulted or by answering questions. External agents define problems and information gathering processes, and so control analysis. Such a consultative process does not concede any share in decision-making, and professionals are under no obligation to take on board people's views.
4. *Participation for Material Incentives*	People participate by contributing resources, for example labour, in return for food, cash or other material incentives. Farmers may provide the fields and labour, but are involved in neither experimentation nor the process of learning. It is very common to see this called participation, yet people have no stake in prolonging technologies or practices when the incentives end.
5. *Functional Participation*	Participation seen by external agencies as a means to achieve project goals, especially reduced costs. People may participate by forming groups to meet predetermined objectives related to the project. Such involvement may be interactive and involve shared decision making, but tends to arise only after major decisions have already been made by external agents. At worst, local people may still only be coopted to serve external goals.
6. *Interactive Participation*	People participate in joint analysis, development of action plans and formation or strengthening of local institutions. Participation is seen as a right, not just the means to achieve project goals. The process involves interdisciplinary methodologies that seek mu ltiple perspectives and make use of systemic and structured learning processes. As groups take control over local decisions and determine how available resources are used, so they have a stake in maintaining structures or practices.
7. *Self-Mobilization*	People participate by taking initiatives independently of external institutions to change systems. They develop contacts with external institutions for resources and technical advice they need, but retain control over how resources are used. Self-mobilization can spread if governments and NGOs provide an enabling framework of support. Such self-initiated mobilization may or may not challenge existing distributions of wealth and power.

Table 6: Typology of Participation (Bass et al. 1995)

According to (Barkin 2010), participation offers local communities the opportunity to maintain and modify their traditions in order to adapt them to changing conditions. It also strengthens the communities' ability to manage their own human, natural, and material resources and enables them to self-government, instead of creating material or political dependencies. Only if these factors are respected, marginalised communities can be empowered to empower themselves, strengthening their communities and their identities (Barkin 2010).

Participatory design is a similar approach in an industrial context. Its goal is to design a product or a system in a way that fits the user as perfectly as possible and considers the interest of all stakeholders. The most important principles of participatory design are teamwork-meetings, needs assessment, and the analysis of prototypes (Dust, Jonsdatter 2008).

2.5.6 Endogenous Development

The term "endogenous" in endogenous development can be defined as "caused by factors inside the organism or system" (Merriam Webster Dictionary). It is an approach that emerged in the 1980s opposing neo-classic exogenous development approaches, which were characterized by uniformity and forces from outside a certain region (Stough et al. 2011; Antonescu 5/9/2012). Endogenous development focuses on long-term economic development and well-being by increasing productivity and innovation within the region, instead of redistributing wealth as the mainstream approaches do (Vázquez-Barquero 2007). The key issue thereby is to adapt development policies to local environmental factors, such as cultures, social statutes, traditions and resources. This can best be done by allowing local communities to take control over their development and fostering their own internal strengths, such as knowledge technologies and networks (Vázquez-Barquero 2007; Antonescu 5/9/2012; Stough et al. 2011).

The most unique characteristic, which distinguishes endogenous development from the mainstream development, is the role of the community that should benefit from the development. In endogenous development, the community is an actor who understands innovation and entrepreneurship as ongoing process that grows from within the community and the inhabited territory. Through capacitation, support of local initiatives and fostering of self-management, an autonomous development can be facilitated and triggered, seeking for a further strengthening of their productivity in a non-linear, flexible and creative manner. Endogenous development can be considered as a process of collective and participatory learning, based on own knowledge and carefully facilitated from the outside in order to improve the individual human capital, and thus the foundation for further economic development (Perozo Suárez 2015; Vázquez-Barquero 2007). This learning process also includes the construction and expansion of networks within the community. Networks of local companies, as well as solidarity between all actors, are an important asset for a sustaining development, because they promote the diffusion of innovation and assure that the benefits of the development remain within the community. Their own symbolic, cultural, moral and social values may be subject to change during this modernization process. But this modernization does not follow the role-model of western societies. It evolves from within. (Perozo Suárez 2015; Vázquez-Barquero 2007; Stough et al. 2011)

2.5.7 Sustainability Assessment by Indicators and Indices

Indicators of sustainability are designed and used for the assessment of sustainability. Such indicators can be of various kinds (Wu, Wu 2012). According to Gallopin (1997), an indicator is "operational representation of an attribute (quality, characteristic, property) of a system. It is used for the quantification of conditions or trends" (Gallopin 1997). Sustainability indicators only make sense if they are related to a "reference, benchmark, or threshold that represents a normal state, desired behaviour, or goal" (Wu, Wu 2012).

In the "Bellagio Principles" (Table 7), ten requirements for sustainability assessment are named (Hardi 1997)

Bradley Guy, Kibert (2010) present additional criteria for sustainability indicators, e.g. that indicators must be responsive and proactive, i.e. they must reveal developments as quickly as possible and thereby allow anticipation rather than reaction.

Principle	Meaning
1. Guiding Vision and Goals	It should follow a clear vison of sustainability and resulting goals.
2. Holistic Perspective	It should include the whole system, all dimensions of sustainability and positive as well as negative aspects.
3. Essential Elements	It should consider all relevant topics concerning all dimensions of sustainability.
4. Adequate Scope	It should include the use of a time horizon and space of study ample enough to assess all effects, and also consider historic conditions.
5. Practical Focus	It should be based on a standardized set of indicators, linked to visions and goals, based on a limited number of key issues, and compared targets or reference values.
6. Openness	All results, judgements and uncertainties should be published.
7. Effective Communication	Its results should be communicated in a clear way that is adequate to the needs of the audience and stimulates decision-making.
8. Broad Participation	It should obtain broad representation of stakeholders, and ensure the participation of decision-makers.
9. Ongoing Assessment	It should develop a capacity for repeated, be adaptive, and responsive to changes, and promote collective learning and feedback to decision-making.
10. Institutional Capacity	It should clearly assign responsibility and provide ongoing support in the decision-making process; provide institutional capacity and support for local assessment capacity.

Table 7: The Bellagio Principles (Hardi 1997)

Many different sustainability indicators are depending on the topic and scale of measurement, and whether a recent state or a development is observed (Mainali et al. 2014; Lee 2015).

Indices are sets of indicators, that are used to simplify assessment and decision-making by summarizing indicators of different kind (Parris, Kates 2003).

3 Justification

A remarkable share of the people living in the vanilla production area of the Huasteca Potosina is categorized as subject to high or very high marginalization (Trinidad García 2014). According to the vanilla producers, the introduction of an accelerated drying process would be a recognisable economic advantage and thus would lead to improved living standards. The vanilla producers could profit in various ways from a shorter drying time. First of all, it reduces the time between the purchase of the green vanilla pods and the achievement of economic benefit. Secondly, accelerated vanilla pod drying requires less effort. Therefore, time for alternative pods. Thus, discharge can be reduced.

The vanilla producers put high emphasis on the artisanal and organic character of their product. For this reason, as well as to avoid negative environmental impacts and the burden of high operation costs, renewable energies and preferably solar energy has to be used in the drying process. Also, the traditional pattern of insolation and sweating must be maintained. Only by avoiding a fundamental change in their methods acceptance among the vanilla producers can be established.

To define the most applicable and sustainable vanilla drying process for the vanilla producers in Tamazunchale, not only a thorough technical analysis is necessary. It also needs effective and interactive participation by the vanilla producers (Bass et al. 1995).

4 Research Gap

Literature on solar vanilla pod drying is very scarce. Additionally, traditional vanilla curing methods differ slightly from region to region. Solar drying for vanilla pods already exists in small scales (Romero et al. 2013) or with the support of additional electric devices (Ratobison et al. 1998; Kamaruddin, Kamaruddin 2007). None of the described processes suits the traditional vanilla curing process, in terms of the drying-sweating-pattern and the required temperatures (Ratobison et al. 1998; Kamaruddin, Kamaruddin 2007; Romero et al. 2013).

(Ratobison et al. 1998), Romero et al. (2013) and Kamaruddin, Kamaruddin (2007) describe the thermo- and fluid dynamics of two solar dryer models at length. However, they do not examine the effect of their drying methods the content of vanillin and other quality factors of the final product, nor do they perform an analysis of the economic, environmental or social consequences of the described technology.

5 Objectives

5.1 Main Objective

To develop a vanilla pod dryer, which makes the traditional vanilla pod drying more efficient, considering the principles of sustainability.

5.2 Specific Objectives

- To identify the constructional and functional parameters for a vanilla pod dryer in cooperation with the vanilla producers of Tamazunchale, based on their traditional methods.
- To design a vanilla pod drying device based on the traditional vanilla production, the principles of sustainability, and local climate factors.
- To prove, that solar drying is applicable to the local climate and to the traditional vanilla curing in the Huasteca Potosina
- To assess collectively, the success of the developing process referring to the principles of sustainable development, with special focus on the quality of the vanilla pods and the effects on the vanilla producers' economic prosperity.

6 Methodology

In the following the introduced and used concepts and methods are explained in depth. Starting with participatory processes in order to encourage the vanilla producers' participation, followed by an introduction of the theoretical drying profile. Then, a description of the two models constructed and tested with the vanilla producers follows, including the process of formation and an analysis of the theoretical basis in literature. After this, a thermal analysis and the analysis of the drying performance of the tested model is given. The second to last part in this chapter then the final design will be introduced alongside the quantitative and qualitative backgrounds and the factors leading to this description. Finally, an evaluation of sustainability will be given in depth introducing different concepts and offering different perspectives of sustainability.

6.1 Participative Process

Following the concepts of sustainability, endogenous development, and appropriate design, participatory workshops were conducted with the vanilla producers, as a high level of participation is vital for the success of this project. Four objectives are of major importance here:

- To learn and analyse the vanilla curing process traditionally applied by the vanilla producers of Tlilixochitl, so as to perfectly adapt the vanilla dryer to that process
- To identify the most important problems occurring in this method which could be solved by the application of a solar dryer
- to give them an understanding of the possibilities of solar application,
- to define the crucial parameters necessary for the development of the vanilla dryer in a needs assessment,
- to establish a strong commitment to the project, in order to ensure sustainability and persistency.

The participants of the workshops were volunteers who expected a practical and concrete benefit for their work and better opportunities to generate an income. This means that the workshops had to be designed clearly and flexibly to focus and match these on their needs and thus to be able to generate a visible benefit for them (NAAEE 2009a). It was also important to design the workshops in a way that provides the vanilla producers with a real influence on the outcome of the project (Bass et al. 1995; NAAEE 2009b).

6.1.1 Applied Concepts and Tools

In order to establish a true interaction with the participants and to obtain usable results and ideas suitable concepts have to be used and applied in workshops and intercultural interaction. In the following, these are explained.

6.1.1.1 The Triangle of Environmental Education According to Nieto Caraveo

As this thesis not only focuses on technical problems and ideas, but also offers an intercultural and interdisciplinary challenge and a bi-directional learning process through the interaction of humans, it seems appropriate and helpful to analyse it under the point of view of environmental education.

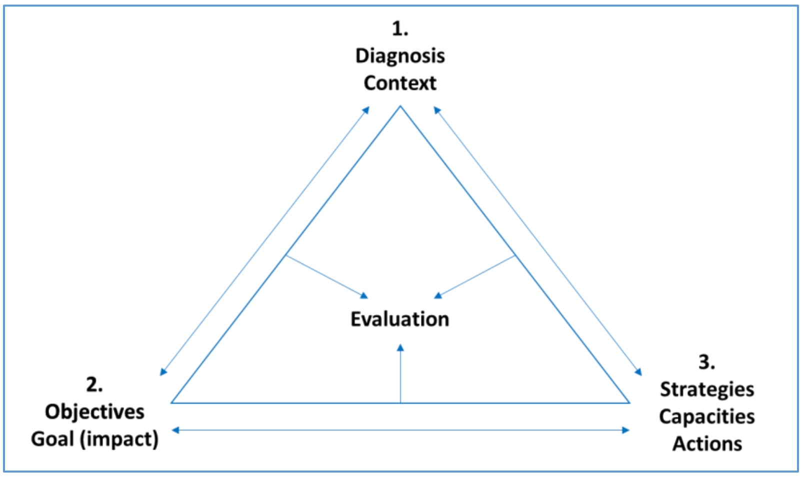

Figure 16: Triangle of environmental education according to Nieto Caraveo

A guideline for the participatory workshops is given in the scheme of environmental education presented at university by Professor Luz María Nieto Caraveo. According to her diagram, a concept for apprenticeship has three basic elements. Even though there is a sequence from diagnosis to objectives to strategies, a strong tension and interference between each of the elements exists. At each point, the congruence of the three elements has to be assured. All three elements are subject to evaluation, which forms the forth element. In the design of the workshops conducted in this project this concept was followed (Figure 16).

6.1.1.2 Needs Assessment

A needs assessment is a crucial part of participatory design. Its goal is the empiric assessment of the futures users, in order to meet their needs and expectations. It includes quantitative methods, such as observation, interviews, and questionnaires (Rabin 2008).

6.1.1.3 Concept of Diagnóstico Rural Participativo

While planning the strategy for the workshops, it is necessary to take into account that the author's personal background, objectives, and working methods as an engineer and master student are substantially different than those of the vanilla producers. Therefore, the choice of vocabulary and tools has to be appropriate in order to receive the needed information in the required accuracy and completeness. The "Diagnóstico Rural Participativo. Una Guía Práctica" ("Praticipative Rural Diagnostics. A Practical Guide") offers a good guideline and a powerful toolset to handle this challenge in the attempt of understanding the methods, advantages, and difficulties of the vanilla curing at Tlilixochitl (Expósito Verdejo 2003).

According to the "Diagnóstico Rural Participativo. Una Guía Práctica", investigation and data collection in a rural community is not considered a relationship of "the investigators" and "the investigated", but a collaborative process. This requires the appreciation of the community's knowledge and culture as well as a both-way communication about different perceptions and expectations. To ensure the quality of the received information, a multidisciplinary team is helpful, as well as a combination of different tools and sources (Expósito Verdejo 2003).

6.1.1.4 Participatory Observation

Participatory observation helps to understand the project partners' perspective and decisions by personally participating in the processes investigated instead of judging and offering solutions from an outside perspective. This serves as a tool for the beginning of the participatory process in order to thoroughly understand the issues (Expósito Verdejo 2003).

6.1.1.5 Semi Structured Interviews

Semi structured interviews consist of about 10-15 prepared key questions. The interview should have the character of a dialogue and offer the interviewee the opportunity to freely express himself without the limits of a fixed questionnaire. The interview can be done with single persons or groups about different topics such as an analysis of problems or possible solutions.

It is important to carefully choose the interview partners as well as the time and place. A familiar place and a time of day when the interview partners are free from other tasks are favourable. It is also recommended to conduct the interview in a team of two persons, so one can concentrate on the talk, while the other one is taking notes. The interviewer should respect opinion and knowledge of the interviewee, and apply to their rules of politeness (Expósito Verdejo 2003).

6.1.1.6 Matrix of Problem Prioritisation

With this tool, it is possible to organize the problems mentioned with reference to their importance and urgency. This new organization should reflect the priority and hierarchy of the problems. In order to obtain and perceive prioritization and thus to focus on the most important issues, the community takes action. To do so, the community forms a group of several people and the previously identified problems are mapped in a matrix. Then the project partners of the community vote for the most important, or most urgent problem(s) (Expósito Verdejo 2003).

6.1.1.7 Scenarios of Alternatives

In order to facilitate decision-making, different alternatives for the solution of a problem can be evaluated in a qualitative or quantitative way, with this tool. In a group, previously identified alternatives are listed. Following certain criteria, those alternatives are cooperatively evaluated and then hierarchised (Expósito Verdejo 2003).

6.1.1.8 Production Flowchart

This matrix represents the production process of a product realised by the community in all its steps. This helps analysing the production in detail to find aspects that can be improved. In group work, the production steps are be listed, brought into the right order, and then completed with details (Expósito Verdejo 2003).

6.1.1.9 SWOT Analysis

The SWOT (Strengths, Weaknesses, Opportunities, and Threats) Analysis can be used to analyse and evaluate a project in different phases and on various levels. In a group discussion, the strengths, weaknesses, opportunities, and threats of the project are gathered in a 4-field matrix. The next step is a discussion about how weaknesses can be eliminated and threats avoided (Brendel 2002).

6.1.1.10 Prototypes

The use of prototypes is a very important tool in participatory design. Prototypes are models of a product that already have the same visual appearance and functionality as the final product. They serve for testing purposes and the performance of adjustments before starting the preparations for serial production. In contrast, functionality models have a different visual appearance than the final product, and only serve for testing the functionality of the whole product or parts of it (Dust, Jonsdatter 2008; Botsch 2008). In this thesis, the solar dryers constructed for testing and demonstration will be referred to as “models”, as they are downsized copies of already existing dryers rather than prototypes for the final design.

6.1.1.11 Blitzlicht

The Blitzlicht (German for flashlight) is a method in presentation or education. It serves to reveal a snap-shot of the participants’ feelings, opinions, and expectations. It is often used for feedback purposes. A question is given, and every participant can answer to this question. An item can be given from participant to participant, in order to indicate who’s turn it is. The answers are neither discussed, nor commented and are left standing on their own The Blitzlicht mainly serves to get an overview about the group's mood (Gugel 2006).

6.1.1.12 Questionnaires

A questionnaire is used for the sustainability evaluation in this master thesis. In the questionnaire, the participants expressed their opinion about the quality, the participatory design process and the resulting vanilla pod dryer. In the questionnaire, the approval to different statements regarding the design process and the dryer could be expressed with Mexican school grades from 5 to 10.

6.1.2 Composition of Workshop Participants

In order to ensure a broad variety of different knowledge and points of view, persons who are occupied with different aspects of the vanilla production process were invited to the workshops. The number and compositions of participants in the workshops changed during one workshop to the next, as the participants often were occupied with their personal work duties. Nevertheless, a group of persons turned out to be the backbone in the participatory workshops, and the main contact persons.

- **Ms. Karina Lizbeth Trinidad García** is a doctorate student at the UASLP. In the research for her thesis "Modelo de Producción Agroecologica para la Vainilla en Sistemas Agroforestales Tradicionales de la Huasteca Potosina" (Spanish for: "Agroecological Production Model for Vanilla in Traditional Agriforestry Systems of the Huasteca Potosina") she has been working with the vanilla producers of Tlilixochitl for several years and is an accepted and well-respected contact for them. She was an important contact person and aid for this thesis as she co-organized the workshops. She often spoke to the vanilla producers on the author's behalf, when he could not get the information he needed due to language or cultural reasons.
- **Ms. Cándida Morales Santos** is the voluntary chairwoman of Tlilixochitl. She is employed as a kindergarten teacher in San Luis Potosí, and works in Tlilixochitl in her spare time. She is responsible for accounting, marketing and the operational decisions about the vanilla curing methods. Strategic decisions have to be agreed on with the associates.
- **Ms. Virginia Cruz Hernández** is responsible for the implementation of the vanilla curing at Tlilixochitl. Due to her experience, she is very important for the cooperative, but still is employed and paid her salary on a daily basis. In the vanilla harvesting and curing season, she is responsible for the instruction of the other day labourers.
- **Mr. Emilio Gonzalez Martinez** is a vanilla pod grower from the nearby municipality Matlapa, and an associate of Cuichapa, the centro de acopio there. He is very interested in the project, and his technical understanding and handicraft skills are of major importance for the project. In the workshops, he always participated vividly, but also expressed his scepticism.
- **Mr. Benito Felix Hernández** is a vanilla grower from Tamazunchale and associate of Tlilixochitl. He participated in the workshops and also in the construction of the models.
- **Mr. Fernando Hernández Ávilez** is a vanilla grower from Matlapa. He is no associate of Tamazunchale, but does the curing of his vanilla pods on his own ground. He is interested in enhancing the results of his curing; therefore, he participated in the capacitation projects held at Tlilixochitl.
- **Mr. Jacobo Hernández Medina** is a teacher from Matlapa and an associate of Tlilixochitl. His father, an associate as well, is growing vanilla in Tamazunchale. Mr. Hernández contributed to the work of Tlilixochitl on a voluntary basis by giving important technical advice and made contacts.

- **Mr. Regulo Sebastian Perez** is a technician paid by the government to serve as a technical advisor for Tlilixochitl. He participated sporadically and in the workshop and took a rather observant role.

6.1.3 Summary of Workshops

In Table 8 and Table 9, a short summary of the first meeting with the vanilla producers of Tlilixochitl and the three following workshops are displayed. The results and observations can be found in chapter 7.1. Photos, and documents are in the Annex.

In the left column of Table 10, the steps and methods of the construction and the test run of the models are briefly represented. The technical details, drawings and photos can be found in chapter 6.3.2 and 6.3.4. As this part was rather an ongoing process of observation, interviews, and meetings, than a series of workshops, it is summarized as one procedure. The observations can be found in chapter 6.3.5, new findings about the vanilla drying process or requirements for the dryer are added in chapter 7.1. The feedback regarding the test run is summarized in chapter7.2.1.

The evaluation displayed in the right column of Table 10 was done by Ms. Karina Lizbeth Trinidad García because the author already had returned to Germany. Additional findings regarding the needs assessment are added in chapter 7.1. The results of the evaluation will be discussed and analysed in chapter 7.2.1. Photos and documents are in the annex.

	First Visit	*Workshop 1*
Date	4th and 5th of March 2016	7th of May 2016
Participants	-	12 Persons, members of Tlilixochitl and vanilla farmers
Diagnosis & Context	• No knowledge about the vanilla production in the Huasteca Potosina, its climatic conditions, and the living circumstances of the local vanilla producers.	• Vanilla producers had little knowledge about the principles of solar drying. • Need for a thorough understanding of the vanilla producers' methods, expectations and necessities.
Objective & Desired Outcome	• To learn about the vanilla production • technical details (techniques, time spans, temperatures, difficulties encountered, etc.), • specific necessities, and • potentials (forms of organisation, value chain, agricultural production of the vanilla pods etc.)	• To exchange information in order to find a solution that fits the expectations and necessities of both author and the vanilla producers. • To enable a fruitful cooperation, it was necessary to inform the vanilla producers in detail about the objectives and methodology of this project. • To support the vanilla producers with an idea about already existing techniques for drying with renewable energies.
Strategy, Actions and Applied Tools	• Assistance in a workshop conducted by Ms. Trinidad which was dedicated to the farming activities of the local vanilla growers • Visit in the "centro de acopio" of Matlapa • Visit in the "centro de acopio" of Tlilixochitl in Tamazunchale. • In both "centros de acopio" a participatory observation was planned. But there were no tasks were participation were possible. Still the author could ask a lot and touch the pods to "feel the quality features" • Semi-structured interview with Ms. Morales Santos and her husband from Tlilixochitl about the steps and important issues of the vanilla curing process and about their previous knowledge of solar dryers.	• Short introducing game with a Blitzlicht for introduction and expressing expectations towards the project • Establishment of a production flow chart with the most crucial key points of the vanilla curing • Matrix of problem prioritisation: naming and then prioritising important characteristics of a future solar dryer for vanilla pods. • Analysis of scenarios of alternatives: Advantages and disadvantages of different possible materials • Availability of professional skills within the association
Results	• Introduction of vanilla curing, difficulties and quality features. • Ms. Morales Santos already had some previous contact and ideas about solar drying, and also with a walk-in gas oven for vanilla pods that had serious effects on the users. • The most important factors of a vanilla pod dryer are the right temperatures, the quality and immaculacy of the vanilla pods and the security of the staff.	• Definition of expectations towards the project • Details about the vanilla curing process with the crucial step: Insolation • Most important characteristics for a solar dryer: • Reduce costs, work and space • Same or better quality of the end product • Generation and regulation of heat • Capacity • Advantages and disadvantages of building materials

Table 8: First Visit and Workshop 1

	Workshop 2	*Workshop 3*
Date	16th of June 2016	22nd – 23rd of July 2016
Participants	8 Persons, members of Tlilixochitl and vanilla farmers	6 Persons, members of Tlilixochitl and vanilla farmers
Diagnosis & Context	• Lack of fundamental knowledge in natural sciences. This makes it difficult for them to imagine the effects of different solar drying • Scepticism towards the applicability of solar irradiation	• The former workshops had a rather informative character, but no decisions have been made yet. • Only the choice of technology seems to be sealed, as the solar oven convinced all of the vanilla producers.
Objective & Desired Outcome	• To give the local vanilla producers a vivid impression about the physical effects of solar radiation. • To explain the theoretical basics, which they will need to be able to participate in the design process. • To familiarize the vanilla producers with common solar thermic application and their backgrounds	• An agreement has to be found about the further procedure and the responsibilities in the project during the author's absence. • Before leaving for Germany, constructional key factors have to be defined, for example material, size and others.
Strategy, Actions and Applied Tools	• Blitzlicht: Knowledge and associations about regenerative energies in general. • Presentation of three functionality models, a solar oven, a parabolic solar cooker and a model of a solar cabinet dryer, were used for the preparation of food. The participants were allowed to see and touch the functionality models, and we explained them how they work. • Power Point presentation of solar-energy-related-theory. • Scenarios of Alternatives: discussion of the advantages and disadvantages of the three functionality models and their applicability for vanilla pod curing.	• The workshop started with a Blitzlicht feedback round by the workshop participants and a résumé of the last workshop • Then every participant wrote down the points that were most important to him/her regarding the design and function for the solar pod dryer • Then the participants were divided in two groups and each group had the task to draw their preferred type of solar vanilla dryer as visualised scenarios of alternatives. • Later on, we discussed advantages and disadvantages as well as the assumed construction costs and the capacity. It is to mention that with capacity we referred to the spatial capacity and not to the thermal drying capacity.
Results	• The perception of renewable energies among the vanilla producers is quite ambivalent. • The functionality models were fascinating for the participants. They listened carefully to the explanations. Relatively early it became visible that the solar oven convinced them the most. • The participants got an idea about how solar energy can be used for the vanilla curing.	• The vanilla producers prefer the greenhouse effect solar dryer • It should be a fix construction of glass, wood and bricks. The dryer should be big enough so that it is possible to enter it with the racks on wheels that are currently used for storing the vanilla pods • That means, that the dryer needs a height of at least 2,5 meters. It should exclusively work with solar power and be big enough to process 250 to 500 kg of vanilla in one batch. • It is highly questionable if such a dryer with the size of a small house would be functioning properly.

Table 9: Workshops 2 and 3

	Construction and Testing of Models	*Conclusion and Evaluation*
Date	19th of February – 2nd of April 2017	9th of July – 14th of August 2017
Participants	• Ms. Karina Lizbeth Trinidad García • Ms. Cándida Morales Santos • Ms. Virginia Cruz Hernández • Mr. Emilio Gonzalez Martinez • Mr. Benito Felix Hernández • Mr. Jacobo Hernández Medina	• Ms. Karina Lizbeth Trinidad García • Ms. Cándida Morales Santos • Ms. Virginia Cruz Hernández • Mr. Emilio Gonzalez Martinez • Mr. Benito Felix Hernández • Mr. Jacobo Hernández Medina • Regulo Sebastian Perez
Diagnosis & Context	• After having exchanged information and expectations, the vanilla producers wanted to see proof for the possibilities of solar vanilla drying.	• The test of the models was finished and the participants could gather experiences • For the design of the final design and the assessment in this master thesis, an evaluation by the participants was needed
Objective & Desired Outcome	• To test solar drying under the climatic conditions of Tamazunchale • To give confidence to the participants • To test the effect of this method on the vanilla's quality • To evaluate the thermic efficiency	• To definitely define the parameters for the final design based on the participants experiences with the models • To let the participants evaluate the level of participation and the applicability and benefit of the vanilla dryer
Strategy, Actions and Applied Tools	• As a project of both way participatory observation, two models of solar dryers were constructed and tested. • During this process, four assemblies were held: 1. The production flow chart from the first workshop was discussed again to clarify questions about details, then the construction plans were shown and the further proceedings discussed. 2. The presentation and inauguration of the models 3. A preliminary and a 4. Final feedback round to discuss the experiences made while using the models and the results. An analysis of scenarios of alternatives for the both models was made, and a SWOT analysis for the direct dryer model.	In the first Workshop on the 9th of July: • A draft for the solar dryer design was discussed by the participants • In another matrix of problem prioritisation, the participants could use their experiences with the models to vote the most important characteristics for the final design and name disadvantages of the three contemplable materials, pine wood, metal, and plywood. In the second Workshop on 18th of August • The dryer design, adapted according to their comments, was discussed again • In a questionnaire, the participants expressed their opinion about the quality, the participatory design process and the resulting vanilla pod dryer. In the questionnaire, the approval to different statements regarding the design process and the dryer could be expressed with Mexican school grades from 5 (failed) to 10 (excellent).
Results	• The main goal in the vanilla drying is the heating rather than the dehumidification. • The participants liked to work with the direct model and were even excited about it • Collectively, the team decided to drop the indirect dryer concept and to concentrate on a direct dryer	• The draft was well received, only slight changes were proposed • The priorities of the participants regarding the characteristics of the solar dryer changed after the test run. They now are more precise. • The feedback turned out predominantly positive.

Table 10: Construction, Testing and Evaluation

6.2 Theoretical Drying Profile

Based on the literature on vanilla pod drying and the explanations of the vanilla producers, a theoretical drying profile for vanilla will be made, which serves for the sizing of the solar dryer models.

6.2.1 First Approximation

With the description of the traditional drying process, given by the vanilla producers in the first meeting and in literature, a drying profile was generated. This profile will be applied as a reference for product quality, assuming that the same drying behaviour will result in the same characteristics of the final product.

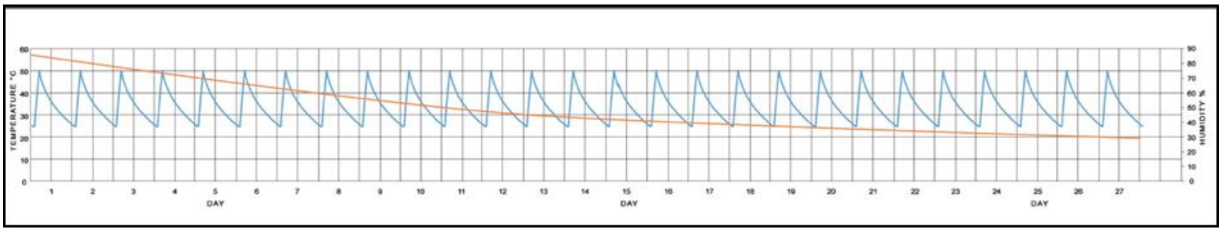

Figure 17: First Approximation of Drying Profile

This first approximation, shown in Figure 17, displays the alternating heating and cooling of the vanilla pods (blue line) and the slowly decreasing moisture content (red line). The vanilla pods cool down slowly as they are wrapped in blankets. The drying rate was considered falling constantly.

6.2.2 Physical Properties of Vanilla Pods

6.2.2.1 Moisture Content

The moisture content of vanilla pods was defined in the Laboratory of soils and waters of the UASLP by drying two batches of ten vanilla pods each in an electric oven at 65 °C until completely dry. The vanilla pods of the first group were left fresh and green, while those of the second batch were scalded in hot water according to the local traditional vanilla curing process, before drying.

The result was 0.96 (wb) of moisture content, which seems too high in comparison with the of 0.80 to 0.85 (wb) offered in literature (Pérez Silva et al. 2011; Hernández Hernández 2014; Jiménez et al. 2013) and named by the vanilla producers. Therefore, a moisture content of 0.83 (wb) was assumed.

6.2.2.2 Specific Heat

The specific heat of vanilla pods depends on the specific heat of the chemical compounds contained in the vanilla, and on their individual share in the total weight. As the moisture content is diminishing during the curing process, the specific heat must be regarded as a function of the percentage of water in the vanilla pods.

The composition of the dry matter can be seen as constant during the entire curing process. The dry matter of vanilla pods approximately consists of 34 % fibre, 23 % carbohydrates, 21 % fat, 15 % ash, and 8 % proteins (Azeez 2008; Charles 2013). Consulting the specific heat of each component as given in ASHRAE (2006), this results in the overall specific heat of the total dry matter of 1.768 kJ/kg*K.

With a reference temperature of 45 °C, water has a specific heat of *C = 4.122 kJ/kgK* (ASHRAE 2006). With this data, the heat capacity of the vanilla pods can be estimated for different moisture contents, i.e. for different states of drying. In the beginning, with the estimated moisture content of 0.83 (wb), the heat capacity is *C = 3.723 kJ/kgK*, in the final stage of the drying, with a moisture content of 0.35 (wb) the heat capacity is *C = 2.597 kJ/kgK*.

6.2.3 Calculation of Drying Profile Based on Literature

The drying profile is generated by applying the observations by Kamaruddin, Kamaruddin (2007) to the traditional vanilla curing process described by Hernández Hernández (2014). In doing so, some assumptions will be necessary. The drying time will be determined in days instead of hours, as it is not known, whether the vanilla pods continue drying while sweating or not.

The initial moisture content of 0.83 (wb) equals 4.88 (db). Kamaruddin, Kamaruddin (2007) suggest, that the critical moisture is 1.59 (db). Between these two values the moisture content (db) decreases lineally. In the falling-rate period, the rate of drying is constantly decreasing. The final moisture content is 0.35 (wb), which is 0.538 (db). For the drying curve, a drying time of 24 cycles of insolation and sweating on 24 consecutive days is assumed.

From the graphs shown in Kamaruddin, Kamaruddin (2007) one can assume that the critical moisture content of 1.59 (db) is reached after two third of the drying time, i.e. after 16 days. The last 8 days, from the 17^{th} to the 24^{th} cycle the drying rate is falling.

Therefore:

$$t_c = 16\ days$$

$$t_f = 8\ days$$

The equations (10) and (11) can be used to validate this assumption. To calculate the coefficient for the time of drying (*mA*), at first the equilibrium moisture content is needed.

As the vanilla pods must not exceed a temperature of 55 °C, this temperature will be assumed as the maximum temperature inside the dryer model. For the relative humidity 25 % are adopted, as given in Kamaruddin, Kamaruddin (2007).

With the “kW Psychrometric Functions Library” for Microsoft Excel (downloaded at www.kw-engineering.com) and the elevation of the location, a wet bulb temperature of 33.8 °C was calculated. Now the equilibrium moisture content and the free moisture at the critical moisture content can be determined with Equation (6):

$$X_e = -1.20875 + 2.47(55 - 33.8) - 0.0993(55 - 33.8)^2 = 0.066$$

$$f_c = X_c - X_e = 1.59 - 0.066 = 1.524$$

The *mA* -value can now be calculated with equation (10):

$$mA = \frac{X_1 - X_c}{t_c \times f_c} = \frac{4.88 - 1.59}{16 \times 0.066} = 0.135$$

$$f = X - X_e = 0.538 - 0.066 = 0.473$$

With Equation (11) the drying time for the falling rate period can be determined:

$$t_f = \frac{1}{mA} \ln\left(\frac{f_c}{f}\right) = \frac{1}{0.135} \ln\left(\frac{1.524}{0.473}\right) = 8.7\ days$$

This means the following: If 16 days are needed to dry the vanilla from the initial moisture content of 4.88 (db) to the critical content of 1.59 (db), the falling rate period until 0.538 (db) will last 9 days. Therefore, the total drying time is corrected to 25 days. This results in the drying profile displayed in Figure 18.

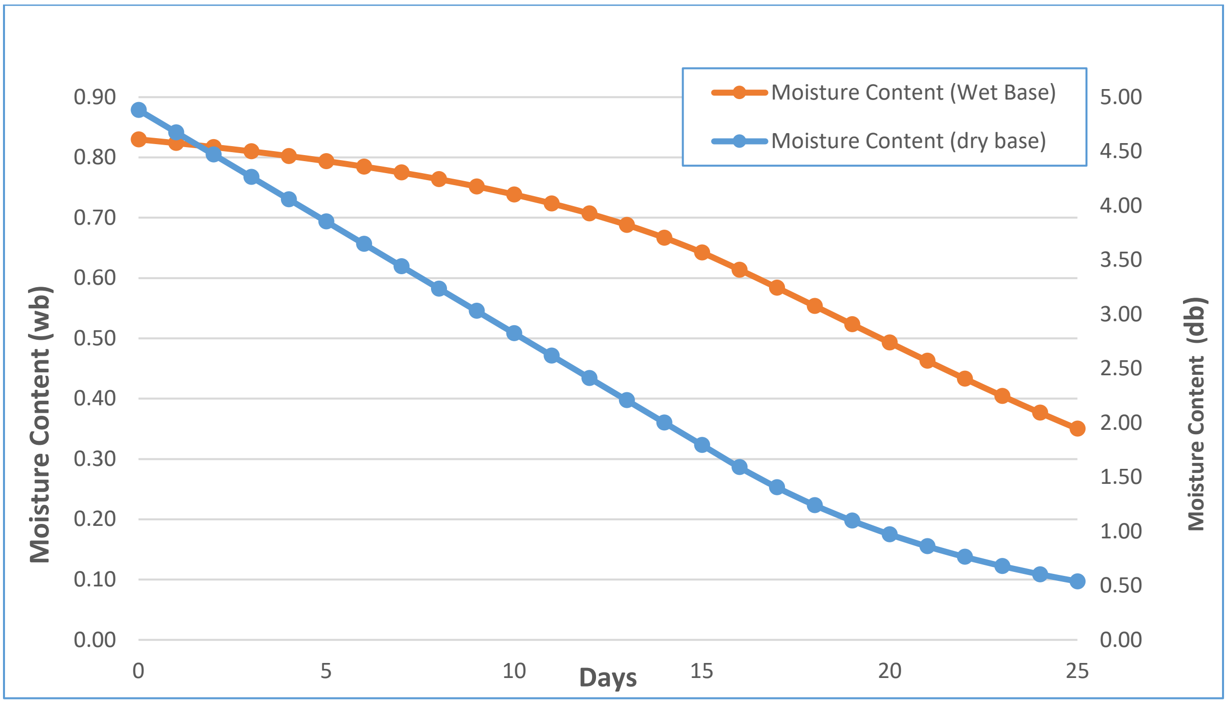

Figure 18: Drying Profile Based on Literature

The drying rate in the constant rate period is:

$$v_c = \frac{X_1 - X_c}{t} = \frac{4.882 - 1.59}{16\ days} = 0.206/day$$

The drying rate in the falling rate period is proportional to the free moisture. The corresponding factor was determined by iteration. It is:

$$v_f = 0.122 \times f\ /day$$

6.3 Experiment with Models of Solar Dryers

In order to test the applicability of a solar dryer for the vanilla curing in the Huasteca Potosina, models of two different solar dryers are made. One is an indirect solar dryer based on the research of Romero et al. (2013), the other is a direct solar dryer as presented by Mohamed Akoy, EL- Amin Omda et al. (2006) and Ogheneruona, Yusuf (2011). In both models, a batch of vanilla pods is dried from the green status of 0.83 to the final moisture of 0.35. Another batch of vanilla is sun dried following the traditional method to serve as reference.

March is the final month of vanilla curing; therefore, fresh vanilla was already scarce. The original plan of testing ten kg of vanilla in each batch had to be changed, as the vanilla producers reported, that only about three kg of vanilla would be available for each batch. In a first step, the required collector surface has to be calculated. It is crucial, that it is the same in both models.

With this experiment, the drying performance of the designs as well as thermal behaviour of the vanilla pods can be analysed. The models also were also for the capacitation of the vanilla producers. By using the models and seeing the results, they are supposed to gain confidence in the technology and skills how to use it.

6.3.1 Sizing of Models

The first step was to determine the collector surface needed to dry three kg of green vanilla pods in 25 days with two hours per day. Irradiation data from NASA (2017) revealed an average inclination θ at solar noon on a horizontal surface for the month of March of 23°. Hence, the slope of the solar collector became 23° degrees as well, in order to yield as much irradiation at noon as possible, when the irradiation is highest.

With an hourly radiation data obtained with the programme Meteonorm, the average irradiation at Tamazunchale in the month of March from 10:00 to 15:00 hours on a surface with a slope of 23 ° is calculated.

$$I_{average} = 542\ W/m^2$$

As the moisture content of the pods is highest on the first day of drying, the energy needed for heating and drying is the highest, too, because water is the ingredient with the highest heat capacity. The vanilla pods have to heated up from an initial temperature of 25 °C to the wanted temperature of 45 °C. With equation (22) the energy needed for heating is:

$$Q_{heat} = m\,C\,\Delta T = 3\ \times\ 3.723\ \times (45-25) = 223\ \text{kJ}$$

At an initial load of 3 kg vanilla the dry mass is:

$$m_d = m_t(1 - x_{i1}) = 3(1 - 0.83) = 0.51\ kg$$

In the constant rate period, the drying rate is 0.206 /day. The mass of water to evaporate is:

$$m_e = m_d(X_1 - X_2) = 0.51 \times 0.206 = 0.105\ kg$$

Following Equation (23) the heat flow needed to evaporate this amount of water:

$$Q = m_e\,\lambda_s = \ 0.105\ x\ 2393.6 = 251\ kJ$$

At Tlilixochitl the vanilla pods are put out to dry for two hours. The collector surface needed to harvest the required energy within two hours can be calculated with equation (29). Choosing the average between Mohamed Akoy, EL- Amin Omda et al. (2006) and Ogheneruona, Yusuf, the dryer's efficiency was assumed to be 0.25.

$$A = \frac{Q_{heat} + Q_e}{I_{av} t\, \eta_c} = \frac{223kWs + 251kWs}{0.570\frac{kW}{m^2} \times 7200s \times 0.25} = 0.46\, m^2$$

To facilitate the construction, a collector surface of 0.5 m^2 was chosen.

6.3.2 Design and Construction of Models

Mohamed Akoy, EL- Amin Omda et al. (2006) and Ogheneruona, Yusuf (2011) constructed their direct solar cabinet dryer with a square collector surface of about 1 m^2. In the direct dryer model of this master thesis (Figure 19), the collector surface has the dimensions 100 x 50 cm. It is made of glass with a thickness of 6 mm and tilted 23 ° horizontally. It was put into a frame with the width of 5 cm. The cabinet is a box made of pine wood with a thickness of one inch (3 cm), as this material is readily and cheaply available in the region. After the grinding and deburring the wooden boards, the thickness was reduced to 2.5 cm. The cabinet had an interior base area of 46 x 100 cm. The bottom was insulated with a styrofoam plate of 1 cm thickness. On top of that, a black metal sheet with a thickness of 0.5 mm was placed to serve as heat absorber. The interior of the four walls was covered with aluminium foil in order to concentrate the irradiation towards the absorber. On the outside, the model was painted black. The glass cover had hinges and served as a lid in order to put the pods inside the cabinet and to retrieve them after drying. The frame of the glass was also painted black. The size of the vents was based on Mohamed Akoy, EL- Amin Omda et al. (2006), as well. As the model only had half the depth and thus half the volume as their prototype, the size of the vents was halved as well. An air inlet with an area of 0.02 m^2 was incorporated on the front side 5 cm above the absorber. The air outlet with an area of 0.1 m^2 was installed on the back 10 cm below the lid. Two tray holders were installed 10 cm and 20 cm above the absorber. The trays had the same area as the absorber.

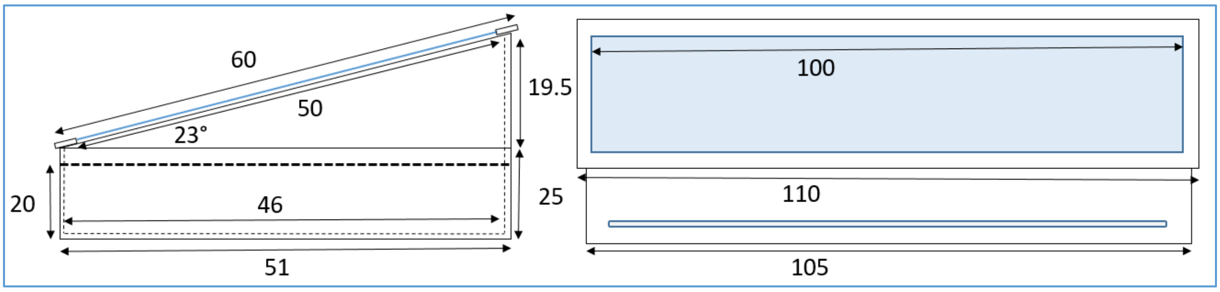

Figure 19: Design of Direct Dryer Model

The indirect cabinet dryer described by Romero et al. (2013) was downsized from a collector surface of 2 m^2 to 0.5 m^2 (Figure 20). All the proportions were kept. In contrast to the original indirect dryer, but equal to the direct model, wood was chosen as construction material. Only the roof and chimney were made of steel sheet. The solar collector consisted of a 100 x 50 cm glass plate and a 159 x 50 cm black steel sheet parallel to the plate. The steel sheet served as heat absorber and was longer than the glass plate because it reached under the cabinet to increase the heat convection from the collector to the cabinet. Underneath the absorber, a styrofoam plate was placed. The distance between glass and absorber was not decreased in order not to stall the air flow. The collector had a tilt of 23 °. The cabinet has 4 trays of 40 x 50 cm, with an equidistance of 10 cm. It also has a two-wing door to reach the trays.

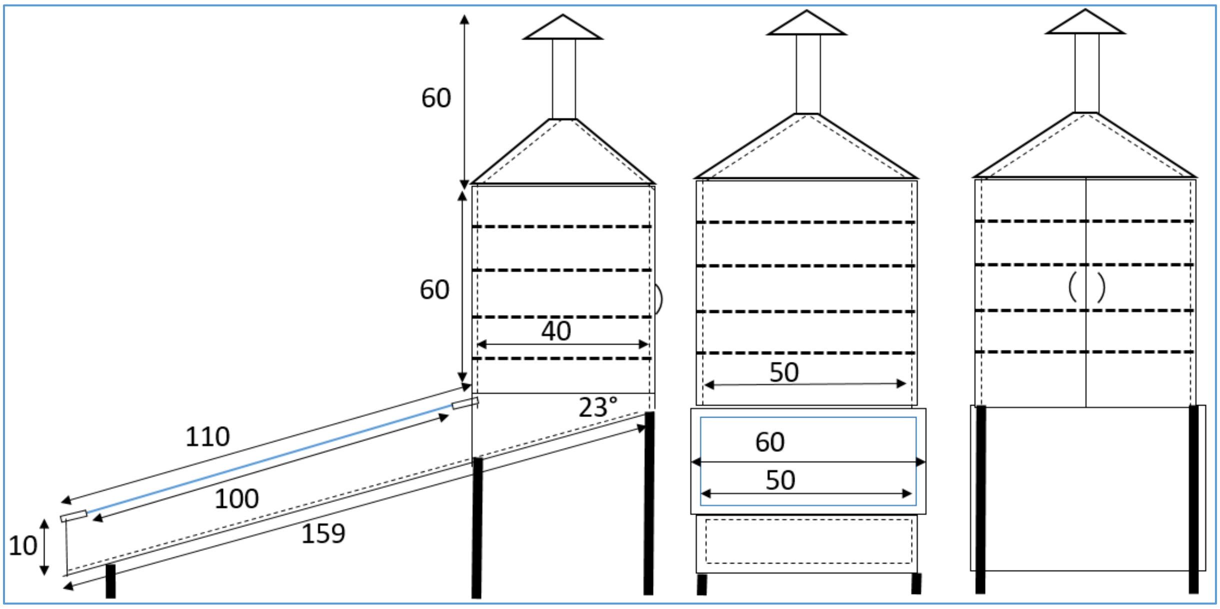

Figure 20: Design of Indirect Dryer Model

The construction took place in an interactive and participatory way. The author paid for materials and tools were provided by the vanilla producers. The construction took about one week. It began on the grounds of a “Colegio de Bachilleres” in Axtla de Terrazas, one of the neighbouring districts of Tamazunchale. Up to three vanilla producers were constantly and actively participating in the construction process. Difficulties and ideas were discussed in an open manner. One problem was the quality of the wood. The wood was available in boards with a breadth of 30 cm. If a breadth of 40 or 50 cm was required, two boards hat to be combined. At the time of purchase, the boards were freshly produced, so while drying out they shrank and bent, which provoked gaps between the connected boards. Those gaps were closed with silicone or a mixture of saw dust and glue.

The vanilla pods also may not have any contact to metal or plastic. As the trays must be stable and at the same time cast as little shadow on the absorber or the tray beneath as possible, they were made by weaving stripes of water reed to a wide-meshed grid and nailing this grid to a frame made of slim wooden slats. In order to protect the vanilla pods from insects, the models were equipped with mosquito nets. VOC-free indoor paint was used for the black colour. The roof and chimney for the indirect dryer model were made by a local blacksmith.

Figure 21:Different Phases in the Construction of the Models

After two weeks of testing, sliding covers were installed to the vent of the direct dryer model. They allowed different positions: completely open, ¾ open, ½ open, ¼ open, and completely closed. At the same time, the vents were enlarged by doubling their height. Hence, in the position ½ open the vents had the same size as before. This setting was used in the further test run. A detailed analysis of the effects of different settings was not made. Yet, the sliding covers were used to validate the air flow inside the model (see Chapter 7.2.2.1).

6.3.3 Measuring Instruments

An overview of the used instruments to measure the various indicators is given in this chapter.

6.3.3.1 Thermometers

Three mercury based partial immersion thermometers from a laboratory supplies store were used. Two of them had a metering range of up to 60 °C, the third up to 100 °C.

6.3.3.2 Temperature and RH Logger

Three HOBO U23 Pro v2 temperature/relative humidity data logger were borrowed from Dr. Javier Fortanelli Martínez from the UASLP institute of Investigation of Desertic Zones. They can log the temperature and relative humidity in adjustable intervals and can be read via an USB adaptor.

6.3.3.3 Infrared Thermometer

An Extech dual laser infrared thermometer was borrowed from Mr. Jean Fritche from the Habitat Faculty of the UASLP. Following the instructions in the manual the emissivity was adjusted to 0.95 for black surface. Two red laser points helped to use the thermometer the correct distance to the measured object.

6.3.3.4 Mobile Weather Meter

A Kestrell 4500 NV mobile weather station was borrowed from Dr. Marcos Algarra Siller of the UASLP Faculty of Engineering. With this hand-held device temperature, relative humidity as well as wind speed and direction can be measured.

6.3.3.5 Photodiode

A photodiode (Edmund Optics 53-378) was borrowed from Dr. Alfonso Lastras Martínez of the Institute for Investigation in Optical Communication of the UASLP. A photodiode generates a voltage depending on the captured irradiation. The photodiode is connected to an amplifier, which generates a linear correlation between irradiation and the resulting voltage, and two 12 V batteries. This apparatus was calibrated with the help of a pyranometer. Starting the experiment, it turned out that the original calibration was not valid as the amplifier reached its voltage of saturation of 12 V already in faint sunshine and no further rise of voltage was possible. Therefore, it was necessary to exchange one electric resistance for a smaller one and repeat the calibration. The calibration curve can be seen in the annex.

6.3.4 Experiment

Two kinds of experiments were conducted with the help of the two models. The first experiment had the aim to investigate the models' applicability to the traditional vanilla curing process in Tamazunchale. The second experiment aimed at the evaluation of the dryer's thermal efficiency.

The evaluation of the applicability of solar dying to vanilla curing included different criteria, namely its manageability, the achievement of desirable temperatures and drying rates, as well as the quality of the dried vanilla pods. For this, a test run was performed on both models. It started with a presentation of the finished models on the 5th of March 2017. Because the vanilla producers should learn how to use a solar dryer, one of them, Ms. Virginia Cruz Hernández, carried out the test run personally.

Before, 6.5 kg of fresh green vanilla were procured by the members of Tlilixochitl. This was less than expected. The reasons for this were that the vanilla harvest was almost over so there was very little left and that the vanilla growers live very dispersed in the region with a lack of modes of transport. Since green vanilla pods cannot be stored more than one day, it was not possible to gather a larger amount. The vanilla pods were of different sizes and degrees of maturity, and from different growers – which means they received different levels of care while growing. Thus, they were mixed randomly before separating them in three different batches. Each batch was then cured in different way. Batch number 1 was cured in the direct dryer model, batch number 2 in open sunlight, and number 3 in the indirect dryer model.

Every morning during the test run, the vanilla pods were weighed. Then the weather was checked whether it allowed drying or not. If it was too cloudy or rainy, the pods were put on shelves inside until the next day. If the weather was considered sunny enough, the models were placed on the terrace of the centro de acopio facing south. Then, the temperature of the vanilla pods was measured with a mercury thermometer and they were put into the models, or on the tray outside, respectively. Their weight and temperature was written down. In the direct dryer model, the upper tray was used.

After some time, usually between one or two hours in the drying process, depending on the intensity of solar radiation and other activities of Mrs. Cruz, the vanilla pods were retrieved. Their weight and temperature were measured and written down again (For results, see Annex). In addition to the measurement of the temperature with the thermometer, Mrs. Cruz estimated with her hands if the vanilla pods were warm enough or not. If the vanilla pods had the right temperature, they were wrapped and let to sweat until the next day, if not they were put on shelves inside the building.

Because the temperature and RH loggers were not available in the beginning, the ambient temperature and relative humidity, as well as temperature and RH inside the models were measured at the beginning and the end of the drying process. From the 23rd of March on, the temperature in the dryer models and the ambiance were logged continuously with the temperature and RH loggers as well.

As the vanilla pods were of different sizes, they did not dry at the same speed. So, the vanilla pods reached their final moisture content on different days. The already dried vanilla pods were removed while the others continued drying. When more small quantities of fresh vanilla pods arrived, they were included to the experiment as new batches with the numbers 4 (1.786 kg), 5 (0.678 kg), and 6 (0.856 kg).

Figure 22: Activities During the Test Run

The measurement of the models' thermal efficiency began significantly later than the test run. In order to measure the irradiation, a photodiode was placed in front of the direct model in a tilt of 23 °, exactly as the glass lid of the model. The voltage was measured with a standard low-cost multimeter. As the irradiation in- and decreased rapidly due to moving clouds, it was helpful to measure the voltage regularly throughout the entire day. Therefore, the author's cell phone was set up above the multimeter with an app, which took a photo of the voltage every 4 minutes.

The measurement of temperature and RH was done with one of the HOBO loggers. It was placed onto the lower tray of the direct model, after putting it into a casing of styrofoam wrapped in aluminium foil to prevent a heating through direct irradiation. The temperature and RH sensor was left unwrapped but shaded. Another logger was put into a case made of an empty toilet paper roll, also wrapped with aluminium foil. The sensor was left unwrapped. This was put into a plastic box with holes and covered by a straw mat, to prevent direct irradiation but allow ventilation.

The temperature of the absorber was measured with the 110 °C mercury thermometer and the infrared thermometer. The mercury thermometer was placed upright onto the absorber in the middle rear part of the model. It was put into a pile of flat washers to prevent slipping and to promote heat convection from the absorber to the thermometer. In intervals of about 1 hour the lid was opened and the temperature of the thermometer was noted. Temperature was also measured with the infrared thermometer in the four corners and in the front middle part of the absorber.

The mobile weather station was used to measure air flow on the inlet and outlet. The third logger and the mobile weather station were used for measuring temperature, RH and air flow in the indirect model. They were put onto one tray inside the cabinet.

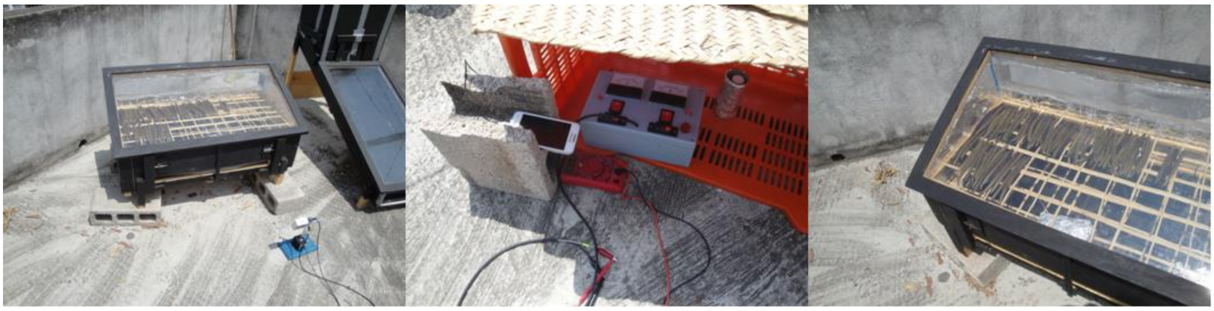

Figure 23:Measuring Instruments and their Arrangement

6.3.5 Observations

The boards used were still very fresh when they were bought and used. Hence, the wood dried out during the experiment. This evaporation probably reduced the drying performance of the drying models. While drying the wood shrank and bent so that cracks occurred that had to be repaired with glue and sawdust.

After four days, the vanilla pods dried in the indirect dryer model began to mould. The vanilla producers stated that this was because the pods did not reach the temperature required in time. This led to a cancellation of the tests of the indirect model and this batch was sundried, the same way as batch number 2.

After two more days, some vanilla pods began to split and disintegrate. According to the vanilla producers, this was because they were harvested pre-mature. If those vanilla pods receive enough heat and are dried quickly enough, their pre-maturity has no effect on their quality. Approximately half of the vanilla pods of the batches 2 and 3 had to be sorted out due to splitting and disintegration. No pods of batch 1 were concerned.

The batches were very heterogeneous mixtures of vanilla pods with different lengths and thicknesses. After twelve days, some of the vanilla pods in the direct model already had reached the desired moisture content. The ready vanilla pods were then removed successively throughout the remaining drying process. After four more days, the same occurred with the sun-dried batch.

6.4 Thermal Analysis

In order to evaluate the use of the vanilla pod dryer from every angle, a thermal analysis of the process is vital and thus dealt with in this part of the thesis

6.4.1 Measured Drying Profile

The vanilla dried noticeably faster in the direct solar dryer model than with traditional sun drying. However, during the different stages of the drying process – insolation, sweating, and the storage of the vanilla pods on shelves – the drying rate was different.

During the experiment described in Chapter 6.3.4, the weight of the vanilla pods was measured and noted every day before and after the insolation. In order to quantify the above-mentioned effects, for every instant of time, the respective moisture contents of the vanilla pods were calculated.

As mentioned in Chapter 6.2.2.1 the initial moisture content was assumed to be x_1=0.83 (wb). With an initial weight and moisture content of the vanilla pods and their weight at the different stages of the drying process, the corresponding moisture content can be calculated. Therefore Equation (1) is converted into Equation (30).

$$x = \frac{m - m_1(1 - x_1)}{m} \tag{30}$$

Where $(m_1(1 - x_1)$ represents the dry mass

This means when in the first drying period in 1.5 hours the weight is reduced from m_1 = 2.166 kg to m = 2.019 kg, the moisture content at the end is:

$$x = \frac{2.091 - 2166(1 - 0.83)}{2.091} = 0.82$$

With Equation (4) the dry base moisture content (db) can be determined:

$$X_1 = \frac{x_1}{1 - x_1} = \frac{0.83}{1 - 0.83} = 4.88$$

$$X = \frac{x}{1 - x} = \frac{0.82}{1 - 0.82} = 4.68$$

This is done for every data-point until the day, the first vanilla pods were removed for already having the desired moisture content (see Chapter 6.3.5). The drying profile can be seen in chapter 7.2.2.4.

6.4.2 Drying Rates

Equation (8) can now be used to calculate the drying rates, as shown on the example mentioned above:

$$v = \frac{\Delta X}{\Delta t} = \frac{4.88 - 4.68}{1.5} = 0.136/h$$

This procedure is repeated for all data-points, in order to obtain the data shown in Table 11. Whereas weight and moisture refer to a specific point in time given in the left-hand column, the drying rate refers to the timeframe between the point in time in the same row and the following row. In the analysis, a distinction has to be established to meet the fact that the vanilla pods were in various different conditions. Therefore, the numbers for the drying rate are highlighted in different colours. Yellow represents insolation, green stands for sweating, and the red colour means that the vanilla pods are resting on shelves inside. The visible decrease of weight of the sun-drying vanilla on March 11th 15:00 h is due to the removal of split and disintegrated pods as described in Chapter 6.3.5 and is supposed to have no effect on the batch's moisture content.

Time	Solar Dryer Model			Sun Drying		
	Weight [kg]	Moisture Content (db)	Drying Rate [1/h]	Weight [kg]	Moisture Content (db)	Drying Rate [1/h]
05.03.2017 12:30	2.166	4.88	0.136	2.166	4.88	0.069
05.03.2017 14:00	2.091	4.68	0.006	2.128	4.78	0.010
06.03.2017 11:45	2.044	4.55	0.186	2.046	4.56	0.149
06.03.2017 13:30	1.924	4.23	0.003	1.950	4.30	0.008
07.03.2017 10:30	1.898	4.15	0.009	1.886	4.12	0.003
08.03.2017 09:30	1.826	3.96	0.008	1.864	4.06	0.005
09.03.2017 13:10	1.740	3.73	0.163	1.814	3.93	0.098
09.03.2017 14:30	1.660	3.51	0.006	1.766	3.80	0.015
10.03.2017 10:15	1.616	3.39	0.174	1.654	3.49	0.080
10.03.2017 13:15	1.424	2.87	0.006	1.566	3.25	0.005
11.03.2017 13:30	1.374	2.73	0.144			
11.03.2017 15:30	1.268	2.44	0.002	1.522	3.13	0.000
11.03.2017 15:30				0.710	3.13	0.010
12.03.2017 10:30	1.251	2.40	0.002	0.676	2.94	0.005
13.03.2017 11:00	1.230	2.34	0.163	0.654	2.81	0.085
13.03.2017 12:30	1.140	2.10	0.005	0.632	2.68	0.003
14.03.2017 13:15	1.091	1.96	0.133	0.620	2.61	0.007
14.03.2017 14:15	1.042	1.83	0.005			
15.03.2017 12:10	1.002	1.72	0.122	0.594	2.46	0.064
15.03.2017 14:10	0.912	1.48	0.003	0.572	2.33	0.004
16.03.2017 12:30				0.558	2.25	0.009
17.03.2017 09:00				0.528	2.07	0.091
17.03.2017 09:50				0.515	2.00	0.011

Table 11: Drying Rates during Insolation (Yellow), Sweating (Green), and Resting on Shelves (Red)

With this data, the average drying rates can be determined:

$v_{Solar\ Dryer,\ Batch\ 1} = 0.153$ /h

$v_{Sun\ Drying} = 0.091$ /h

$v_{Sweating} = 0.005$ /h

$v_{Resting\ on\ Shelves} = 0.008$ /h

A statistical t-Student analysis with a confidence interval of 99% showed that the drying rate in the solar dryer model is significantly higher that the drying rate of sun drying.

The drying rate of the additional batches dried in the solar dryer model were:

$v_{Solar\ Dryer,\ Batch\ 4} = 0.163$ /h

$v_{Solar\ Dryer,\ Batch\ 5} = 0.256$ /h

$v_{Solar\ Dryer,\ Batch\ 6} = 0.180$ /h

As those batches were partly dried simultaneously, the corresponding drying rates will not be used for further evaluation.

6.4.3 Thermal Efficiency

The efficiency of a solar dryer is the ratio of energy utilised for heating and moisture removal to the total solar irradiation on the collector. With the data of the drying rate and the measured irradiation data the efficiency for the direct solar dryer models used in the experiment, the efficiency can be calculated.

However, due to the limited availability of vanilla pods in March and due to a delay in the procurement of the photodiode, there is an inconsistency. For the days with reliable data about the drying process (5^{th} - 15^{th} of March), there is no measured irradiation data, and for the days with measured irradiation data (30^{th} of March – 3^{rd} of April), there is no reliable data about the drying process. As described in chapter 6.3.4, when the first vanilla pods reached the final moisture content, they had to be sorted out. Thus, the moisture content of the remaining pods was no longer definable.

In order to overcome this obstacle as exactly as possible, weather data from the German Weather Service ("Deutscher Wetterdienst") (Frank 9/4/2017) for a weather station in Matlapa, the neighbouring community was used. With this data, two days with reasonably similar weather could be identified. In the considered time of day, the 6^{th} of March and the 3^{rd} of April (Test 1) as well as the 10^{th} and the 30^{th} of March (Test 2) had similar characteristics in terms of total coverage and hours of sunshine (Table 12). Hence, the measured irradiation data of the 30^{th} of March could be combined with the measured drying rate of the 10^{th} of March. The same is true for the data for Test 1. The weather date can be found in the annex.

Day	**Total Coverage [1/8]**	**Temperature [°C]**	**RH [%]**	**Pressure (sea-level) [mbar]**	**Duration of Sunshine [h]**
10.03.2017	3.8	25.6	83.4	1017.1	5.0
30.03.2017	4.0	28.4	71.8	1011.0	5.1
06.03.2017	1.8	24.2	79.4	1015.78	7.4
03.04.2017	2.4	29.3	75.6	1011.0	7.9

Table 12: Weather Data for Selected Says (Averaged from 9:00 to 13:30)

The models were put into the sun some time before the vanilla pods were inserted. So, they heated up before the actual drying. To take into account this fact, two different degrees of efficiency were calculated: one including the irradiation during heating up, and one without. The calculation of the energy need is done in an analogous manner as in chapter 6.3.1. The results are displayed in Table 13.

Test	**1**		**2**	
Day, Time	**06.03.2017 11:45**	**06.03.2017 13:30**	**10.03.2017 10:15**	**10.03.2017 13:15**
Weight [kg]	2.044	1.924	1.616	1.424
Moisture Content (wb)	4.55	4.23	3.39	2.87
Moisture [kg]	1.676	1.556	1.248	1.056
Temp. [°C]	26.5	56.5	30	59
Heat Capacity [KJ/kg*K]	3.693		3.568	
Energy for Drying [Wh]	79.8		127.7	
Energy for heating [Wh]	61.1		43.7	

Table 13: Energy Need for Drying and Heating

The measured solar irradiation data was summed up for the time of drying and time of heating. The resulting amount of energy was used to calculate the thermal efficiency with equation (29) and the data shown in Table 13. The results are shown in Table 14.

Test	**1**	**2**
Day	**03.04.2017**	**30.03.2017**
Start Heating	09:00	09:10
Start Drying	11:45	10:15
End Drying	13:15	13:15
Irradiation Including Heating [Wh/m2]	2381	2363
Irradiation Without Heating [Wh/m2]	1388	1798
Collector Surface [m2]	0.50	
Efficiency Including Heating	11.8%	14.5%
Efficiency Without Heating	20.3%	19.1%

Table 14: Irradiation and Efficiency

For further calculations, the efficiency without heating will be considered. Putting the dryer into the sun seems to be the standard procedure, and in the case of drying more than one batch in one day, for the second bath, the dryer will be pre-heated anyway. The used efficiency is the average of the two tests:

$$\mu = \frac{\mu_{Test1} + \mu_{Test2}}{2} = \frac{20.3 + 19.1}{2} = 19.7\%$$

6.5 Establishment of Final Design

After the test run of the direct dryer model, the vanilla producers decided to stick to the concept of the solar dryer and to adopt the tested design in a larger size with some adjustments. The parameters named in Chapter 7.1 and the evaluation in Chapter 7.2 are considered in this part.

6.5.1 Collector Slope

As the solar dryer will not only be used in March, but also in December, January, and February, the tilt of the collector surface has to be adjusted to allow the highest possible energy yield in these months. Therefore, the method of Perez as described in Duffie, Beckman (2013) was used to calculate the total irradiation on the collector surface. The hourly irradiation data on a horizontal surface in Tamazunchale from 1st of December to 31st of March was applied. For every hour between 9:00 to 16:00 h the hourly irradiation on a tilted surface was calculated. Then, these values were summed up. In the final step, this was repeated for various collector slopes, in order to find the maximum of energy yield. The coordination of the contemplated location is: Latitude = 21.243746, Longitude = -98.777049.

The maximum was found at 25 ° and an energy yield of 401.7 kWh/m^2. The calculation will be exemplified for the 1st of December, 9:00 to 10:00 h.

With the method of Perez, the total Irradiation I_t on a tilted surface, including all kinds of diffuse radiation is:

$$I_t = I_{dr}\, R_b + I_{df}(1 - F_1)\left(\frac{1 + cos\beta}{2}\right) + I_{df} F_1 \frac{a}{b} + I_{df}\, F_2\, sin\beta + I\left(\frac{1 + cos\beta}{2}\right)\rho_g \tag{31}$$

Where:

ρ_g is the reflectance of the surrounding, which is assumed to be 0.2 according to Eke (2011).

I_{dr} can be determined with Equation (20):

$$I_{dr} = I - I_{df} = 210 - 201 = 2\, Wh/m^2$$

R_b is the geometric factor, i.e. the ratio of the direct radiation on a tilted surface to the direct radiation on a horizontal surface. It can be calculated with the Equations (13) and (14).

For the hour angle ω the value of the middle of the time span, in this case 9:30 h, was chosen. At first the reference time for the hour angle has to be adjusted to the solar time, as the longitude of Tamazunchale is different to the reference median of the central Mexican time zone (-90°).

$$n = 335$$

$$B = \frac{(335 - 1)360}{365} = 329.4$$

$$E = 229.2(0.000075 + 0.001868\cos(329.4) - 0.032077 sin(329.4) - 0.014615\cos(2 \times 324.9) - 0.04089\, sin(2 \times 324.9)) = 10.72$$

$$Solar\ time - standard\ time = 4(90 - 98.777049) + 10.72 = -24.39\, min$$

This means that to obtain the solar time, from the legal time 24.39 minutes or 0.41 hours must be deducted.

As the dryer will directly be placed facing south, the azimuth γ equals zero.

$$a = cos\theta = \cos(21.43 - 25)\cos(-21.11)\cos(-36.1) + \sin(21.43 - 25) + \sin(-21.11) = 0.772$$

$$b = \theta_z = \cos(21.43)\cos(-21.11)\cos(-36.1) + \sin(21.43)\sin(-21.43) = 0.561$$

$$R_b = \frac{a}{b} = \frac{0.772}{0.561} = 1.375$$

To calculate the circumsolar and horizon brightness factors F_1 and F_2, other parameters have to be calculated, first:

I_{drn} is the normal direct radiation:

$$I_{drn} = \frac{I_{dr}}{cos\theta_z} = \frac{9}{0.561} = 16\, {}^{Wh}/_{m^2}$$

ε is the clearness:

$$\varepsilon = \frac{\frac{I_{df} + I_{drn}}{I_{df}} + 5.535 \times 10^{-6}\theta_z^3}{1 + 5.535 \times 10^{-6}\theta_z^3} = \frac{\frac{201 + 16}{201} + 5.535 \times 10^{-6}56^3}{1 + 5.535 \times 10^{-6}56^3} = 1.041$$

m is the air mass:

$$m = \frac{1}{cos\theta_z} = \frac{1}{0.561} = 1.781$$

I_{on} is the extra-terrestrial normal-incidence radiation

$$I_{on} = G_{sc}\left(1 + 0.033\cos\left(360 \times \frac{n}{365}\right)\right) = 1367\left(1 + 0.033cos\left(360 \times \frac{335}{365}\right)\right) = 1406W/m^2$$

Δ is the brightness parameter

$$\Delta = m\frac{I_{df}}{I_{on}} = 1.781\frac{201}{1406} = 0.255$$

With ε = 1.041, the factors, f_{11} = 0.008, f_{12} = 0.588, f_{13} = -0.062, f_{21} = -0.06, f_{22} = 0.072, f_{23} = -0.022 were obtained from the table in Duffie, Beckman (2013).

With this data:

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_z}{180}f_{13}\right)\right] = -0.008 + 0.588 \times 0.255 + \frac{\pi \times 56°}{180} \times -0.062 = 0.0813$$

$$F_2 = \left(f_{21} + f_{22}\Delta + \frac{\pi\theta_z}{180}f_{23}\right) = -0.06 + 0.072 \times 0.158 + \frac{\pi \times 57°}{180} \times -0.022 = -0.0631$$

(In contrast to F_1, F_2 can be negative on very overcast days (Perez et al. 1988).)

Now the irradiation on the 1st of January, from 9:00 to 10:00h on a surface with a tilt of 25 ° at the location of Tamazunchale can be calculated. As the circumsolar diffuse irradiation in Meteonorm is included in the direct radiation, the respective term is equated to zero.

$$I_t = 9 \times 1.375 + 201 \times (1 - 0.0813)\left(\frac{1+\cos(25)}{2}\right) + 0 + 201 \times (-0.0631)\sin(25) + 210\left(\frac{1+\cos(25)}{2}\right)0.2 = 223.1 W/m^2$$

This is done for all hours from the 1st of December to 31st of March, from 9:00 to 10:00. A collector slope of 25 ° was proven to be optimal. Figure 24 shows the effect of the slope on the irradiation. Within the range between 20 ° and 30 ° the effect of the slope is nearly insignificant, which presumably is an effect of the high amount of diffuse radiation.

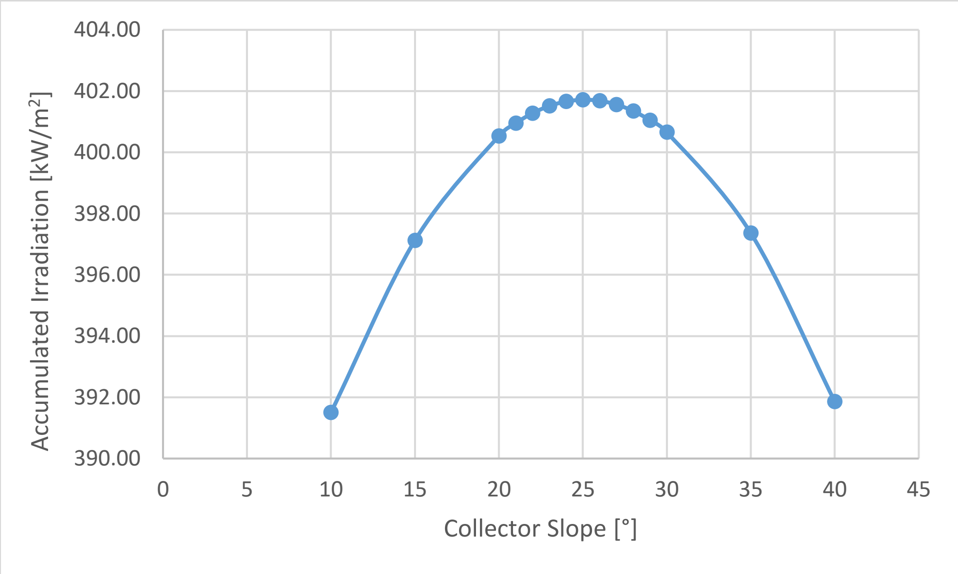

Figure 24:Accumulated Irradiation (1st of December to 31st of march, 9:00 to 10:00)

6.5.2 Capacity

The capacity of the solar dryer will be determined in kg of vanilla per m² of collector surface.

$$Capacity/A = \frac{t\, I_t\, \mu}{(C\,\Delta T + \lambda_s m_e\, t)/3.6} = \frac{2 \times 474 \times 0.197}{(3.723 \times (50-30) + 2393.6 \times 0.026 \times 2} = 3.377\ kg/m^2$$

I_t is the hourly average of total insolation on a surface faced south with a tilt of 25 ° from December to March, determined in chapter 6.5.1.

μ is the thermal efficiency of the model, determined in chapter 6.4.3.

t is the drying time.

m_e is the rate of kg water to evaporate in one hour per kg of vanilla. It was determined with the drying rate and the initial moisture content.

v = 0.153 1/h (see chapter 6.4.2)

$$m_e = x_1 - X_2(1 - x_1) = 0.823 - 4.729(1 - 0.830) = 0.026 kg\ Water/_{kg\ Vanilla\ h}$$

	X	x
1	4.882	0.830
2	4.729	0.825

6.6 Evaluation of Sustainability

Applying the concept of sustainable development to the vanilla curing process in the Huasteca Potosina, more aspects than just the drying performance are important to ensure a sustainable and persistent benefit. Thus, all of the four dimensions of sustainability are interpreted and evaluated. In the following chapter, sustainability for the four dimensions of sustainability will be elaborated.

6.6.1 The Relevance of Sustainability in this Project

The optimisation of the vanilla curing by accelerating the drying process has the potential to increase its sustainability in the economic dimension. Discard and costs for energy and labour can be reduced. This savings must be high enough to justify the costs of the dryer. Or put in the other way, the dryer must be constructed in way that its costs do not exceed the economic advantages. The costs can be differentiated into fixed and running costs. Fixed costs are the costs for material and construction. Running costs are the costs occurring for operation, maintenance, and repairs. All of these costs can be reduced by the right choice of materials and energy source.

In this project, it is valid to add the dimension of technical sustainability. In this context, technical sustainability primarily refers to an adequate technology, adapted to the climatic conditions of the Huasteca Potosina and the living circumstances of the future users to assure its functionality. Additionally, technical sustainability requires the capacitation of the vanilla producers to fully understand how to construct and correctly use the vanilla dryer, and thus to be able to sustain it without the developer's assistance. Functionality and capacitation as well as the use of locally and inexpensively available materials that are easily workable with the means of the community allow maximum persistency of benefits.

In the environmental dimension, it is important to avoid as much external energy input as possible. This not only refers to the direct use of energy in the drying process, such as heat or electricity (e.g. for a ventilator), but also to indirect energy input, such as energy for transport and fabrication of materials. Building materials also can be a source of contamination, for example some varieties of plastics contain toxic compounds.

In the social dimension, the previously described concepts of appropriate technology, endogenous development, and participation are important to guarantee the future users' commitment, the usability of the technology, and thus a long-lasting benefit. Hence, the question is whether the vanilla producers feel like they have participated to their personal satisfaction in the development process and how much do they believe their traditional vanilla curing methods were included. The enhancement of their working and living conditions is an important factor for social sustainability, also.

6.6.2 Themes and Indicators of Sustainability

The evaluation of the solar dryer and the evaluation process will be conducted with indicators which represent the four dimensions of sustainability. Two different kinds of indicators are used. Where possible the indicators are based on hard facts. As for many indicators, the collection of reliable data in the context of this master thesis is not possible, the perception and expectations of the vanilla producers will be assessed in a questionnaire. This assessment by questionnaire also serves for the validation, if the calculated indicators, are recognized in the same way by the beneficiaries. This is crucial for the persistence and sustainability of the benefit of this project. In the choice of indicators, the criteria named in chapter 2.5.7 have to be respected. However, this project is conducted in a very small scale. Thus, the sets of indicators as presented e.g. by United Nations (2007) and Wu, Wu (2012) which mostly are designed for policy-making are not applicable in this thesis. Additionally, the sustainability assessment given in this thesis is more a concluding evaluation than an ongoing monitoring. For these reasons, the choice of indicators is based on the concept of sustainable development presented in chapter 2.5, and on the on the functional parameter and expectations to the development process named in chapter 7.1.4.

6.6.2.1 Technical Sustainability

In Table 15, the chosen indicators for technical sustainability are displayed. Here, important themes are the drying performance and the quality of the vanilla pods. To assess the drying performance, the drying rate was calculated in chapter 6.4.2. For the solar dryer to be functional, it should allow a drying rate higher than the one of sun-drying. For the evaluation of the vanilla quality, the vanillin content of sun-dried vanilla and solar-dried vanilla were measured and compared (chapter 6.6.3.1). The dryer will only be accepted if it produces at least the same vanilla quality as sun-drying.

For both, drying performance and vanilla quality, the perception of the vanilla producers toward these themes were inquired in a questionnaire (chapter 6.6.4). The participants' perception of the vanilla quality was elaborated by a sensory analysis (chapter 6.6.3.2). For the solar vanilla pod dryer to be implemented successfully in the long term, the vanilla producers must be convinced about its technical advantages. The minimum acceptable grade of approval for the respective statements is 8 which means "good".

Theme	Subtheme	Indicator	Method	Target Value
Drying performance	Drying rate	Moisture content removed per hour [1/h]	Measurement / calculation	Higher than sun drying
Drying performance	Perception of drying performance	Grade of approval of statements in chapter 6.6.4	Questionnaire	>= 8 (Good)
Vanilla quality	Vanillin content	Percentage of vanillin in vanilla pods	Measurement	At least equal as sun-drying
Vanilla quality	Perception of Vanilla quality	Grade of approval of statement in chapter 6.6.4.2	Questionnaire	>= 8 (Good)

Table 15: Indicators of the Technical Dimension of Sustainability

6.6.2.2 Economic Sustainability

Table 16 shows indicators for the assessment of the economic dimension of sustainability. Here, two indicators are used. Considering a live time of five years, the net present value will be determined. Here, the costs of construction, repairs, and maintenance are offset against the benefit of the solar dryer. As the dryer itself does not generate any cash-flow, the benefits appear in the form of savings by the avoidance of quality losses, discharge, and costs for energy and manpower.

Theme	Subtheme	Indicator	Method	Target Value
Costs and benefits	Net present value	Net present value after 5 years [MXN]	Ascertainment/ calculation	NPV > 0
Costs and benefits	Perception of cost advantage	Grade of approval of statements in chapter 6.6.4.3	Questionnaire	>= 8 (Good)

Table 16: Indicators of the Economic Dimension of Sustainability

6.6.2.3 Social Sustainability

In Table 17, the indicators of the social dimension can be seen. These indicators represent six aspects of social sustainability. For each aspect one or more statements were given in the questionnaire (questions can be seen in chapter 6.6.4). The grade of approval of those statements should show how much this aspect have been represented in the project.

For the interactive participation, three statements were made about how the participants in their own opinion could follow and influence the project's outcome. In the case of endogenous development, the statements were about how the vanilla producers felt about their capacitation and the consideration of their own traditional methods. In order to evaluate the appropriateness of the applied solar drying technology, the participants were asked about the dryer's usability and how its development considered their personal living conditions. As in the scope of this project, the influence of a solar vanilla dryer on the vanilla producers' working and living conditions cannot be measured, it was estimated by asking them about their expectations towards these important aspects. Finally, the quality of the mutual learning processes was estimated by asking the vanilla producers if they learned new things, and how the author tried to learn about their traditional methods.

To assure a high commitment of the vanilla producers and their ability to construct, maintain, and use the solar dryer, all of the statements mentioned above have to be considered sufficiently. This condition is considered to be fulfilled, if all of the statements have been approved with a grade of at least 8.

Theme	Subtheme	Indicator	Method	Target Value
Interactive participation	Perception of interactive participation	Grade of approval of statements in chapter 6.6.4.4	Questionnaire	>= 8 (Good)
Endogenous development	Perception of endogenous development	Grade of approval of statements in chapter 6.6.4.5	Questionnaire	>= 8 (Good)
Appropriate Technology	Perception of appropriateness of technology	Grade of approval of statements in chapter 6.6.4.6	Questionnaire	>= 8 (Good)
Working Conditions	Expectation of effect on working conditions	Grade of approval of statements in chapter 6.6.4.7	Questionnaire	>= 8 (Good)
Living Conditions	Expectation of effect on living conditions	Grade of approval of statements in chapter 6.6.4.8	Questionnaire	>= 8 (Good)
Intercultural and inter-disciplinary Learning	Perception of mutual learning	Grade of approval of statements in chapter 6.6.4.9	Questionnaire	>= 8 (Good)

Table 17:Indicators of the Social Dimension of Sustainability

6.6.2.4 Environmental Sustainability

The indicators of the environmental dimension are shown in Table 18. Solar power is regarded eco-friendly and climate neutral because no fossil energy is utilised. Nevertheless, even the utilisation of renewable energies can provoke environmental impacts. In a short eco balance sheet (chapter 6.6.5) the CO2-emissions of the construction of the dryer will be determined. As reference, those emissions will be compared to the CO2-emissions released by drying the vanilla on a gas oven.

For the construction of the solar dryer, materials are used which could have a negative effect on the environment and even contaminate the vanilla pods. The paint and glue used for the construction are relatively low-polluting in normal usage, but it is not as clear what happens to the painted wood, at the end of its life cycle, and what contamination could possibly be caused when it is burned. Also, the effect of the high temperatures inside the dryer must be discussed. The quantitative prediction or evaluation of those two effects is not possible in the scope of this thesis. Nevertheless, possible effects will be discussed and a recommendation for future actions will be given.

In the last step, the participants' perception of the environmental effects of the solar dryer will be assessed. This is crucial because contamination, health and the purity of the vanilla pods are important topics for them, and their willingness to use the dryer will depend on their confidence in the absence of negative effects.

Theme	Subtheme	Indicator	Method	Target Value
Greenhouse effect	Greenhouse gas emissions caused by construction of dryer	g CO_2 equivalents / kg produced vanilla	Eco balance sheet	Lower than drying with gas
Eco-toxicity	Toxicity of used materials	In the scope of this master thesis, no reliable quantitative analysis is possible. Therefore, a qualitative discussion and a recommendation for further actions will be mad on this topic.		
Human health	Contamination of vanilla Pods			
General environmental impact	Perception of environmental impact	Grade of approval of statement in chapter 6.6.4.10	Questionnaire	>= 8 (Good)

Table 18: Indicators of the Environmental Dimension of Sustainability

6.6.3 Evaluation of Vanilla Pod Quality

In the following chapter, the analysis of the vanilla pod quality as part of technical sustainability is explained.

6.6.3.1 HPLC Analysis

HPLC (High Performance Liquid Chromatography) analysis is a chromatographic separation method. The liquid sample with different components alongside the solvent is pumped through a column containing the solid phase (an adsorbent material). Every substance has a retention time. The substances can then be detected through their physical properties (luminescence, absorption of light, thermal conductivity, etc.). The output is received as a curve (chromatogram). Through calibration with an external standard solution with a known concentration of the substance to detect, its retention time and sensitivity can be determined. The area under this curve is proportional to the substance's concentration.

The HPLC analysis was done by M.Sc. Eva Rausch and Dipl. Ing. Marcus Schief of the Faculty of Applied Natural Sciences of the TH Köln in their laboratory at the Campus Leverkusen. They created a method based on the method described by Waliszewski et al. (2007).

The method was developed with standard solutions of vanillin. The peak of vanillin is found between 5.0 and 6.6 minutes. An example of a chromatogram can be seen in Figure 25.

The further parameters of the HPLC analysis method were:

- Injection volume = 10 µL
- Separation column: C8 Chromasil 150*4,6 mm; 5 µm
- UV-Detector with wavelength 231 nm (Maximum adsorption for vanillin)
- 60 °C column oven
- Eluent: H_2O pH 2 with H_3PO_4 (A); MeOH (B)
- Gradient programme:
  - Start with 15 % B
  - at 8 min: 30 % B, at 8,1 min: 95 % B
  - hold 95 % B until 11,2 min
  - at 11,3 min: 15 % B
  - hold 15% B until 15 min
- Flow rate: 1,2 mL/min (2 mL/min between 8,2 min and 14,9 min)

In a first step, 64 vanilla extracts were prepared. Therefore, the vanilla pods were cut into pieces with scissors. Each extract was made from one vanilla pod. Two different variants of extracts, A and B, were produced. Eight extracts form variant A for each drying method were treated further after the HLPC analysis and measured again as variant A+. The extracts were numbered:

- No. 101-116 for vanilla from the solar dryer in variant A
- No. 101-108 were further used for variant A+
- No. 117-132 for vanilla from the solar dryer in variant B
- No. 201-216 for sun-dried vanilla in variant A:
- No. 201-208 were further used for variant A+
- No. 217-232 sun-dried vanilla in variant B

The extracts were produced as follows:

Variant A:

- Intermixture with 20 mL Ethanol
- 67,5 h maceration at room temperature without motion
- 5 h overhead shaker
- 2 h ultrasonic bath

Variant A+

- Additional 17 h of standing at room temperature and 48 h in an overhead shaker

Variant B:

- 20 mL Ethanol with 2,5 mg/mL ethyl-vanillin (internal standard)
- 68 h overhead shaker
- 2 h ultrasonic bath

For the analysis, 40 µL of each extract were diluted with 1,940 µL of a mixture of methyl alcohol and water (30:70). This solution was filled into the vial for analysis with a 0,2 µm syringe filter.

The measurement was calibrated in two different ways. Before the measurement, a calibration was done with a vanillin-standard (0,01-0,1 mg/mL, r2 = 1) as external standard. During the analysis of variant B, the concentration of ethyl-vanillin was measured as internal standard. The average recovery rate was 98.5 % which indicates a high reliability of the analysis.

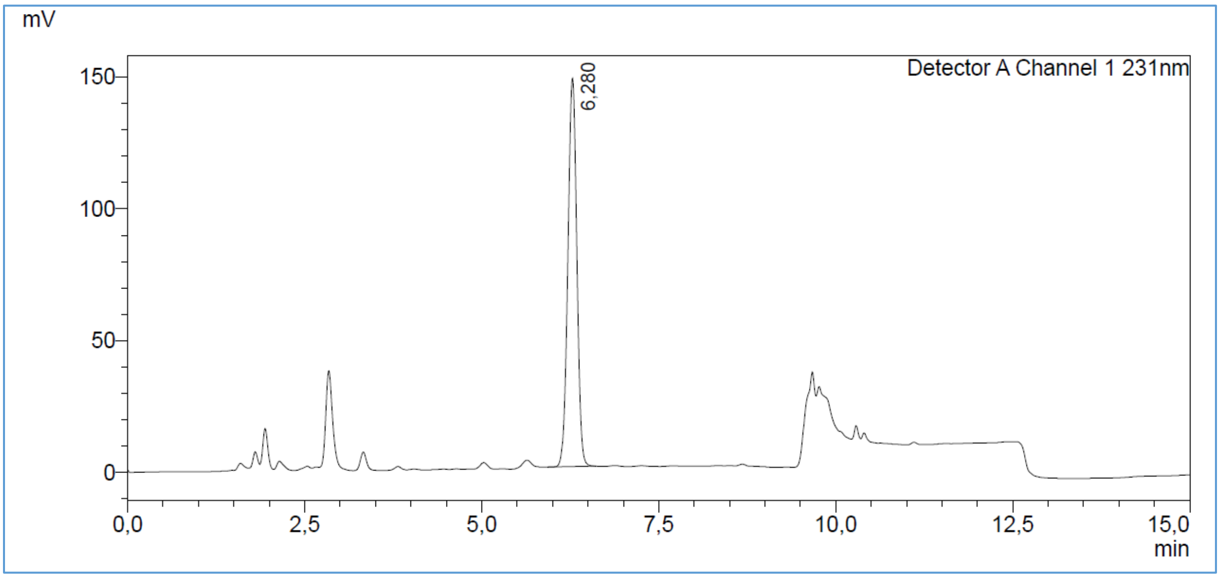

Figure 25: HPLC Analysis of Vanillin in Sun-Dried Vanilla (Extract 211) – The Peak of vanillin can be spotted between 5.0 and 6.6 Minutes.

In Table 19, the results of the HPLC analysis is shown. For all extracts, the vanillin content was lower than 2.08 % measured in a former analysis (chapter 7.1.1). Possible reasons are the extraction method and the low moisture content of the vanilla pods. No statistically significant difference between the two vanilla drying methods can be seen in a t-Student-test in the variants A and A+. Only for variant B, the solar dried vanilla pods have a statistically significant higher vanillin content than the sun-dried at a confidence interval of 99%.

	Solar Drying	Sun Drying
Variant A	0.95%	0.91%
	0.18%	0.13%
Variant A+	1.10%	1.08%
	0.21%	0.17%
Variant B	0.94%	0.76%
	0.17%	0.11%
Total	0.98%	0.89%
	0.19%	0.18%

Table 19: Average Vanillin Content of the Vanilla Pods and Standard Deviation.

However, there remains an uncertainty about the influence of the moisture contents on the vanillin content. In order to take into account a possible decay of vanillin in the sun-dried vanilla pods while drying out from 0.23 to 0.17 moisture content, a theoretic logarithmic decay rate was extrapolated from the data for vanillin content and moisture content given in Jiménez et al. (2013) by usage of the Microsoft Excel trend line. According to the corresponding equation, the vanillin content would decay by 13.5 %. So, the vanilla content values were raised by 13.5 and the t-Student test was repeated. It showed no statistically significant difference between the vanillin contents of sun-dried vanilla and vanilla from the solar dryer model at a confidence interval of 99%. Hence, it can be considered as proved, that drying vanilla pods in the solar dryer model does not have a negative effect on the content of vanillin and therefore on the quality.

6.6.3.2 Sensory Analysis

The Sensory Analysis was done two times. On the first occasion Ms. Cándida Morales Santos did the analysis directly after the first vanilla pods from the direct solar dryer model and from sun-drying were ready on the 18th of March. After this, in an evaluation meeting on the 9th of July, the quality of the was assessed by the group of vanilla producers named in Table 10. The results are displayed in Table 20. The quality of the vanilla pods dried in the direct solar dryer model was evaluated in comparison to the vanilla which was sun-dried at the same time. This was done in two different ways. The vanillin content was determined by HPLC analysis and the vanilla pods were assessed by the vanilla producers by their odour, their haptics and their optical appearance.

Drying Method		**Sun drying**	**Solar Drying**
Evaluation 18th of March	**Odour**	Same	Same
	Colour, Brilliance	Less Colour	More Colour
	Flexibility	Same	Same
Evaluation 9th of July	**General Appearance**	Feel roasted	Better characteristics
	Colour, Brilliance	Coffee colour, more skin damage	Skin not damaged, dark colour, (black), fatty
	Flexibility	Medium dried out	Softer, not roasted, more humidity
	Aroma, Odour	Normal	Better odour

Table 20: Results of Sensory Analysis of Vanilla

Due to a misunderstanding between the author and the vanilla producers, the vanilla pods were not stored correctly after being dried. Therefore, they dried out before the evaluation. Fortunately, both batches, the sun-dried vanilla as well as the vanilla dried in the solar dryer model dried out almost equally, so that a comparison still were possible. As Jiménez et al. (2013) and Odoux (2011) show that the vanillin also content decreases if the moisture content decreases to less than 0.34. The sun-dried vanilla had a moisture content of 0.17 and the vanilla dried in the solar dryer model of 0.23.

6.6.4 Evaluation of Questionnaires

For measuring the success and sustainability of the project, not only objective physical or chemical indicators are important. It is also crucial that the future users of the technology subjectively see its benefit. The vanilla producers' perception of different aspects of the solar dryer and the development process were assessed in a questionnaire. In this questionnaire, the participants expressed their opinion about the quality, the participatory design process and the resulting vanilla pod dryer. In the questionnaire, the approval to different statements regarding the design process and the dryer should be expressed with Mexican school grades from 5 to 10. The questionnaire was introduced to the vanilla producers by Ms. Karina Lizbeth Trinidad García. Seven participants answered the questionnaire. The answers of all participants were first averaged, and then different statements were clustered in order to form sustainability indicators.

Grade	**Meaning**
10	Excellent
9	Very Good
8	Good
7	Sufficient
6	Pass
5	Fail

Table 21: Mexican School Grades

6.6.4.1 Perception of Drying Performance

The drying performance was calculated in the chapter above. For evaluating, how the vanilla producers perceive this drying performance, the following questions were asked:

"With the solar dryer, the temperatures which are necessary for vanilla curing can be achieved"	9.4
"With the solar dryer, insolation is possible, when sun-drying is not"	9.1
"The solar dryer has a sufficient capacity (in relation to its size)"	8.1
Average:	**8.9**

6.6.4.2 Perception of Vanilla Quality

In the evaluation questionnaire, the perception and expectation of the vanilla producers regarding the quality of the vanilla dried in a solar dryer was inquired by the average grade of their approval of the following statement:

"The vanilla dried with the solar dryer has (at least) the same quality as the vanilla dried in the open sun."	**9.6**

6.6.4.3 Perception of Economic Advantage

The economic cost and benefits of the solar dryer will be calculated in chapter 6.6.4.10. The indicator obtained by summarisation the following questions, serves to see if the vanilla producers perceive the economic advantages of the dryer the same way.

"The solar dryer has low costs of investment/construction."	8.4
"The solar dryer has low costs of operation and maintenance"	8.6
"With the solar dryer, we can safe costs of energy and manpower"	9.4
"With the solar dryer, we can avoid quality losses or losses of vanilla pods"	9.1
"With the solar dryer, Tlilixochitl can improve its profit"	9.3
Average:	**9.0**

6.6.4.4 Perception of Interactive Participation

Interactive participation is a very important aspect of this project. The following questions are clustered according to this indicator, in order to see if participation was a success, and if the vanilla producers felt like having participated.

"I believe that I had the opportunity to participate well in the process."	8.3
"I believe that the information and comments I gave, and the demands I made were taken into account."	9.0
"I was well informed about the process at all time."	8.7
Average:	**8.7**

6.6.4.5 Perception of Endogenous Development

Endogenous development, development from within, demands capacitation and the consideration of local knowledge and methods. If the project meets these requirements can be shown with the indicator made by summarizing the following questions:

"I feel capacitated to construct this solar dryer."	7.9
"I feel capacitated to use and maintain this solar dryer."	7.9
"The design of the solar dryer takes into account our traditional vanilla curing methods."	9.1
Average:	**8.3**

6.6.4.6 Perception of Appropriateness of Technology

Appropriate technology is technology adapted to the living conditions and capabilities of its users. If this also is true for the applied solar drying technology can be assessed with this indicator, consisting of the following questions:

"The solar dryer can easily be constructed."	8.3
"The solar dryer can be used easily and conveniently."	9.0
"The design of the solar dryer takes into account our living conditions."	9.6
Average:	**9.0**

6.6.4.7 Perception of Effect on Working Conditions

Another positive aspect of the solar dryer could be the improvement of working conditions. If that is the fact can be proved with this indicator.

"The solar dryer can be moved easily (with wheels)."	8.9
"The solar makes my work easier."	9.0
"With the solar dryer, my work is more interesting."	8.7
Average:	**8.9**

6.6.4.8 Perception of Effect on Living Conditions

Vanilla is an important cash crop for the vanilla dryers. Therefore, it is interesting to see if the vanilla dryers expect to be able to personally profit from the introduction of the dryer.

"I believe that the introduction of the solar dryer can improve my income and my quality of life."	**8.4**

6.6.4.9 Perception of Intercultural and Interdisciplinary Learning

This project is not only a technical project. It also is about the encounter and cooperation of experts who are very different in terms of cultural background, economic background, educational background, and the approach of problem solving. This heterogeneity can be obstacle or enrichment. Which of both it was, can be shown with this indicator:

"I liked the participatory process and I learned new and interesting things."	9.1

"The engineer Clemens Brauer cooperated with us with curiosity and respect, and at the end he understood well our traditional vanilla curing methods."	9.6
Average:	**9.4**

6.6.4.10 Perception of Environmental Impact

Because of rare data, the environmental assessment of this project is rather difficult. Much easier is the assessment of the vanilla producers' perception of the environmental impact.

"The solar dryer does not cause high energy consumption."	9.6
"The solar dryer does not cause emissions and contamination of the environment."	9.7
"The solar dryer does not contaminate the vanilla pods."	9.3
Average:	**9.5**

6.6.5 Net Present Value (NPV)

The net present value of an investment is a common tool for the monetary evaluation of an investment. After discounting future benefits for the entire life time of the investment, the benefits are summed up and reduced by the projects costs.

$$Net\ present\ value\ =\ Present\ value\ of\ the\ expected\ benefits - Cost\ of\ the\ project$$

If the investment has a positive NPV, the investment produces earnings, the higher the NPV, the higher the earnings (Fields 2009).

6.6.5.1 Costs

For the cost calculation, the exact material costs were enquired. Some of the costs were known from the construction of the models, other costs were acquired in stores and through estimation of the vanilla producers. A direct solar vanilla pod dryer as described in chapter 7.3 will have the costs described in Table 22.

Material	Unit Size	Price per unit Unit [MXN]	Units needed	Price total dryer [MXN]
Plywood	Board (2.44 x 1.20 m)	434.00	1.50	651.00
Steel	1 m^2	300.00	1.25	375.00
Glass	1 m^2	350.00	1.34	469.00
Stryrofoam	1 m^2	43.00	5.00	215.00
Slats	1 m	20.00	15.00	300.00
Wheels	Piece	100.00	4.00	400.00
Handles / hinges	Piece	50.00	8.00	400.00
Aluminium foil	Roll (0.3 x 20 m)	60.00	1.00	60.00
Nails	1 kg	50.00	0.10	5.00
Glue Resistol	Bottle 110 g	20.00	1.00	20.00
Paint	Pot 4.5 l	465.00	0.20	93.00
Water Reed	1 stipe	10.00	10.00	100.00
Mosquito net	1 m^2	40.00	0.25	10.00
Work	Day's wage	150.00	6.00	900.00
Total				**3,998.00**

Table 22: Costs of one Solar Dryer with a Collector Surface of 2.5 x 0.5 m

6.6.5.2 Benefits

The monetary benefits of the solar dryer can be:

- avoided loss of vanilla pods,
- avoided loss of quality and
- reduced costs for manpower and energy.

The main cause for vanilla loss is the fact that some vanilla pods are softer than others and thus disintegrate and split if they do not receive sufficient heat (see chapter 7.1.3). 15 % of the first quality vanilla pods have to be downgraded to the second or third quality for that reason. 1 % of the vanilla pods are lost entirely. However, the total amount of soft and vulnerable vanilla pods is not known, and it cannot be said how many of those pods are lost or lose quality.

Therefore, the following assumption is made:

- Percentage of soft and vulnerable vanilla pods in first quality = 50%
- Chance of soft and vulnerable first quality vanilla pods to degrade to a lower quality standard = 30 %
- Chance of soft and vulnerable first quality vanilla pods to degrade to be lost entirely = 2 %

From the total sales of the season 2015/16 (see chapter 7.1.2), the following conclusion is made:

- Percentage of first quality in total vanilla sales = 40 %
- Percentage of second and third quality in total vanilla sales = 60 %

According to the data provided by Ms. Cándida Morales Santos, in season 2016/17, the costs of electricity were 5,834 MXN. These costs are mainly caused by a dehumidifier, which is used on cloudy days when the vanilla pods have to be stored inside on shelves to prevent them from moulding. For season 2015/16 the same amount is assumed, as the energy consumption of the dehumidifier is not dependent on the quantity of vanilla stored in the room. With 452 kg cured vanilla pods sold in that season, the proportionate energy costs are 13 MXN/kg cured vanilla. If the pods could be insolated on those days, these costs would not appear, because the pods would be sweating in blankets instead of being kept on the shelves. According to an estimation by Ms. Cándida Morales Santos, 50 % of the electricity costs could be saved by a decreased use of the dehumidifier if the vanilla pods were dried by a solar drier.

According to Ms. Cándida Morales Santos, the total costs of manpower in season 2015/16 were 121,211 MXN. Again, with 452 kg of cured vanilla, the costs are 268 MXN/kg cured vanilla pods. One third of the manpower could be saved if the pods would not have to be transferred from the sun to the shelves when they do not reach the temperature.

The capacity of a solar dryer with a collector size of 2.0 x 0.5 m is 127 kg of green vanilla per season (see chapter 7.3.2). As 5 kg of green vanilla is needed for 1 kg of cured vanilla (see chapter 7.1.1), the capacity is 25 kg of cured vanilla.

As the very high prices of cured vanilla pods on season 2016/17 are only considered temporary (Bidder, dpa 2017), the prices and quantities of the season before are considered (see chapter 7.1.2).

For the estimation of the benefits of the solar dryer, two scenarios will be considered:

1. The construction of a dryer which only is used for the soft and vulnerable vanilla pods of the first quality

2. The construction a set amount of solar dryers to dry all the vanilla pods of one season. In 2015/16 this were 2,000 kg green pods. To guarantee consistency of this calculations, it is assumed that 1 kg of cured vanilla per 5 kg of green vanilla is produced. With a capacity of 127 kg green vanilla pods per year, this would be 16 kg. But in the middle of the vanilla curing season there is a peak of ripe green vanilla pods, hence a need of 20 solar vanilla dryers is estimated.

6.6.5.2.1 One Dryer

For the usage of one single dryer for soft and vulnerable first grade vanilla pods, the following benefits are assumed:

- Energy: The usage of one dryer would not have any impact on the energy costs, as the electric dehumidifier would still be used for the other pods which are still resting on the shelves.
- Manpower: One third of the manpower for 25 kg can be saved.
- Avoided loss 2 % of the capacity (cured vanilla) with the price of first quality
- Avoided quality loss: 30 % of the capacity with the difference between first and second grade.

6.6.5.2.2 20 Dryers

For the usage of 20 dryers for all vanilla pods, the following benefits are assumed:

- Energy: 50 % of the energy is saved for 400 kg.
- Manpower: One third of the entire manpower can be saved.
- Avoided loss: 1 % of 40 % of the capacity (cured vanilla) with the price of first quality
- Avoided quality loss: 15 % of 40 % of the capacity with the difference between first and second grade.

6.6.5.2.3 Summary

In Table 23 the benefits of the solar dryer per season are summarised.

	One solar dryer (only soft 1st grade)	**20 solar dryers (all vanilla pods)**
Energy [MXN]	0	2,577.00
Workforce [MXN]	2,263.00	35,755.00
Avoided Losses [MXN]	962.00	3,040.00
Avoided Quality Losses [MXN]	2,849.00	9,000.00
Total [MXN]	**6,074.00**	**50,372.00**

Table 23: Benefit of the Introduction of one Solar Dryer for selected vanilla pods and of 20 solar dryers for all vanilla pods

6.6.5.3 Discounting and Result

With a yearly discount rate of 5 % and a lifespan of 5 years, the NPV is calculated. As plywood is vulnerable to humidity, the solar dryer will have to be repaired frequently and parts have to be replaced. Therefore, the following yearly costs of are assumed:

- Steel, glass, wheels, handles, and hinges: 0%
- Plywood and Wooden slats: 50 %
- All other Materials: 100%

The NPV for one dryer and for 20 solar dryers are displayed in Table 24.

	One solar dryer (only soft 1st grade)		20 solar dryers (all vanilla pods)	
Year	Costs [MXN]	Benefits [MXN]	Costs [MXN]	Benefits [MXN]
1	3,998.00	6,074.00	79,960.00	50,372.00
2	1,785.00	5,770.00	35,692.00	47,854.00
3	1,695.00	5,482.00	33,907.00	45,461.00
4	1,611.00	5,208.00	32,212.00	43,188.00
5	1,530.00	4,947.00	30,601.00	41,029.00
Total	10,619.00	27,481.00	212,371.00	227,904.00
	NPV [MXN] =	16,862.00	NPV [MXN] =	15,533.00

Table 24: NPV of the Introduction of one Solar Dryer for selected vanilla pods and of 20 solar dryers for all vanilla pods

6.6.6 Eco Balance Sheet

An eco-balance sheet (also called life cycle assessment) is a tool for the thorough assessment and comparison of environmental impacts along the entire life cycle of a product or service. It consists of three parts:

1. Definition of goals and boundaries of the assessment
2. Life Cycle Inventory Analysis: here the relevant energy and mass flows are analysed and quantified.
3. Life Cycle Impact Analysis: in this part, the environmental impacts of the Life Cycle Inventory Analysis are quantified and clustered in impact categories, e.g. greenhouse effect, soil acidification and others. In the example of the impact category greenhouse effect, all emissions that contribute to global warming are pondered by their global warming potential and summed up to CO^2-equivalents (Umweltbundesamt 1999).

6.6.6.1 Definition of goals and boundaries

In this eco-balance sheet, the greenhouse effect of the production the solar dryer and its use for five years will be assessed. As no information is available on how parts of the dryer will be disposed, this part will be excluded.

The greenhouse gas emissions which would occur by drying an identical amount of vanilla pods with LPG serves as benchmark.

6.6.6.2 Life Cycle Inventory Analysis

According to the design of the solar dryer presented in chapter7.3, the amounts of each material needed for the construction of the solar vanilla pod dryer is calculated or estimated and shown in Table 25.

Material	**Volume [m³]**	**Density [kg/ m³]**	**Weight [kg]**
Plywood	0.044	700	30.7
Steel	0.0015	7860	11.8
Glass	0.0081	2400	19.3
Styrofoam	0.05	15	0.75
Slats	0.018	470	8.46
Wheels/handles/hinges	-	-	0.60
Aluminium Foil	0.00004	2700	0.11
Nails	-	-	0.10
Total			**71.9**

Table 25: Materials of the solar dryer

In the next step, the energy needed for drying the vanilla pods is calculated.

With the solar dryer's yearly capacity (see chapter 7.3.2) as well as the dry mass and the moisture content at the beginning and in end of the drying process, the amount of water to be evaporated was determined:

$$m_e = 126.6(1 - 0.83)(4.88 - 0.54) = 93.5\ kg$$

Then, the heat need to evaporate this amount of water is calculated with formula (23):

$$Q_e = m_e\ \lambda_s = 93.4 \times 2393.6 = 0.000224\ TJ$$

With the average mass and the specific heat of the vanilla pods, the temperature difference and the 20 repetitions, the heat quantity for the heating of the vanilla pods can be calculated with formula (22):

$$Q_{heat} = m_{av}\ C_{av}\ \Delta T\ n = \frac{(126.6+(126.6-93.5)}{2} \times \frac{3.723+2.597}{2} \times 20 \times 20 = 0.000101\ TJ$$

In total, Q = 0.000325 TJ are needed for drying 126.6 kg of vanilla pods.

In 5 years, this will be Q = 0.001624 TJ

6.6.6.3 Life Cycle Impact Analysis

For the Life Cycle Impact Analysis, the Probas data base of the German Federal Environmental Agency (Umweltbundesamt, http://www.probas.umweltbundesamt.de/php/index.php) is used. This data base provides detailed information about the environmental impact of the provision of a variety of goods and services including pre-processes. With the data from the Probas data base, the greenhouse gas emissions for the materials are calculated. Paint and glue are neglected in these calculations, as their share in the total weight is rather small and no data sets in Probas exist for those substances.

Material	Weight [kg]	Greenhouse gas emissions [g CO_2-Equivalents /kg Vanilla]	Greenhouse gas emissions [g CO_2-Equivalents]
Plywood	30.7	461 (Umweltbundesamt 2004)	14173
Steel	11.8	1712 (Umweltbundesamt 2000d)	20184
Glass	19.3	1040 (Umweltbundesamt 2000e)	20098
Styrofoam	0.75	3690 (Umweltbundesamt 2000b)	2768
Slats	8.46	6.93 (Umweltbundesamt 2000a)	59
Wheels/handles/hinges	0.60	1712	1027
Aluminium Foil	0.11	12500 (Umweltbundesamt 2005)	1350
Nails	0.10	1712	171
Total	**71.9**		**59830**

Table 26: Greenhouse Gas Emissions for Production of Solar Dryer

The construction of the vanilla pod dryer has an impact on global warming of 60.0 kg CO_2-equivalents. The material requirements for repairs are calculated the same way as in the calculation of the NPV (chapter 6.6.5.3).

- Steel, glass, wheels, handle, hinges, and s: 0%
- Plywood and wooden slats: 50 %
- All other materials: 100%

This results in yearly greenhouse gas emissions of 11.4 kg CO_2-equivalents for repairs from the second year on.

This results in greenhouse gas emissions of

$$m_{GHG,Solar\ Dryer} = 59.8 + 4 \times 11.4 = 105.4\ \text{kg CO2} - \text{equivalents}$$

According to the Probas data base, the greenhouse gas emissions for 1TJ of heat provided by a gas stove are 144431 kg CO_2-equivalents (Umweltbundesamt 2000c).

Hence, the greenhouse gas emissions for drying the vanilla pods by LPG instead of in the solar dryer is:

$$m_{GHG,LPG} = 0.001624\ \times 144431 = 234.5\ \text{kg CO2} - \text{Equivalents}$$

7 Results

In this chapter the results of the needs assessment, the thermal analysis, the design of the dryer, and of the sustainability assessment are summarized and explained

7.1 Parameters and Needs Assessment

In the workshops, the economic and organisational conditions of Tlilixochitl, their special vabilla curing methods, and the occurring problems were found out. At the end of this part a summary of all the expectations and necessities of the solar dryer expressed by the vanilla producers are summarized.

7.1.1 The Vanilla Curing Process at Tlilixochitl

The vanilla pod harvest and curing takes place from November to March. The months of November to January are characterised by a cloudy climate with little sunshine and drizzle. The months of February and March are dryer but still there are cloudy and rainy days. The vanilla plants require attention all year for trimming, pest-control, fertilising and pollination.

Even though some farmers in the municipality of Tamazunchale cure their own vanilla pods, the majority of the green pods is sold the “centro de acopio” of Tlilixochitl. The price per kg rose from 130-140 MXN in season 2015/16 to 200 MXN in the season 2016/17. The quantity of raw material received in 2016/17 grew from 2 tons to 3.5 tons. In the previous season, Tlilixochitl even resold green vanilla pods.

Vanilla processing at Tlilixochitl follows the traditional Mexican curing methods with some exceptions: Instead of killing the vanilla pods in an oven or in the sun, they are scalded in boiling water. The pods are then put into the sun on nylon blankets for two to three hours per day until they reach a temperature of about 45 °C. The temperature is measured by hand. Once this temperature is reached, it is important to remove the pods from the sunlight preventing the diminution of quality. This is repeated up to 28 times. Achieving the desired temperature is crucial for the development of the quality.

For one kg of cured vanilla, 5 kg of green vanilla is needed. However, the measured moisture content was found from 0.25 to 0.30 in an analysis. After drying, the vanilla pods are sealed in plastic bags for the conditioning of about three months. During this time, the vanilla pods are regularly checked for mould, fungus, and other damages. A previous revealed a vanillin content in the vanilla of Tlilixochitl of 2.08 %.

7.1.2 Vanilla sales at Tlilixochitl

The numbers of sales and the prices could not be determined completely. Hence, the following values are mostly estimations:

The sales price for the finished cured vanilla pods rose from 1,525-1,900 MXN in 2015/16 to up to 5,565 MXN per kg in 2016/17 because of a worldwide vanilla scarcity due to a hurricane in Madagascar (Bidder, dpa 2017), with vanilla pods harvested by certified organic farmers achieving higher prices.

In season 2015/16, 2,000 kg of green vanilla were cured. 185 kg of first grade and 267 kg of second and third grade were sold. In season 2016/17, 3,480 kg green vanilla were cured. The sales were 729 kg altogether. In this season, also green pods were sold.

The sales of Tlilixochitl were 784,450 MXN in the season 2015/2016 and 1,530,375 MXN in 2016/17.

7.1.3 Disadvantages of the Traditional Sun Drying of Vanilla

In the beginning of the workshops only very general statements about the disadvantages of the traditional drying process were made. Further in and during the participative observation during the test run, more concrete information about possible problems could be obtained. Very rarely, concrete numbers could be named by the vanilla producers. The most important problems of the traditional sun drying of vanilla mentioned are:

- On cloudy and rainy days, the vanilla pods have to be stored inside on shelves. Through the moist air emerging, the vanilla pods are vulnerable to mould and fungus. The affected pods are cleaned and assigned to a lower quality category. Through the usage of an electric dehumidifier, the rate of vanilla pods lost entirely through mould and fungus at Tlilixochitl has decreased to about one per cent.
- However, the electric dehumidifier causes high costs of electricity. The consumption of electricity for the vanilla curing is estimated to be around 800 MXN per month for lighting and the dehumidifier, of which the latter consumes by far the most.
- A problem which does not occur at Tlilixochitl, but during the vanilla curing done by farmers on their farmland are moths that lay their eggs in the vanilla pods. The larvae there destroy the skin of the vanilla from the inside.
- Damage of the vanilla pods' skin can also be caused by too much contact to human skin or through wind, which dries out the skin of the pods. This damage becomes visible by a different colour, lack of brilliance, and marks which look like scars or scratches.
- The skin of prematurely harvested vanilla pods is softer than normal. If these pods do not dry fast enough, their skin splits or bursts, so that the seeds fall out. These vanilla pods can only be sold in the lowest quality grade. About 15 % of the production of the highest grade is degraded to the lowest grade through this effect. If the vanilla pods do receive enough heat, their skin gets harder and they result in the same quality as the maturely harvested ones.

7.1.4 Expectations and Parameters for the Solar Vanilla Pod Dryer and the Development Process

Besides the decision for a direct dryer type, the participants expressed a variety of features, important for the dryer, which sometimes even were contradictory. They also expressed their expectations in respect to the process of the development of the dryer.

The quintessence of the expectations and parameters mentioned by the participants during the entire process, were:

7.1.4.1 Functional Parameters for the Solar Dryer

- The vanilla has to have the same quality (colour, flexibility, brilliance, aroma and content of vanillin) as in the current processes
- Low costs of construction, operation, and maintenance
- Easy construction and operation
- Eco-friendliness and no contamination of the vanilla through contact with plastic or smoke, etc.
- Possibility of drying and sweating in the same device
- Sufficient capacity
- Thermometer and adjustment of temperature – maintain adequate temperature according to pods' size
- Mobility and flexibility (wheels for easy shifting and storing)

- Conservation of traditional techniques
- The heat must not harm people
- Heating is more important than actual dehumidification

7.1.4.2 Constructional Parameters for the Solar Dryer

- The size of the trays should resemble the current tray size of the storage racks of the vanilla pods: 2.5 x 0.5 m.
- A height, which allows working without bending
- Instead of doors on the rear part as preferred by Ampratwum (1998) the transparent cover should be used as two independently opening lids.

7.2 Evaluation of Test Run

In this chapter, the results of the experiments are summarized and discussed.

7.2.1 Evaluation by the Vanilla Producers

In the Scenarios of Alternatives, the participants named the following advantages of the direct model over the indirect model:

- Faster heating
- Works with little sunlight
- Less manipulation (less damage on the vanilla's skin)
- Higher immaculacy
- Cheaper
- Less weight

It was noticeable and interesting that as mentioned in chapter 7.1.4.1 for the vanilla producers the heating performance of the dryer was much more important than the drying speed. This could be noticed, when the vanilla producers referred to the dryer model as "horno", which means oven.

The advantages they named for the indirect dryer model were a smoother heating and dehydration. They made plans to use this model afterwards for drying fruit and other food, which does not need those high temperatures.

The SWOT Analysis for a direct solar dryer revealed the following results:

Strengths: • Fast drying • Vanilla becomes flexible and with brilliance • Training of construction • Faster and more adequate (than the other model)	**Opportunities:** • Available materials • Usable in every farmyard • Various batches can be dried in one dryer • Less discard (because soft vanilla pods do not disintegrate) • Less labour needed
Weaknesses: • Cost and weight	**Threats:** • Results of laboratory analysis • Needs protection because it will wet in the rain

7.2.2 Thermal Analysis

Here the physical energy and mass flows happening in the dryer are analysed.

7.2.2.1 General Thermal Behaviour and air Flow

In Figure 26 it can be seen that inside the solar dryer the temperature is significantly higher than outside. At the same time, the relative humidity is reduced drastically. Once heated up, the temperature inside the dryer stays constantly above the 45 °C which is the desired temperature for the vanilla pods. This temperature is sustained until late afternoon, when the solar irradiation already has ceased. Additionally, the cabinet protected the vanilla pods from being cooled down by wind.

However, variations in temperature and relative humidity profiles can be spotted. Those are caused by the opening of the lid for temperature measurement or insertion, checking and retrieval of the vanilla pods. During these moments, temperature sinks and humidity rises. Two sharp peaks of humidity can be seen. They occurred when the sliding covers were closed and the evaporated humidity of the vanilla pods could not exit the model.

These peaks can be considered a proof for the air flow, which could not be measured with the anemometer function of the Kestrel weather station that can measure wind speed at a minimum of 0.1 m/s. Hence, the air flow must have been lower. This is not a problem as the evacuation of moisture seems sufficient. However, the sliding covers can be used for preventing overheating by allowing a bigger air flow.

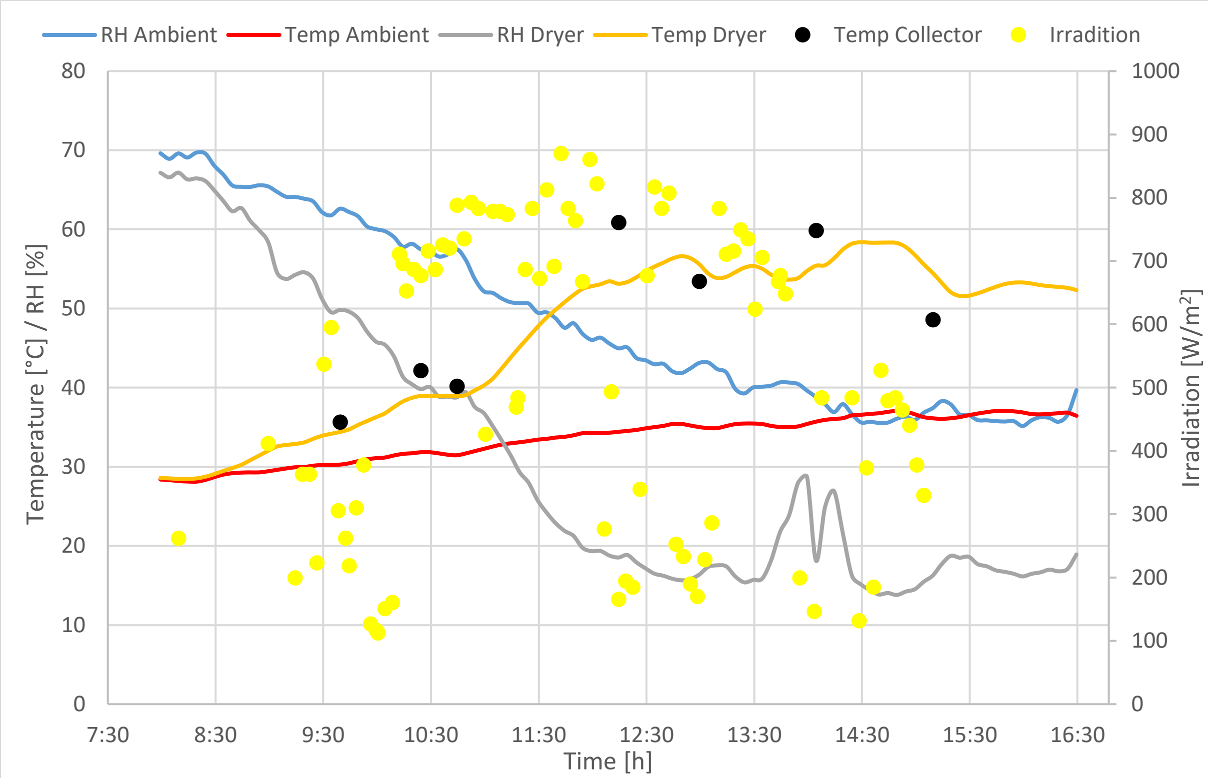

Figure 26: Thermal Behaviour of the Direct Dryer Model on the 30th of March

7.2.2.2 Vanilla Temperature

The vanilla pods reached quite high temperatures. After one or two hours, the temperature usually was between 50 and 60 °C. This was very high because the in the vanilla curing at Tlilixochitl the desired temperature is 45 °C. However, this temperature has never been proved but always measured by hand. The validation of the temperature estimation by hand done by Ms. Virginia Cruz Hernandez revealed, that the vanilla pods were considered hot enough at temperatures of 48 °C or higher. As mentioned in chapter 2.3.3.2, the vanilla can be dried at temperatures up to 55 °C, higher temperatures should be avoided. However, in the main vanilla drying time in December and January the risk of overheating is not as high as in March because of the lower temperatures.

The variation of the vanilla temperature can not only be achieved with the sliding covers, but also by the usage of the different trays. In the experiments, usually the upper tray was used. A variation showed, that when both trays are used, the vanilla on the lower tray does not get as hot, as the vanilla on the upper one. If only the lower tray is used, the vanilla ends up with a higher temperature than if only the upper tray were used.

7.2.2.3 Acceleration of the Drying Process

As described in chapter 6.3.5, the vanilla pods were not dry at the same time. In Table 27 one can see after how many days the first and the final vanilla pods were ready for batches 1 and 2. Insolation days are those days on which the vanilla pods were put into the sun and reached the desired temperature.

"No Work" indicates days when no drying could take place, because Ms. Virginia Cruz Hernández did not work due to her engagement in the community. The total number of days includes days on which the vanilla pods did not reach the desired temperature or when the vanilla pods instantly were put on shelves inside the building due to rain or bad weather.

It was expectable that the vanilla pods in the direct solar dryer model dried faster than the sun-dried pods. Yet it is surprising that the pods from the dryer had more days of successful insolation in a shorter time.

Batch	Drying Mode	First Ready			Last Ready		
		Total Days	Insolation Days	No Work	Total Days	Insolation Days	No Work
1	Direct Solar	11	8	0	20	15	2
2	Sun-Drying	15	5	1	24	10	2

Table 27: Drying Time of Vanilla Pods of Batch 1 and 2

7.2.2.4 Drying profile, Drying Rate, and Thermal Efficiency.

A drying profile established in chapter 6.4.1 can be seen in Figure 27. The short and steep sections represent phases of insolation, while the more smoothly decreasing parts stand for sweating or storage on shelves inside. It can be seen that the vanilla pods which were dried in the solar dryer model have a faster decrease of moisture content than those which dried in the sun.

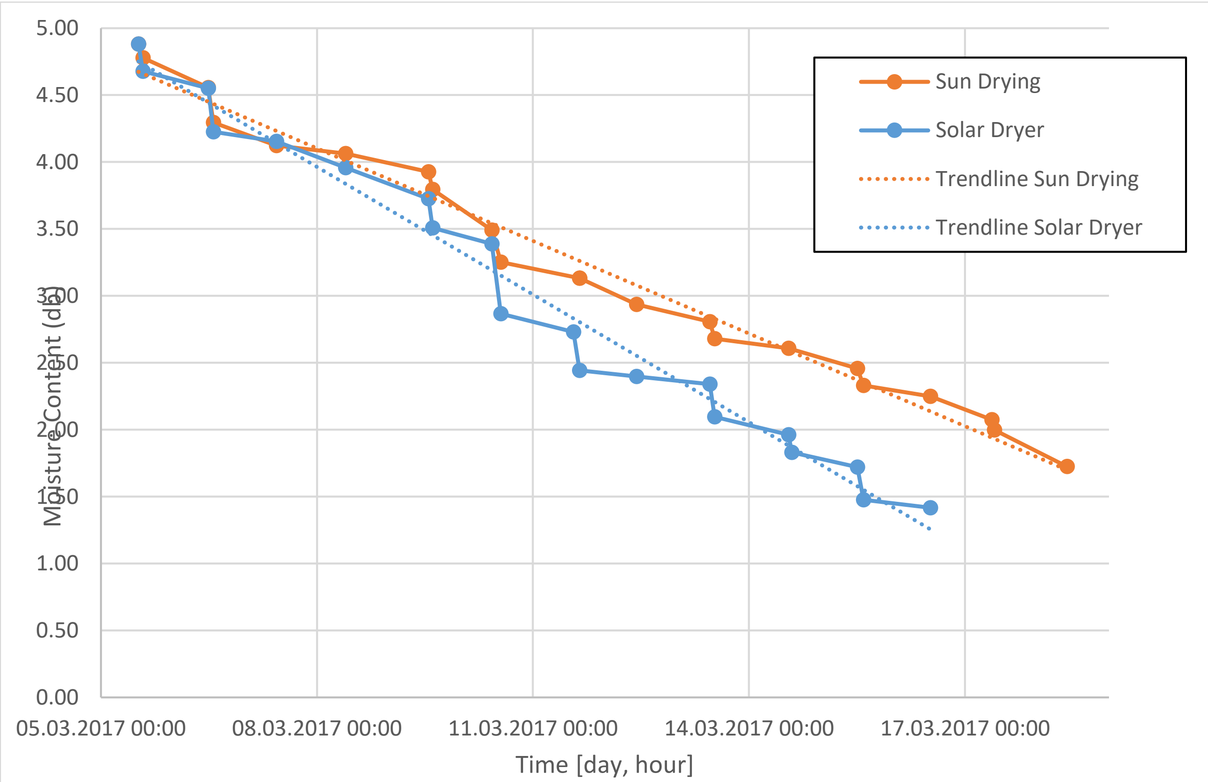

Figure 27: Drying Profile of Vanilla Pods in Solar Dryer Model and Sun Drying

In chapter 6.4.2 the drying rates for drying in the direct solar dryer model, sun-drying, sweating, and resting on shelves was determined. The results are:

$v_{\text{Solar Dryer, Batch 1}} = 0.153$ /h

$v_{\text{Sun Drying}} = 0.091$ /h

$v_{Sweating}$ = 0.005 /h

$v_{Resting\ on\ Shelves}$ = 0.008 /h

The thermal efficiency is:

$$\mu = \frac{\mu_{Test1}+\mu_{Test2}}{2} = \frac{20.3+19.1}{2} = 19.7\%$$

7.3 Final Design

In this part, the design of a solar dryer fitted for the vanilla producers in Tamazunchale, based on all the information gathered in the project, is presented.

7.3.1 Decision about Type of Dryer

In order to test the applicability of solar drying in for vanilla drying in the Huasteca Potosina, two models of solar dryers were constructed (see Chapter 6.3.2). One model was based on the direct solar dryer presented by Ampratwum (1998), the other one was based on the indirect solar vanilla pod dryer presented by Romero et al. (2013).

After constructing and testing both types, the vanilla producers expressed their disapproval of the indirect model as it was more complicated and expensive to construct, very heavy, and did not achieve the desired temperatures. On the contrary, the direct model was much easier and cheaper to construct, and showed a remarkably better heating and drying performance than the indirect model and the traditional sun drying. Therefore, the decision to drop the indirect dryer concept and to follow the direct dryer concept in the further process was made easily and unanimously by the participants.

7.3.2 Tilt, Collector Size, and Capacity

The dryer's base area of cabinet and size of tray was collectively determined as 250 x 50 cm (the standard size of the trays already used by the vanilla producers for insolation and storage of the pods). This size allows simple moving and handling of the dryer.

The optimal angle of the solar collector is 25 ° (see chapter 6.5.1) for the entire vanilla harvesting season. If radiation in December was considered only, the optimal angle would have been 29 °. However, within this range of angle, the differences in energy yield are marginal.

The capacity of the dryer, considering the calculated drying rate and thermal efficiency, is 3.377 kg of vanilla per m^2 of collector. With a collector size of 2.5 m^2, 8.44 kg of vanilla can be dried in order to heat up the vanilla pods and achieve a drying rate of 0.153 /h over a period of 2 hours.

With a constant drying rate from the initial to the final moisture content, the drying time would be 27 hours, with 2 hours of drying a day. This would be 13.5 days. However, the drying rate decreases at the end of the drying process and drying is not possible every day. So, a drying time of 20 days is considered, like shown in chapter 7.2.2.3.

As the pods remain in the dryer for only about two hours each day during the entire drying period, three different batches can be dried per day, alternately. In total, this allows 25.3 kg to be dried within these 20 days. During the vanilla curing season which lasts four months, this can be repeated five times, so the total capacity of the dryer is 126.6 kg per season.

7.3.3 Constructive Details

The indirect dryer model was rejected by the vanilla producers because it did not produce the temperature necessary. The direct dryer model was perceived well, as it was easy and cheap to construct and also delivered a good drying and heating performance. Nevertheless, some modifications were suggested by the vanilla producers which result in the final design of a direct solar vanilla pod dryer with the following attributes:

- The collector size is 250 x 55 cm. The collector serves as a lid and is divided in two parts which can be opened separately. Each segment of the glass cover of 6 mm thickness is framed in wood of a width of 3 cm. The resulting collector surface is (250 – 6) x 55 = 1.34 m^2.

- The cabinet will be constructed of plywood of 1 cm thickness instead of 2.5 cm pine wood, in order to avoid the high weight of the solar dryer models. This will decrease the weight, but also the dryer's ability to retain its heat. Therefore, the walls have to be covered with Styrofoam on the inside. That makes them 2 cm thick.
- On the plywood bottom of the cabinet a 1 cm layer of styrofoam and a 0.5 mm black steel sheet will be placed, for isolation and heat absorption respectively.
- The height of the cabinet is 25 cm above the absorber sheet on the front side and 49 cm on the back.
- Supports for 2 trays will be placed 10 cm and 20 cm above the absorber respectively.
- The dryer is placed on legs in order to facilitate usage. The upper tray will be at a height of 1 m. Each leg is equipped with a small wheel, which makes the dryer easier to move.
- An air inlet of 250 x 4 cm is placed directly above the absorber on the front side. An air outlet of 250 x 10 cm is placed 5 cm below the lid on the back side. Both vents can be adjusted by sliding covers in order to control air flow.
- The dryer is painted black on the outside, and aluminium foil is glued on the inside wall.

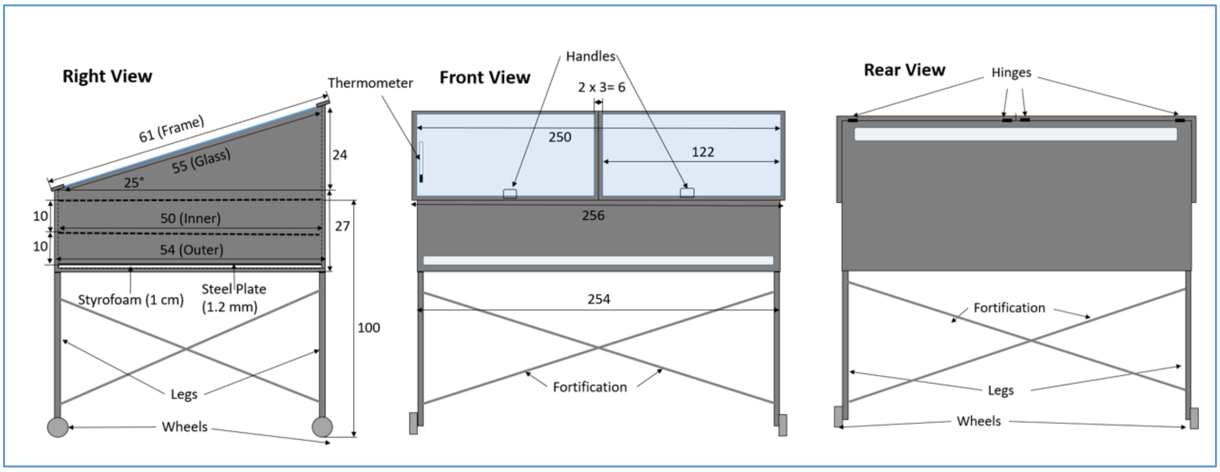

Figure 28: Final Dryer Design

7.3.4 Construction Process

It was agreed with all involved persons that the dryer will be constructed by the vanilla producers with the help of Mr. Jacobo Hernández Medina and Ms. Karina Lizbeth Trinidad García. As they know best about available tools and materials and their working procedures, the construction will be left up to them. The design presented in this thesis is a guideline for how the dryer should look like and an invitation for further improvements and adjustments, not an elaborate instruction of how to combine part A to part B.

7.4 Results of Sustainability Assessment

In this chapter, the results of the sustainability assessment are summarized and explained.

7.4.1 Technical Sustainability

The target values for the drying rate and the vanillin content were both achieved. While in the case of the drying rate the solar dryer clearly outperforms sun-drying with statistical significance, the values for the vanillin content are not as clear-cut. The vanillin content of solar-dried vanilla seems to be higher than of sun-dried. Yet, because of high differences even between individual vanilla pods cured with the same method, no statistically significant difference between the vanillin content of solar-dried and sun-dried vanilla could be found out. However, the target value still is achieved.

The vanilla producers' perception of drying performance and vanilla quality also excels the desired value of at least 8, which means that they are convinced that the introduction of a solar vanilla pod dryer effectively can improve the efficiency of their traditional vanilla curing methods.

Theme	Subtheme	Indicator	Method	Target Value	Results
Drying performance	Drying rate	Moisture content removed per hour v [1/h]	Measurement / Calculation	Higher than sun drying	v(Solar Dryer) = 0.153 /h v(Sun Drying) = 0.091 /h
Drying performance	Perception of drying performance	Grade of approval of statements in chapter 6.6.4	Questionnaire	>= 8	8.9
Vanilla quality	Vanillin content	Percentage of vanillin in pods c [%]	Measurement	At least equal as sun-drying	c(Solar Dryer) = 0.98 % c(Sun Drying) = 0.89 %
Vanilla quality	Perception of vanilla quality	Grade of approval of statement in chapter 6.6.4.2	Questionnaire	>= 8	9.6

Table 28: Result of Assessment of Technical Sustainability

7.4.2 Economic Sustainability

The economic sustainability is assessed by the solar dryer's NPV. Two scenarios were shown. Interestingly the NPV of 20 solar dryers is even lower than the NPV of only one solar dryer. For this, there are two reasons. At first, one solar dryer will be used continouously at its capacity limits during the entire vanilla season, while some of the 20 dryers estimated to also cope with the peaks of vanilla input, will partly remain unused most of the time. Secondly, the biggest benefit from the usage of one solar dryer, which is only used for soft and vulnerable vanilla pods, is the avoidance of loss of quality due to splitting and disintegration. This effect is much lower if all vanilla pods are cured in solar dryers.

The grade of approval of the perception regarding cost advantage is 9.0. which is "very good". The lowest value is 8.4 for the statement "The solar dryer has low costs of investment/construction", the highest is 9.4 for the statement "With the solar dryer, we can safe costs of energy and manpower". So, the vanilla producers' opinion represents the result of the NPV. The investment is relatively high for the standard of Tlilixochitl, but the benefits are as well.

Theme	Subtheme	Indicator	Method	Target Value	Results
Costs and benefits	Net present value	Net present value after 5 years [MXN]	Ascertainment / calculation	NPV > 0	NPV (1) = 16,862 MXN NPV (20) = 15,533 MXN
Costs and benefits	Perception of cost advantage	Grade of approval of statements in chapter 6.6.4.3	Questionnaire	>= 8 (Good)	9.0

Table 29: Result of Assessment of Economic Sustainability

7.4.3 Social Sustainability

The grade of approval of 8.7 in the statements about interactive participation indicates that the participatory process in this project can be considered a success. An interesting aspect is the remarkable difference between the grade of approval of the statement "I believe that I had the opportunity to participate well in the process" (8.3) and of the statement "I believe that the information and comments I gave, and the demands I made were taken into account" (9.0). One could assume that both statements should have quiet similar grades of approval. Ms. Karina Lizbeth Trinidad García who organised the participants' responses to the questionnaire explained that the phrase "I had the opportunity" was not understood in the sense of "to be allowed to", but as "to be able to". As all of the vanilla producers have their own businesses to attend, the limiting factor in terms of interactive participation was not a missing invitation to participate but lack of time to accept it.

In the topic of endogenous development, the total grade of approval is 8.3. But while the statement concerning the consideration of traditional vanilla curing methods were approved to a high grade (9.1), the grade of approval to the statements regarding capacitation were below the threshold of 8. This clearly is a weakness of the project which could put at risk the sustainability and persistency of the project. Unfortunately, there was little time for more practise to gain confidence in this technology, which still is new to many of the producers. On the other hand, the participants who answered the questionnaires are part of a very heterogeneous group. Some of them approved the statements concerning capacitation with a 9 or even a 10. This means that within the community in fact there is a potential for a successful follow-up for the project.

The grade of approval of the statements regarding the appropriateness of the technology is 9. This indicates that the dryer is well adapted to the vanilla producers' abilities and living conditions. The statement "The solar dryer can easily be constructed" has the lowest grade of approval (8.3), with a range from 7 to 9. This again may indicate that in the construction of the solar dryer, the participants with constructional expertise can take a leading role.

Theme	Subtheme	Indicator	Method	Target Value	Results
Interactive participation	Perception of interactive participation	Grade of approval of statements in chapter 6.6.4.4	Questionnaire	>= 8	8.7
Endogenous develop-ment	Perception of endogenous development	Grade of approval of statements in chapter 6.6.4.5	Questionnaire	>= 8	8.3 (2 x 7.9 !)
Appropriate Technology	Perception of appropriateness of technology	Grade of approval of statements in chapter 6.6.4.6	Questionnaire	>= 8	9.0
Working Conditions	Expectation of effect on working conditions	Grade of approval of statements in chapter 6.6.4.7	Questionnaire	>= 8	8.9
Living Conditions	Expectation of effect on living conditions	Grade of approval of statement in chapter 6.6.4.8	Questionnaire	>= 8	8.4
Intercultural and inter-disciplinary Learning	Perception of mutual learning	Grade of approval of statements in chapter 6.6.4.9	Questionnaire	>= 8	9.4

Table 30: Result of Assessment of Social Sustainability

The approval of the statements regarding the effect on the vanilla producers' working and living conditions is 8.9 and 8.4 respectively. An interesting point is the fact that while the approval on the statement "With the solar dryer, Tlilixochitl can improve its profit" is 9.3, the approval of the statement "I believe that the introduction of the solar dryer can improve my income and my quality of life" only is approved by a grade of 8.4. This has to do with the circumstance, that many of the participants are vanilla producers associated to Tlilixochitl, but not vanilla growers who profit the most of Tlilixochitl's earnings (see chapter 2.2 and 7.1.2).

The statements regarding the mutual learning process were approved by a grade of 9.4, which means that the participants were regarding the intercultural and interdisciplinary exchange of knowledge between them and the author a success.

7.4.4 Environmental Sustainability

In a useful life of five years, the solar dryer causes less than half of the greenhouse gas emissions than drying of the same amount of vanilla by LPG in a normal household oven. However, this is more than expected. Moreover, In the first year of usage, the solar dryer even causes more greenhouse gas emissions, than the LPG would. This is because of the usage of materials that need a high energy input for construction, such as plywood, glass, and steel. A solar dryer made from simple pine wood would have much lower emissions, but again be heavier and more difficult to construct. However, even if the advantage is lower than expected, in terms of greenhouse gas emissions, the solar dryer still is better than drying with gas.

The approval of the statements regarding the environmental impact is 9.5. This indicates, that the vanilla dryers consider the solar dryer a clean energy source.

Theme	Subtheme	Indicator	Method	Target Value	Results
Greenhouse effect	Greenhouse gas emissions caused by construction of dryer	g CO_2 equivalents / kg produced vanilla	Eco balance sheet	Lower than drying with gas	m(GHG,Solar Dryer) = 105.4 kg CO2-Equivalents m(GHG,LPG) = 234.5 kg CO2-Equivalents
General environmental impact	Perception of environmental impact	Grade of approval of statement in chapter 6.6.4.10	Question naire	>= 8 (Good)	9.5

Table 31: Result of Assessment of Environmental Sustainability

The usage of glue and paint in the solar dryer is a critical point. The glue can be regarded non-toxic (Henkel AG &Co. KGaA 2017) and a paint with very low VOC content was chosen (BEHR Process Corporation 2015). However, the effects of heat on both products was not evaluated in the scope of this thesis. Thus, the possible toxicity for the environment and a contamination of the vanilla pods cannot be ruled out. On the other hand, a negative effect of the aluminium foil, can be ruled out, as it does not have direct contact to the vanilla pods, and no hint for any gaseous emissions of aluminium foil could be found in literature.

8 Conclusion and Outlook

In this master thesis, a solar dryer for vanilla pods was developed for the vanilla producers in the Huasteca Potosina. The development and introduction of such a solar dryer promised a faster and more efficient drying process. The sun-drying of vanilla pods is a very important part in the traditional Mexican vanilla curing process as in this step the vanillin, which is the most important component of the vanilla's aroma, develops.

Traditional sun-drying results in marketable high-quality vanilla, and the vanilla producers highly identify with that technique. However, sun-drying has some disadvantages, such as low drying rates and discharge because of mould or disintegration of pods.

The challenge in the development of the solar dryer was to eliminate these disadvantages while respecting the local traditions and living conditions of the rural community to which the vanilla producers belong. It is necessary respect these prerequisites in order to assure the sustainability and persistence of the project. As key tool for finding an appropriate technology, interactive participation was identified.

In participatory workshops with the vanilla producers, the traditional vanilla curing process was analysed, and the basic constructional and functional parameters for a vanilla pod dryer were defined. The most important parameters for the solar dryer were

- the adaption to the traditional methods,
- a faster drying,
- the achievement of the necessary temperatures,
- the purity and quality of the cured vanilla pods,
- and a flexible, economical and easy-to-use design.

Another critical point was the moist cloudy weather during the drying season, which might make the application of solar drying difficult.

To prove the applicability of solar drying under these prerequisites and circumstances, two models of solar dryers were constructed and tested in cooperation with the vanilla producers. One model was constructed according to the principle of indirect drying, the other one was a direct dryer model. Three batches of vanilla were dried in the test-run in March 2017, one in the direct model, one in the indirect model, and one in the open sun as reference.

While the indirect model did not achieve the desired temperature, the direct model did and showed very satisfactory drying performance. During the drying period the already dry vanilla pods had to be sorted out continuously and the drying rate was improved from a rate of 0.091 /h in the sun to 0.153 /h in the direct dryer model. The model had a thermal efficiency of about 20 %, when it was put into the sun and allowed to heat up before drying. The total time of drying for the batch of the direct dryer could be reduced from 24 to 20 days. On the majority of days, the vanilla pods in the direct dryer model achieved the desired temperature, while the sun-dried vanilla did not, or was not even put outside because it would not have made any sense due to non-adequate weather conditions. Hence, the solar-dried vanilla pods did not only dry faster, they also received more sunlight. This is because with the solar dryer even on cloudy days the desired temperature of the vanilla pods can be achieved, which is an advantage that might be even stronger in the months from December to February, when the weather is less sunny than in March.

With the results of this test run and the feedback of the vanilla producers who at this point mainly focussed on usability, a direct solar vanilla pod dryer was developed. It mainly consists of a frame of plywood and styrofoam on a wooden structure which allows working without having to bend over. Its base has a size of 2.5 x 0.5 meters and is covered by glass cover, which can be opened, with a tilt of 25 ° facing south. On the bottom, a black steel plate was added, which serves as heat absorber. With the data obtained during the test run, a thermal capacity of 8.44 kg green vanilla pods was calculated.

As the vanilla pods only remain in the dryer for about two hours per day, three batches of 8.44 kg can be dried at the simultaneously during one drying phase. With a drying time of 20 days in one vanilla season this can be repeated 5 times. This results in a yearly capacity of 126.6 kg vanilla pods.

At the end of the process, the solar dryer was assessed by the principled of sustainable development. Four basic dimensions were considered in this assessment.

The technical sustainability included the vanilla quality and the drying rate. A clear improvement of the drying rate was shown, and a HPLC analysis as well as sensory assessment revealed that the vanilla pods from the solar dryer did not suffer from a quality decline compared to those dried in the the sun. Also, the vanilla producers' perception of drying performance and vanilla quality was assessed. This revealed that they do believe in the technical advantages shown by calculation and analysis.

The assessment of economic sustainability compared the costs of the designed solar vanilla dryer with the benefits of avoided quality losses and less costs for manpower and energy. Two scenarios were evaluated, with the result that the solar dryer offers a high economic benefit if only used in a small scale for the most vulnerable vanilla pods of the highest quality grade. If used for the entire vanilla production, the economic benefit almost vanishes in comparison to the high investment. The perception of the vanilla producers, expressed in a questionnaire on this topic, showed that they realize that the solar dryer, despite its investment costs, can bring an economic benefit.

For social sustainability, the concepts of interactive participation, endogenous development, appropriate technology, as well as intercultural and inter-disciplinary learning were taken into account, in order to evaluate the design process, in terms of considering the vanilla producers' expectations, necessities, living conditions and traditional methods. The expected effect of the introduction of a solar dryer to the vanilla producers' working and living conditions also were evaluated. The assessment was performed with a questionnaire. Good to excellent grades were achieved. This is very promising with respect to the sustainability of the entire project. Only their own capacitation to construct and use the solar dryer was seen critically by the vanilla producers. If they think that they are not able to construct and use the solar dryer independently, it might become an obstacle to the persistence of the project. A solution in this case can be found through the leadership of individuals with sufficient skills within the community.

Last but not least, the environmental aspects of sustainability were assessed. In an eco-balance sheet, the greenhouse gas emissions occurring during the construction of the solar dryer were compared to the greenhouse gas emissions that would occur using a LPG, under the same prerequisites. The result was not as clear as one should have expected, but still the greenhouse gas emissions of drying with the solar dryer are lower than of drying with LPG. The vanilla producers' perception of the environmental impact is positive as well. Only the effects of substances such as glue and paint on the vanilla and on the environment still have to be investigated.

All in all, the direct solar drying technology has proved to be applicable for the drying of vanilla pods in the Huasteca Potosina. Through interactive participation, the most important parameters for the solar dryer could be found out, and its introduction seems to be sustainable.

After the end of this thesis project, it is up to the vanilla producers if, when and why they are willing to build the direct dryer. Financial funds and manpower have to be provided to construct the designed vanilla dryer by the vanilla producers themselves, probably supported by the UASLP. Yet, the design is not set in stone as the vanilla producers are invited to further adapt it to their needs.

9 Publication Bibliography

Altieri, Miguel A.; Nicholls, Clara I. (2005): Agroecology and the search for a truly sustainable agriculture. 1a ed. Mexico, D.F.: United Nations Environmental Programme, Environmental Training Network for Latin America and the Caribbean (Basic textbooks for environmental training, 9).

Ampratwum, D. B. (1998): Design of Solar Dryer for Dates. In *AMA, Agricultural Mechanization in Asia, Africa and Latin America* 29 (3), pp. 59–62. Available online at https://www.scopus.com/inward/record.uri?eid=2-s2.0-0002896589&partnerID=40&md5=c486073b18951ab63dc574048eebfc4c.

Andersen, Otto (2013): Unintended Consequences of Renewable Energy. Problems to be Solved. London: Springer London (Green Energy and Technology), checked on 1/12/2017.

Antonescu, Daniela (2012): Theoretical approaches of regional development. Institute of National Economy. Munich, 5/9/2012.

Arana, Francisca E. (1944): Vanilla curing and its chemistry.

ASHRAE (2006): 2006 ASHRAE handbook. Refrigeration. Inch-pound ed. Atlanta, GA.: ASHRAE.

Azeez, Shamina (2008): Vanilla. In V. A. Parthasarathy, B. Chempakam, T. J. Zachariah (Eds.): Chemistry of Spices: CABI, pp. 287–311.

Barkin, David (2010): The Struggle for Local Autonomy in a Multiethnic Society Constructing Alternatives with Indigenous Epistemologies. In Fred Gifford, Stephen Lawrence Esquith (Eds.): Capabilities, power, and institutions. Toward a more critical development ethics. University Park, PA: Pennsylvania State University Press, pp. 141–162.

Barlev, David; Vidu, Ruxandra; Stroeve, Pieter (2011): Innovation in concentrated solar power. In *Solar Energy Materials and Solar Cells* 95 (10), pp. 2703–2725. DOI: 10.1016/j.solmat.2011.05.020.

Barnwal, P.; Tiwari, G. N. (2008): Grape drying by using hybrid photovoltaic-thermal (PV/T) greenhouse dryer. An experimental study. In *Solar Energy* 82 (12), pp. 1131–1144. DOI: 10.1016/j.solener.2008.05.012.

Bass, Stephen; Dalal-Clayton, Barry; Pretty, Jules (1995): Participation in Strategies for Sustainable Development. London.

BEHR Process Corporation (2015): SAFETY DATA SHEET Premium Plus Interior Flat - Deep Base No. 1300. Available online at http://www.actiocms.com/VIEW_MSDS/AuthorDisplay_V402/msdsdisplaycode_author_new_MASTER.cfm?edit_msds_id=5070&dbname=production&Hide_Section_Numbers=N&formatcode=7&language=1&noprint_label_fax_email=Y, checked on 9/11/2017.

Behrendt, Siegfried; Jasch, Christine; Peneda, Maria Constança (1997): Life Cycle Design. A Manual for Small and Medium-Sized Enterprises. N. Berlin/Heidelberg: Springer Berlin Heidelberg.

Bhandari, Ramchandra; Arndt, David; Straub, Günther (2017): Unit B.1 Renewable Energy Ressources and Technology. In GIZ (Ed.): SUSTAINABLE ENERGY FOR FOOD Massive Open Online Course – Reader, pp. 19–44.

Bidder, Benjamin; dpa (2017): Missernte in Madagaskar: Vanillepreis explodiert -. SPIEGEL ONLINE - Wirtschaft. Hamburg. Available online at http://www.spiegel.de/wirtschaft/unternehmen/vanille-preis-explodiert-nach-missernten-in-madagaskar-a-1149359.html, updated on 5/26/2017, checked on 9/10/2017.

Bolea, Yolanda; Grau, Antoni; Miranda, Alexandre (2012): SDSim. A Novel Simulator for Solar Drying Processes. In *Mathematical Problems in Engineering* 2012 (3), pp. 1–25. DOI: 10.1155/2012/976452.

Botsch, Marcus (2008): Prototyp. In Michael Erlhoff, Tim Marshall (Eds.): Wörterbuch Design: Begriffliche Perspektiven des Design. Basel: Birkhäuser Basel, pp. 330–331. Available online at https://doi.org/10.1007/978-3-7643-8142-4_249.

Bradley Guy, G.; Kibert, Charles J. (2010): Developing indicators of sustainability. US experience. In *Building Research & Information* 26 (1), pp. 39–45. DOI: 10.1080/096132198370092.

Brendel, Christine (2002): Partizipation und Partizipative Methoden in der Arbeit des DED. Bonn: DED, checked on 8/15/2017.

Brillouet, Jean-Marc; Odoux, Eric; Conejero, Geneviève (2010): A set of data on green, ripening and senescent vanilla pod (Vanilla planifolia; Orchidaceae): anatomy, enzymes, phenolics and lipids. In *Fruits* (65(4)), pp. 221–235.

Busono, Suryo (2000): The Application of Solar Tunnel Dryer in Indonesia. In A. A. M. Sayigh (Ed.): World Renewable Energy Congress VI: Elsevier, pp. 2194–2197.

Cai, Donghan; Ye, Hui; Gu, Longfei (2014): A Generalized Solow-Swan Model. In *Abstract and Applied Analysis* 2014, pp. 1–8. DOI: 10.1155/2014/395089.

Charles, Denys J. (2013): Antioxidant properties of spices, herbs and other sources. New York, NY: Springer, checked on 6/16/2016.

Chel, A.; Kaushik, G. (2011): Renewable energy for sustainable agriculture. In *Agronomy Sust. Developm.* 31 (1), pp. 91–118. DOI: 10.1051/agro/2010029.

Correll, Donovan S. (1953): Vanilla-its botany, history, cultivation and economic import. In *Econ Bot* 7 (4), pp. 291–358. DOI: 10.1007/BF02930810.

Damirón Velázquez, Rafael (1994): La vainila y su cultivo. Veracruz.

De La Cruz Medina, Javier; Rodriguez Jiménes, Guadalupe C.; García, Hugo S. (2009): VANILLA Post-harvest Operations. Post-harvest Compendium, checked on 4/26/2017.

Dignum, Mark J.W; Kerler, Josef; Verpoorte, Rob (2002): Vanilla curing under laboratory conditions. In *Food Chemistry* 79 (2), pp. 165–171. DOI: 10.1016/S0308-8146(02)00125-5.

Duffie, John A.; Beckman, William A. (2013): Solar engineering of thermal processes John A. Duffie, William A. Beckman. 4th ed. Hoboken: John Wiley, checked on 2/2/2017.

Dust, Fred; Jonsdatter, Gitte (2008): Participatory Design. In Michael Erlhoff, Tim Marshall (Eds.): Wörterbuch Design: Begriffliche Perspektiven des Design. Basel: Birkhäuser Basel, pp. 307–308. Available online at https://doi.org/10.1007/978-3-7643-8142-4_223.

Eke, Akachukwu Ben (2011): Prediction of optimum angle of inclination for flat plate solar collector in Zaria, Nigeria. In *Agricultural Engineering International: CIGR Journal* 13 (4).

Eltrop, Ludger (2013): Chapter 2 Renewable Energy: Resources and Technologies. In Till Jenssen (Ed.): Glances at Renewable and Sustainable Energy. Berlin: Springer (Green Energy and Technology).

Encyclopedia Britannica (2012): San Luis Potosi state, Mexico. Available online at https://www.britannica.com/place/San-Luis-Potosi-state-Mexico, checked on 1/19/2017.

Esther Magdalene Sharon, M.; Banuu Priya, E. P.; Subhashini, S. (2016): Thin layer and deep bed drying basic theories and modelling: a review. In *Agricultural Engineering International: CIGR Journal* 18 (1), pp. 314–325, checked on 7/15/2017.

Expósito Verdejo, Miguel (2003): Diagnóstico rural participativo. Una guía práctica. Santo Domingo, República Dominicana: Centro Cultural Poveda, Proyecto Comunicación y Didáctica.

FDA (1984): Inspection Technical Guides - Water Activity (aw) in Foods. Office of Regulatory Affairs. Available online at http://www.fda.gov/ICECI/Inspections/InspectionGuides/InspectionTechnicalGuides/ucm072916.htm, checked on 2/10/2017.

Fields, Gary (2009): Making Investment Decisions. Rate of Return and Net Present Value. In Gary Fields (Ed.): Bottom Line Management. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 77–89. Available online at https://doi.org/10.1007/978-3-540-71447-7_7.

Flores Hernández, Ulises (2011): Energías Renovables para el Desarrollo Sustentable en Comunidades Indígenas dentro de la Huasteca Potosina. San Luis Potosí.

Frank, Norbert (2017): Wetterdaten Mexiko. Email to Clemens Brauer. Hamburg, Berlin, 9/4/2017.

Gallopin, Gilberto Carlos (1997): Indicators and their use. Information for decision-making. In *Scope-Scientific Committee on Problems of the Environment International Council of Scientific Unions* 58, pp. 13–27.

Gewali, Mohan B.; Bhandari, Ramchandra (2005): Renewable energy technologies in Nepal. In *World Review of Science, Technology and Sustainable Development* Vol. 2 (No. 1), pp. 92–106.

GIZ (2011): Modern Energy Services for Modern Agriculture. A Review of Smallholder Farming in Developing Countries. With assistance of Veronika Utz. Eschborn.

Gugel, G. (2006): Methoden-Manual "Neues Lernen". Tausend Vorschläge für die Schulpraxis: Beltz (Basis-Bibliothek Unterricht). Available online at https://books.google.de/books?id=k3ZLhkUt1UwC.

Hardi, Peter (Ed.) (1997): Assessing sustainable development. Principles in practice. Winnipeg: Internat. Inst. for Sustainable Development.

Henkel AG &Co. KGaA (2017): Resistol 850 Escolar. Available online at http://www.resistol.com.mx/es/productos/pegamentos-liquidos-escolares/resistol-850-escolar.html, checked on 9/11/2017.

Hernández Hernández, Juan (2014): Beneficiado artesanal de vainilla en México. In Carlos Araya Fernández, Roberto Cordero Solórzano, Amelia Paniagua Vásquez, José Bernal Azofeifa Bolaños (Eds.): I Seminario Internacional de la Vainilla. Promoviendo la investigación, la extensión y la producción de vainilla en Mesoamérica. Heredia, Costa Rica, pp. 133–141.

http://de.climate-data.org: http://de.climate-data.org. Available online at http://de.climate-data.org/location/766467/, checked on 5/27/2016.

INAFED (2016): San Luis Potos - Tamazunchale. Available online at http://www.inafed.gob.mx/work/enciclopedia/EMM24sanluispotosi/municipios/24037a.html, updated on 5/25/2016, checked on 5/28/2016.

Issa, Tomayess; Isaias, Pedro (2015): Sustainable Design. HCI, Usability and Environmental Concerns. 1st ed. 2015. London, s.l.: Springer London. Available online at http://dx.doi.org/10.1007/978-1-4471-6753-2.

Janjai, S.; Bala, B. K. (2012): Solar Drying Technology. In *Food Eng Rev* 4 (1), pp. 16–54. DOI: 10.1007/s12393-011-9044-6.

Jiménez, Perla; Rosales, Teresa; Tapia, Adriana; Jiménez, Christian; Dávila, Gloria (2013): Microbial Ecology of Traditional Mexican Vanilla Curing. Escuela Nacional de Ciencias Biológicas-Departamento de Microbiología e Ingeniería Bioquímica (Instituto Politécnico Nacional). Mexico City. Available online at http://www.smbb.com.mx/congresos%20smbb/cancun13/TRABAJOS/SMBB/BiotecnologiaAlimentosBebidas/III-C54.pdf, checked on 4/27/2017.

Kabongo, Jean D. (2013): Design for Environment. In Samuel O. Idowu, Nicholas Capaldi, Liangrong Zu, Ananda Das Gupta (Eds.): Encyclopedia of Corporate Social Responsibility. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 780–786. Available online at https://doi.org/10.1007/978-3-642-28036-8_40.

Kamaruddin, Abdullah; Kamaruddin, Mursalim (2007): Drying Of Vanilla Pods Using A Greenhouse Effect Solar Dryer. In *Drying Technology* (15(2)), pp. 685–698.

Karthik Kumar, RB (2013): Factors affecting the quality of Vanilla-A Review. In *Research and Reviews: Journal of Agriculture and Allied Sciences* 2 (3), pp. 37–41, checked on 4/26/2017.

Koizumi, Tatsuji (2015): Biofuels and food security. In *Renewable and Sustainable Energy Reviews* 52, pp. 829–841. DOI: 10.1016/j.rser.2015.06.041.

Kumar, Mahesh; Sansaniwal, Sunil Kumar; Khatak, Pankaj (2016): Progress in solar dryers for drying various commodities. In *Renewable and Sustainable Energy Reviews* 55, pp. 346–360. DOI: 10.1016/j.rser.2015.10.158.

Kumar, S.; Bhattacharya, S. C. (2005): Technology Package: Solar, Biomas and Hybrid Dryers.

Lalage, Gayatri; Jain, Sudhir; Panwar, N. L.; Kothari, Surendra; Sharma, G. P. (2010): Design and development of solar paraboloid concentrator for ginger drying. In *International Journal of Agricultural Engineering* 3 (2), pp. 228–231, checked on 7/25/2017.

Lee, Gwan Gyu (2015): Sustainability assessment of site-scale development projects — Focusing the assessment system based on greenspace gross volume. In *KSCE J Civ Eng* 19 (5), pp. 1238–1247. DOI: 10.1007/s12205-015-0670-z.

Lewis, W. K. (1921): The Rate of Drying of Solid Materials. In *J. Ind. Eng. Chem.* 13 (5), pp. 427–432. DOI: 10.1021/ie50137a021.

Mainali, Brijesh; Pachauri, Shonali; Rao, Narasimha D.; Silveira, Semida (2014): Assessing rural energy sustainability in developing countries. In *Energy for Sustainable Development* 19, pp. 15–28. DOI: 10.1016/j.esd.2014.01.008.

McCall, Morgan W. (2010): Recasting Leadership Development. In *Industrial and Organizational Psychology* 3 (1), pp. 3–19. DOI: 10.1111/j.1754-9434.2009.01189.x.

Menck, Karl-Wolfgang (1973): The concept of appropriate technology. In *Intereconomics* 8 (1), pp. 8–10. DOI: 10.1007/BF02927517.

Merriam Webster Dictionary: Definition of ENDOGENOUS. Available online at http://www.merriam-webster.com/dictionary/endogenous?utm_campaign=sd&utm_medium=serp&utm_source=jsonld, checked on 11/30/2016.

Mohamed Akoy, EL- Amin Omda; Ismail, Mohamed Ayoub; Ahmed, El-Fadil Adam; Luecke, W. (2006): Design and Construction of A Solar Dryer for Mango Slices. Bonn, checked on 7/31/2017.

Mujumdar, Arun S.; Devahastin, Sakamon (2000): Mujumdar's Practical guide to industrial drying. [principles, equipment and new developments]. Montreal: Exergex Corp.

Musembi, Maundu Nicholas; Kiptoo, Kosgei Sam; Yuichi, Nakajo (2016): Design and Analysis of Solar Dryer for Mid-Latitude Region. In *Energy Procedia* 100, pp. 98–110. DOI: 10.1016/j.egypro.2016.10.145.

Mustayen, A.G.M.B.; Mekhilef, S.; Saidur, R. (2014): Performance study of different solar dryers. A review. In *Renewable and Sustainable Energy Reviews* 34, pp. 463–470. DOI: 10.1016/j.rser.2014.03.020.

Muthusivagami, R. M.; Velraj, R.; Sethumadhavan, R. (2010): Solar cookers with and without thermal storage—A review. In *Renewable and Sustainable Energy Reviews* 14 (2), pp. 691–701. DOI: 10.1016/j.rser.2008.08.018.

NAAEE (2009a): Guía para elaborar programas de educación ambiental no formal 1. Ciudad de México: Semarnat.

NAAEE (2009b): Guía para elaborar programas de educación ambiental no formal 2. Ciudad de México: Semarnat.

Nagel, Robert L.; Pappas, Eric C.; Pierrakos, Olga (2012): On a Vision to Educating Students in Sustainability and Design—The James Madison University School of Engineering Approach. In *Sustainability* 4 (12), pp. 72–91. DOI: 10.3390/su4010072.

NASA (2017): NASA Surface meteorology and Solar Energy - Available Tables. Available online at https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?&num=081112&lat, checked on 4/28/2017.

Nelson, Lindsey Anne (2012): Design for the Other 90% and Appropriate Technology. The Legacies of Paul Polak and E.F. Schumacher. In ASEE (Ed.): 2012 ASEE Annual Conference & Exposition. San Antonio, Texas: ASEE Conferences.

Nelwan, Leopold O. (2017): Equilibrium Moisture Content of Vanilla. Researchgate Message to Clemens Brauer. Bogor, Indonesia / Karlsruhe, Germany, 7/17/2017.

Nijkamp, Peter; Capello, Roberta (Eds.) (2009): Handbook of regional growth and development theories. ebrary, Inc. Cheltenham, UK, Northampton, MA: Edward Elgar. Available online at http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10298464.

Norgaard, Richard B. (1989): The Case for Methological Pluralism. In *Ecological Economics* (1), pp. 37–57.

Odoux, Eric (2011): Vanilla Curing. In Eric Odoux, Michel Grisoni (Eds.): Vanilla. Boca Raton, Fla.: CRC Press (Medicinal and aromatic plants, 47), pp. 173–188.

Ogheneruona, Diemuodeke E.; Yusuf, Momoh O.L. (2011): Design and Fabrication of a Direct Natural Convection Solar Dryer for Tapioca. Port Harcourt, Nigeria: University of Port Harcourt,, checked on 7/31/2017.

Okoroigwe, Edmund C.; Ndu, Evidence C. (2015): Comparative evaluation of the performance of an improved solar-biomass hybrid dryer. In *Journal of Energy in Southern Africa* (Vol 26 No 4), pp. 38–51.

Parris, Thomas M.; Kates, Robert W. (2003): Characterizing and Measuring Sustainable Development. In *Annual Review of Environment and Resources* 28 (1), pp. 559–586. DOI: 10.1146/annurev.energy.28.050302.105551.

Parthasarathy, V. A.; Chempakam, B.; Zachariah, T. J. (Eds.) (2008): Chemistry of Spices: CABI. Available online at https://books.google.de/books?id=5WY08iuJyawC.

Patranon, R. (1984): Solar thermal processes in Thailand. A study on natural convection cabinet drying, final report. In *USAID-Thai Renewable Non-Conventional Energy Cooperation Project, King Mongkut's Institute of Technology Thonburi, Bangkok*.

Pearce, Joshua M. (2012): The case for open source appropriate technology. In *Environ Dev Sustain* 14 (3), pp. 425–431. DOI: 10.1007/s10668-012-9337-9.

Perez, Richard; Stewart, R.; Seals, R.; Guertin, T. (1988): The development and verification of the Perez diffuse radiation model. Sandia National Labs., Albuquerque, NM (USA) State Univ. of New York, Albany (USA). Atmospheric Sciences Research Center.

Pérez Silva, Araceli; Gunata, Ziya; Lepoutre, Jean-Paul; Odoux, Eric (2011): New insight on the genesis and fate of odor-active compounds in vanilla beans (Vanilla planifolia G. Jackson) during traditional curing. In *Food Research International* 44 (9), pp. 2930–2937. DOI: 10.1016/j.foodres.2011.06.048.

Perozo Suárez, Daniel Alberto (2015): ENDOGENOUS DEVELOPMENT, THEORY AND PRACTICE: INTERVENTIONS IN THE RURAL AREAS OF RIO DE JANEIRO, BRAZIL. THESIS TO OBTAIN THE DEGREE OF MASTER OF SCIENCE. UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ / COLOGNE UNIVERSITY OF APPLIED SCIENCES, San Luis Potosí / Köln, checked on 11/30/2016.

Polak, Paul (2010): The Death of Appropriate Technology I : If you can't sell it don't do it. Edited by Out of Poverty. Available online at http://www.paulpolak.com/the-death-of-appropriate-technology-2/, updated on 9/10/2010, checked on 8/6/2017.

Practical Action: History - ITDG to Practical Action. Practical Action. Available online at https://practicalaction.org/history, checked on 8/8/2017.

Practical Action: Zeer pot fridge. Practical Action. Available online at https://practicalaction.org/zeer-pot-fridge, checked on 8/7/2017.

Rabin, Michael D. (2008): Needs Assessment. In Michael Erlhoff, Tim Marshall (Eds.): Wörterbuch Design: Begriffliche Perspektiven des Design. Basel: Birkhäuser Basel, p. 289. Available online at https://doi.org/10.1007/978-3-7643-8142-4_203.

Ratobison, R.; Zeghmati, B.; Reddy, T.A; Daguenet, M. (1998): Sizing of solar supplemented liquid and air heating systems for the treatment of vanilla. In *Solar Energy* 62 (2), pp. 131–138. DOI: 10.1016/S0038-092X(97)00118-7.

Remund, Jan; Müller, Stefan; Kunz, Stefan; Huguenin-Landl,, Barbara; Studer, Christian; Cattin, René (2017): Meteonorm Handbook part I: Software. Bern: Meteotest, checked on 9/5/2017.

Richardson, J. F.; Harker, J. H.; Backhurst, J. R. (2002): Drying. In John Francis Richardson, John Hadlett Harker, J. R. Backhurst, John Metcalfe Coulson (Eds.): Coulson and Richardson's chemical engineering. Vol. 2: Particle technology and separation processes. 5th ed. Oxford: Butterworth-Heinemann, pp. 901–969.

Rogall, Holger (2002): Neue Umweltökonomie - Ökologische Ökonomie. Ökonomische und ethische Grundlagen der Nachhaltigkeit, Instrumente zu ihrer Durchsetzung. Wiesbaden, s.l.: VS Verlag für Sozialwissenschaften. Available online at http://dx.doi.org/10.1007/978-3-322-99733-3.

Roling, W. F.; Kerler, J.; Braster, M.; Apriyantono, A.; Stam, H.; van Verseveld, H. W. (2001): Microorganisms with a taste for vanilla. Microbial ecology of traditional Indonesian vanilla curing. In

Applied and environmental microbiology 67 (5), pp. 1995–2003. DOI: 10.1128/AEM.67.5.1995-2003.2001.

Romero, V. M.; Cerezo, E.; Garcia, M. I.; Sanchez, M. H. (2013): Simulation and validation of vanilla drying process in an indirect solar dryer prototype using CFD Fluent program. In *Energy Procedia* (57), pp. 1651–1658.

Schumacher, Ernst F. (1983): Die Rückkehr zum menschlichen Maß. Alternativen für Wirtschaft und Technik. 34.-37. Tsd. Reinbek bei Hamburg: Rowohlt.

Sianipar, Corinthias Pamatang Morgana; Yudoko, Gatot; Adhiutama, Akbar; Dowaki, Kiyoshi (2013): Community Empowerment through Appropriate Technology. Sustaining the Sustainable Development. In *Procedia Environmental Sciences* 17, pp. 1007–1016. DOI: 10.1016/j.proenv.2013.02.120.

Sreedhar, R. V.; Roohie, K.; Maya, P.; Venkatachalam, L.; Bhagyalakshmi, N. (2009): Biotic elicitors enhance flavour compounds during accelerated curing of vanilla beans. In *Food Chemistry* 112 (2), pp. 461–468. DOI: 10.1016/j.foodchem.2008.05.108.

Stelzer, Kevin (2006): Sustainability = Good Design. In *Les ateliers de l'éthique* 1 (2), pp. 27–40.

Stough, Roger R.; Stimson, Robert J.; Nijkamp, Peter (2011): An Endogenous Perspective on Regional Development and Growth. In Karima Kourtit, Peter Nijkamp, Roger R. Stough (Eds.): Drivers of Innovation, Entrepreneurship and Regional Dynamics. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 3–20. Available online at https://doi.org/10.1007/978-3-642-17940-2_1.

Tiwari, G. N.; Tiwari, Arvind K.; Shyam (2016a): Handbook of Solar Energy. Theory, Analysis and Applications. Singapore: Springer Singapore (Energy Systems in Electrical Engineering), checked on 7/28/2017.

Tiwari, Sumit; Tiwari, G. N.; Al-Helal, I. M. (2016b): Performance analysis of photovoltaic–thermal (PVT) mixed mode greenhouse solar dryer. In *Solar Energy* 133, pp. 421–428. DOI: 10.1016/j.solener.2016.04.033.

Tonkinwise, Cameron (2008): Nachhaltigkeit. In Michael Erlhoff, Tim Marshall (Eds.): Wörterbuch Design: Begriffliche Perspektiven des Design. Basel: Birkhäuser Basel, pp. 282–288. Available online at https://doi.org/10.1007/978-3-7643-8142-4_202.

Trinidad García, Karina Lizbeth (2014): Caracterisación Agroecológica de al Vainilla (Vanilla spp.) en la Huasteca Potosina. San Luis Potosí.

Umweltbundesamt (1999): Valuation as an element of life cycle assessments - German Federal Environmental Agency method for impact indicator standardization, impact category grouping (ranking), and interpretation in accordance with ISO 14042 and 14043. Berlin: Umweltbundesamt, checked on 9/10/2017.

Umweltbundesamt (2000a): ProBas - Prozessdetails: HolzWirtschaftSchnittholz-techn-getrocknet-Fichte. Umweltbundesamt. Available online at http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={0E0B293D-9043-11D3-B2C8-0080C8941B49}, checked on 9/11/2017.

Umweltbundesamt (2000b): ProBas - Prozessdetails: KunststoffEPS-DE-2000. Umweltbundesamt. Dessau-Roßlau. Available online at http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={0E0B2749-9043-11D3-B2C8-0080C8941B49}, checked on 9/11/2017.

Umweltbundesamt (2000c): ProBas - Prozessdetails: LPG-Herd-ZA. Umweltbundesamt. Available online at http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={B11C69BD-A5B4-11D3-B42D-FED95173DC12}, checked on 9/11/2017.

Umweltbundesamt (2000d): ProBas - Prozessdetails: Stahl. Umweltbundesamt. Dessau-Roßlau. Available online at http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={19E7D6CB-2337-4ED1-A096-3DF3961DDA87}, checked on 9/11/2017.

Umweltbundesamt (2000e): ProBas - Prozessdetails: Steine-ErdenGlas-flach-generisch. Umweltbundesamt. Dessau-Roßlau. Available online at http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={B11C6B2C-A5B4-11D3-B42D-FED95173DC12}, checked on 9/11/2017.

Umweltbundesamt (2004): ProBas - Prozessdetails: Spanplatte. Umweltbundesamt. Dessau-Roßlau. Available online at http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={A4227C48-C799-4A17-AC4B-8A5988F135D1}, checked on 9/11/2017.

Umweltbundesamt (2005): ProBas - Prozessdetails: MetallAluminiumfolie-EU-2005. Umweltbundesamt. Dessau-Roßlau. Available online at http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={B7063B81-B42C-45FE-B0FE-E0B918C5EDE1}, checked on 9/11/2017.

United Nations (2007): Indicators of sustainable development. Guidelines and methodologies. 3rd ed. New York: United Nations, checked on 9/4/2017.

Van Dyk, Sahar; McGlasson, William Barry; Williams, Mark; GAIR, Cathy (2010): Influence of curing procedures on sensory quality of vanilla beans. In *Fruits* (65 (6)), pp. 387–399.

Vanilla Review (2008): Daintree Vanilla & Spice (Australia). Available online at http://www.vanillareview.com/2008/daintree-vanilla-spice-australia/, checked on 6/6/2016.

Vázquez-Barquero, Antonio (2007): Endogenous development: Analytical and policy issues. In Allen John Scott (Ed.): Development on the ground. Clusters, networks and regions in emerging economies. 1. publ. London u.a.: Routledge (Routledge advances in management and business studies, 33), pp. 24–43.

Wagner, Andreas (2010): Photovoltaik Engineering. Berlin, Heidelberg: Springer Berlin Heidelberg, checked on 7/27/2017.

Waliszewski, Krzysztof N.; Pardio, Violeta T.; Ovando, Sandy L. (2007): A simple and rapid HPLC technique for vanillin determination in alcohol extract. In *Food Chemistry* 101 (3), pp. 1059–1062. DOI: 10.1016/j.foodchem.2006.03.004.

WECD (1987): Our common Future. New York: Oxford University Press.

Weiss, Werner; Buchinger, Josef (2003): Solar Drying. Gleisdorf, Austria, checked on 7/17/2017.

Wilhelm; R, Luther; Suter, Dwayne A.; Brusewitz, and Gerald H. (2004): Drying and Dehydration. In Wilhelm, Luther R, Dwayne A. Suter, and Gerald H. Brusewitz (Eds.): Food & Process Engineering Technology. St. Joseph, MI: American Society of Agricultural and Biological Engineers, pp. 259–284.

Wu, J.; Wu, T. (2012): Sustainability indicators and indices: an overview. In Christian N. Madu, C. Kuei (Eds.): Handbook of Sustainable Management. London: Imperial College Press, pp. 65–86.

www.worldatlas.com (2017): The Leading Countries In Vanilla Production In The World. www.worldatlas.com. Available online at http://www.worldatlas.com/articles/the-leading-countries-in-vanilla-production-in-the-world.html, updated on 2/24/2017, checked on 7/18/2017.

Zelenika, Ivana; Pearce, Joshua M. (2011): Barriers to Appropriate Technology Growth in Sustainable Development. In *JSD* 4 (6). DOI: 10.5539/jsd.v4n6p12.