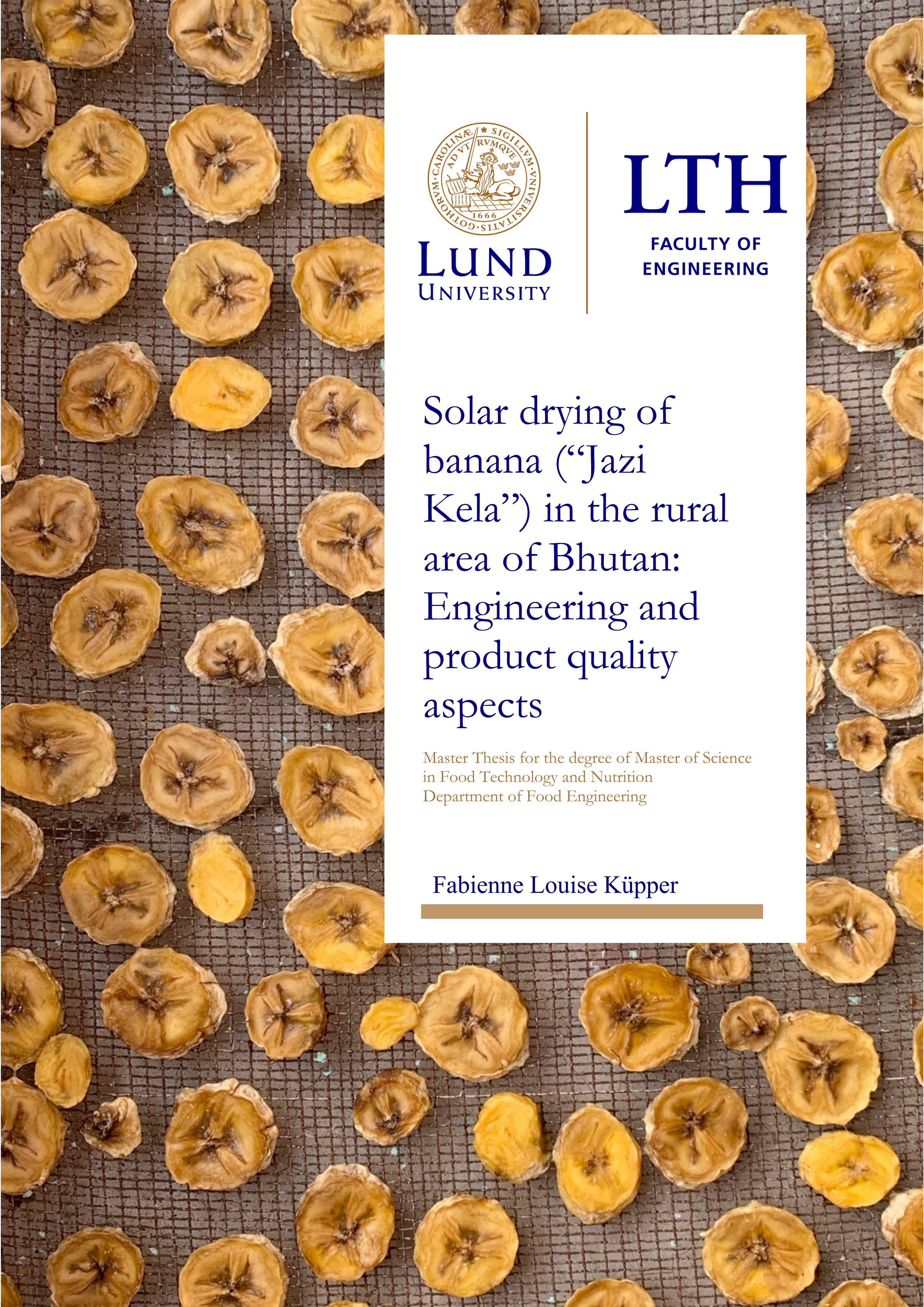

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Solar drying of banana ("Jazi Kela") in the rural area of Bhutan: Engineering and product quality aspects

Master Thesis for the degree of Master of Science in Food Technology and Nutrition
Department of Food Engineering

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Abstract

Agriculture is the main employment in Bhutan, making it an agriculture-based economy. The project “Solar Food: Reducing post-harvest losses through improved solar drying” is to help indigenous people to preserve their food crops in a more efficient but still natural way by using solar energy for drying. A new idea arose to commercialize food items dried in the solar dryer instead, which would affect not only the income of farmers but the Bhutanese economy and society. The present paper investigates whether an old and a new solar dryer model situated in Bhutan are drying banana slices sufficiently and which model functions more efficient. Experiments on if the maturity of the banana or a pre-treatment affect the drying were done and the nutritional value of the samples was looked at. A focus group discussion helped to understand whether their consumers would like solar-dried food and a market for it exists. Furthermore, an investigation on socio-economic impacts for the commercialization of solar-dried banana in Bhutan was conducted. Outcomes show that the new dryer model in Bhutan dried banana slices sufficiently within 20 hours conducted throughout two days which can be explained by its design. Maturity stages of the banana did not significantly affect drying times. A focus group discussion showed that panelists with a South-East Asian Background are interested in solar-dried bananas and would consume them regularly. The nutritious value was found to change mainly regarding its moisture content before and after drying. A commercialization potentially influences socio-economic aspects. Especially food security would be increased and a steadier availability of healthy foods for the Bhutanese would exist, as well as an additional source of income for farmers develops. The pre-treatment with salt showed a reduced drying time of banana slices, which should be investigated in further research.

This project was carried out between January and June 2024, both in Deothang, Bhutan, and Lund, Sweden. The purpose of this project was the collection of data in the scope of a master thesis at the Food Department of LTH for the master's degree in food technology and nutrition.

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Abbreviations

JNEC Jigme Namgyel Engineering College
LMIC Lower middle income country
GDP Gross Domestic Product
NCD Non-communicable disease
WHO World Health Organisation
FAO Food and Agriculture Organization of the United Nation
DS Direct sundrying
IS Indirect sundrying

OD Old Dryer
ODM Old Dryer Model
ND New Dryer
NDM New Dryer Model
OAnF Open-air sundrying no Fan
OAwF Open-air sundrying with Fan
Kg kilogram
mm milimeter
MCwb Moisture content wet basis

1 Introduction

The following thesis reports about the solar drying of food project conducted in Bhutan, where bananas were dried and analyzed according to certain food quality aspects.

1.1 Project description

Agriculture is the main employment in Bhutan with more than half of all jobs in this sector, making it an agriculture-based economy. (UNDP 2024) However, agriculture comes with challenges as it is extremely nature-dependent and crop growing, as well as harvesting, takes place very unregularly and seasonal.
To ensure a food supply with nutritious foods over a long time of storage, the project “Solar Food: Reducing post-harvest losses through improved solar drying” was developed between Lund University and Jigme Namgyel Engineering College (JNEC), the Royal University of Bhutan. The project idea is based on a successfully implemented Solar crop dryer for foods in Thailand. With this inspiration, Tshewang Lhendup started a similar project in Bhutan with the aim of helping local farmers to maintain a regular food supply throughout the year by means of preservation. (Lhendup 2005)
The project “Solar Food: Reducing post-harvest losses through improved solar drying” is to help indigenous people to preserve their food crops in a more efficient but still natural way by using solar energy for drying. Thereby, achieving no or as few nutrition losses as possible in the food is highly beneficial for the local population. Drying by solar energy makes this preservation method more accessible for farmers due to less costs for energy, which is especially beneficial in Bhutan as it is still lower-middle income country. (World Bank 2024)

A new idea which arose is to commercialize the food items dried in the solar dryer instead of solely selling them on the market. An increased shelf-life of dried fruits and vegetables can make them interesting and safe to be sold in supermarkets on local, regional and maybe even national scale in Bhutan. This could lead to an increased income for farmers and prevent them from income losses due to post-harvest losses. Moreover, food security and thereby the nutritious status of the country may be enhanced by an increased shelf-life of certain food products.

1.2 Status Quo

The project in Bhutan

The project “Solar Food” integrates an investigation of the dryer design and energy engineering part together with a food engineering and product quality related part. Until today, product quality aspects of the food post-drying have not been investigated.

For the past year, one food dryer model had been used in Bhutan in the scope of the project. Within this dryer set-up, research was done on the dryer's efficiency by using ginger and eggplant as food items to be dried. Changes in the dryer set-up were tested, aimed to be optimized and analyzed. (Rissler 2023; Mahmoodi 2023)

Based on the results of the series of experiments with this food dryer model, a new layout was created. A new food dryer was built with major differences in the set-up and firstly used at the same time of the conductance of the present work. Consequently, both the old food dryer and new food dryer model are included in the present work. Their set-up, including similarities and differences, is described in more detail in section 4.2.1 Food Dryer Models.
Currently, within the scope of this project the food dryer is analyzed according to the airflow within, different options of fans and their effect on the drying rate of the food item. However, the quality aspects of the food items during and post-drying were not further investigated and taken into account for the overall results of the functionality of the dryer. This work will therefore focus on the quality aspects of the food after drying, thereby giving an indication on the performance of both the old and new dryer design from a food engineering perspective.

Banana Drying and quality aspects

Up to today, several researchers have focused on the achievement of the fastest drying time for banana slices (Pruengam, Pathaveerat, and Pukdeewong 2021; Lingayat and V.P 2021). The application of pretreatments on bananas has been researched on and quality aspects like color post-drying were analyzed. Findings included that an osmotic pretreatment like the application of a salt solution to banana slices before drying could shorten the drying time, as well as enhance the color of the dried banana (Adepoju and Osunde 2015).

Solar-Drying of banana

Furthermore, there has been research conducted on drying of bananas in Thailand, in a similar project using a greenhouse Solar dryer. During these experiments, solely drying time and temperature were investigated, whereas a comparison of the nutritious value or an investigation of color, texture or water activity post-drying was not included in the results. (Kreetachat et al. 2023)

For now, the link between the investigation of post-drying product quality aspects when using a solar dryer for food in Bhutan is missing. Therefore, a validation of current energy engineering results for both solar-dryer models should be validated by doing an investigation of product quality aspects pre- and post-drying of bananas.

1.3 Research questions

Based on two existing Dryer Models in Bhutan the following research questions are to be answered:

- How does the drying curves differ between a drying session of the New Dryer Model, the Old Dryer Model and Control Drying in Open-air sunlight with and without fan?
- How does the maturity of the raw material affect the drying?
- How does drying change the overall nutrition of the product? Is this change positive/desired or negative/undesired out of the nutrition recommendation perspective?

- By doing a focus group interview, is commercialization of the solar-dried banana slices an option in Bhutan?
- What societal impacts could a commercialization of the solar-dried bananas have?

2 Aim and objectives

The overall aim of this research is to evaluate the design of different Dryer Models for the efficient solar dehydration of the bananas locally called “Jazi Kela”, a *Musa Acuminata* species, in the rural area of Bhutan. For the first time in the Solar-Food project, a close investigation of the food samples will be done to validate the functioning of the dryer models. It is to be investigated whether the solar dried bananas can potentially be commercialized in Bhutan. Therefore, consumers views were further included and evaluated in this research.

Dried banana samples are to be analyzed and results compared according to the Solar Dryer Model used for drying. The moisture content pre- and post-drying are looked at, as well as water activity determined to evaluate safety for consumption.
It is to be determined which of the three Solar-drying options is achieving a low moisture content the fastest and if complete drying of the food was achieved. As bananas are a food item which goes through several maturity stages while ripening, it is to be analyzed in how far the maturity stage of the dried food sample may affect the drying process and result.

Furthermore, the nutritious value before and after drying will be compared and in accordance to the countries’ nutrition status, the societal impact of a commercialization of the dried bananas is to be assessed.
The focus group interview is conducted to see if the dried banana is liked by consumers according to its visual and sensory characteristics and if a commercialization is therefore reasonable.

3 Background

3.1 Bhutan

The small Kingdom of Bhutan is located between China, bordering Bhutan in the North, and surrounded by India in the West, South and East. (World Bank 2024) The country with its population of about 770.276 people projected for the year of 2023 (NSB 2024) lays in the eastern Himalaya region, showing a mountainous landscape with deep valleys. Due to the rangy landscape the inhabitants are dispersedly settled throughout the 38.390 km^2 big country. (FAO 2011) The governmental structure had been switched to a democratic constitutional monarchy in year 2008 and since then follows the ideology based on the Gross National Happiness. (World Bank 2024)

Bhutan’s climate is very diverse, comprising humid and subtropical regions, to temperate ones in valleys and colder ones in higher altitudes. Therefore, temperatures differ in relation to the altitude, and it becomes colder with a higher elevation level. Winter season in Bhutan starting from mid-November to March is usually very dry, whilst summer is the time of monsoon, and

it becomes more humid and hotter. Rainfalls set in around mid-April and last until late September. Spring and fall seasons are characterized by both sunny and rainy days, with spring being a little bit drier. (FAO 2011)
With heavy rainfalls especially in summer and fall and the mountainous landscape, the risk of floods and landslides is very high. (FAO 2011)

The thesis project was carried out in Deothang in the district of Samdrup Jongkhar, located in the south-east of Bhutan. With an altitude of 800m (Phuntsho, Ghalley, and Tashi Wangchuk 2020), this area holds rather mild to warm temperatures throughout the year, making it possible to grow tropical and exotic fruits and vegetables.

3.1.1 Economy

Bhutan is ranked as a Lower Middle-income country (LMIC) with hydropower plants and agriculture building the basis of the economy. (UNDP 2024) (World Bank 2024)
The Gross Domestic Product (GDP) per Capita summed up to 3833 US$ with the GDP Growth Rate being noted to be 5.21% in the year of 2022. (NSB 2024)

Generally, within the past years the country has experienced economic growth due to an investment in hydroplants. (UNDP 2024) India counts as the most important trading partner with Bhutan in terms of hydropower, agricultural products and many other. (World Bank 2024) Especially in the districts close to the Indian border, for example of Samdrup Jongkhar, locals receive many of their food items from India.

Furthermore, agriculture forms an important part to maintain the livelihood of the Bhutanese and serves the purpose of self-supply. Primary crops grown include cereals, which account for approximately 70 percent of the acreage, with maize, rice, wheat and other cereals being the main varieties. A cultivation and sale of cash crops like apples and oranges has led to an increased income for farmers. Orchards are being more and more established, as these appear to be more viable than other cropping. (FAO 2011)

When it comes to employment, overall, 94.1% of the population had a job in 2022. Agriculture forms the biggest share of employment with 43.5% of Bhutanese working in this field. Second forms occupation in services (42.8% people employed) while the fewest amount is working in industry (13.7%).
A bigger share of women (53.3%) is occupied in agricultural work compared to men (36.1%), which is the opposite for service and industry occupation. (NSB 2022)

3.1.2 Nutrition status

The nutrition status of the Bhutanese population is characterized by different types of malnutrition. Over and under nutrition, as well are micronutrient deficiencies are very prevalent which have a negative effect on the overall health status of the population. The combination of these types of malnutrition is often referred to as ‘triple burden of malnutrition’ in Bhutan (MoH 2021).

In terms of undernutrition, children suffer from stunting (21.2% in 2015) and wasting (4.3% in 2015) and about 3% of adults showed to be underweight in the year of 2019. (MoH 2020)

When it comes to micronutrient deficiencies, especially anemia forms a big problem. More than a third of all women suffer from anemia, as well as more than a third of all children in the country do. A relation can therefore be seen that low iron levels of women should be treated in order to prevent anemia in children. Generally, the tendency of anemia has decreased over the past years but still remains a risk to public health. (MoH 2021)

Apart from anemia, not many data are available concerning the micronutrient status of the population. However, as the day-to-day diet of Bhutanese is rather similar, assumptions are made by the Ministry of Health that further deficiencies in A and B vitamins, just as folate, iodine and zinc are a problem. (MoH 2021)

One third of all Bhutanese adults (age 15-69 years) are overweight and 11.4% obese, of which women are predominantly affected. Almost 90% of the population does not eat high enough amounts of fresh fruits and vegetables. As the poverty rate in Bhutan accounted up to 12.7% in 2022, life circumstances are showing to influence food security and access to fresh and healthy food (NSB 2024). The dietary patterns of overweight parents are shown to significantly increase childhood overweight and obesity. (MoH 2020)

The displayed nutrition status of the country's population leads to a high number of deaths being caused by the development of non-communicable diseases (NCD). (MoH 2021) One of the most common NCDs in Bhutan was found to be diabetes, with 8.6% of men and 7.7% of women suffering from it, especially in higher age. (Giri et al. 2013)
Furthermore, raised blood cholesterol and blood pressure are rather common issues noted by Bhutanese. This may be enhanced through high daily salt intakes, which are double as high as the recommended amount by the World Health Organisation (WHO) per day. (MoH 2020)

3.2 "Jazi Kela" - a *Musa Acuminata species* and its nutritive value

The plant *Musa Acuminata* is an evergreen perennial. (Yadav 2021) This wild species belongs to the *Musaceae* family and counts as a tropical fruit which is predominantly occurring in Southeast Asia, as for example India. (Kumar et al. 2021)
The fruits of the plant *Musa Acuminata* are bananas which are botanically classified as being berries. (Lopez, Barclay, and Badal 2024) When fully mature, the fruits peel will show a vibrant yellow color and the pulp will show a cream-yellow. There are several potential health benefits found to exist when consuming the fruits of *Musa Acuminata*, which predominantly result from the fruits nutritious composition. (Yadav 2021) In the area of Deothang, Bhutan, the present banana species is called "Jazi Kela" and belongs to the same family as the *Cavendish* banana, found in European supermarkets. However, characteristics like a bright yellow flesh color and a distinctly sweet taste even in a less mature state clearly distinguish the present *Musa Acuminata* species "Jazi Kela" from the *Cavendish*.

For the present *Musa Acuminata*, Figure 1 shows both macro- and micronutrients of the fruit per 100g fresh weight. (Kumar et al. 2021)
As can be seen in the Figure, on a macronutrient level *Musa Acuminata* especially is a source of Carbohydrates with 22.84g per 100g. In the human diet, carbohydrates serve as main energy providing macronutrient, which should therefore form a major part of the diet. The amount needed in order to maintain a normal energy balance differs individually. (Jéquier 1994)
When it comes to micronutrients, Musa Acuminata shows high levels in Pyridoxine (0.36mg) and Vitamin C (8.7mg).
Pyridoxine is part of the group of B Vitamins. Positive effects of pyridoxine (Vit B6) on the human body include risk prevention for cardiovascular diseases by reducing homocysteine levels. Moreover, adequate intake may enhance the maintenance of cognitive function in higher age and for woman, Vitamin B6 was found to decrease premenstrual symptoms. The recommended daily intake for adults is about 1.3mg. Adverse effects on health have not been noted until today. (NIH 2023)
In terms of Vitamin C, this substance plays a crucial role in the collagen synthesis which is a structural element in connective tissues. In addition to this, Ascorbic Acid is known to contribute to the synthesis of hormones and neurotransmitters, thereby forming an important component in their household. Due to its antioxidative capacity, it may prevent inflammations in the body and enhances the liver's task of cleansing the body form unwanted substances. The recommended daily intake for adults is between 30-100mg. (Walingo 2005)

Furthermore, particularly the minerals Manganese (0.27mg), Copper (70µg), Potassium (358mg) and Magnesium (27mg) are contributing to the nutritive value and potential health benefits of the fruit.

The mineral Manganese is an essential component in the body's development and growth. Osteoporosis and immune system impairment could result from too few Manganese uptake. A daily intake of about 2mg for adults is recommended. (NIH 2021) However, potential negative effects on health when consumed in large excess could lead to neurotoxicity, wherefore an upper intake limit of about 11mg for adults per day exists. (Santamaria and Sulsky 2010; NIH 2021)
Copper is an essential mineral which functions as coenzyme in various processes in the human body, for example brain development, the immune system, or gene expression. It takes part in the iron metabolism, wherefore a deficiency could result in anemia. The recommended daily intake is about 900µg for adults. (NIH 2022a)
As part of the human diet, it is necessary to consume Potassium in adequate amounts. It is an important element in muscle and nerve stimulation, as well as preventive against coronary heart diseases which may be due to its blood pressure lowering effect. The recommended daily intake lies around 4700mg for adults. (Weaver 2013)
Magnesium forms a component that is necessary in many physiological processes in the body. It is needed for muscles to function properly, nerve impulse conduction and may prevent heart diseases. Furthermore, it becomes relevant for energy production and the synthesis of DNA. The daily recommended amount of intake for an adult is around 320-420mg, amounts rising with higher age. (NIH 2022b)

The listed nutrients generally contribute to some pharmacological effects. Regular consumption of *Musa Acuminata* thereby may show antioxidative, antidiabetic and blood pressure and blood cholesterol lowering effects. (Kumar et al. 2021)

Ingredients		Nutritional Value	Recommended daily allowance
Energy		90 kcal	4.5 %
Carbohydrates		22.84 g	18 %
Protein		1.09 g	2 %
Fat		0.33 mg	1 %
Cholesterol		0 mg	0 %
Dietary fiber		260 mg	7 %
Vitamin	Folates	20 µg	5 %
	Niacin	0.66 mg	4 %
	Pantothenic acid	0.33 mg	7 %
	Pyridoxine	0.36 mg	28 %
	Riboflavin	0.07 mg	5 %
	Thiamin	0.031 mg	2 %
	Vitamin A	64 IU	2 %
	Vitamin C	8.7 mg	15 %
	Vitamin E	0.10 mg	1 %
	Vitamin K	0.5 µg	1 %
Electrolytes	Sodium	1 mg	0 %
	Potassium	358 mg	8 %
Minerals	Calcium	5 mg	0.5 %
	Copper	0.07 mg	8 %
	Iron	0.26 mg	2 %
	Magnesium	27 mg	7 %
	Manganese	0.27 mg	13 %
	Phosphorus	22 mg	3 %
	Selenium	1.0 µg	2 %
	Zinc	0.15 mg	1 %
Phytonutrients	α- Carotene	25µg	--
	β- Carotene	26µg	--
	Lutein-Zeaxanthine	22µg	--
Carbohydrates	Glucose	22.84 g	18 %
	Fructose		
	Sucrose		

Figure 1: Nutritive value of Musa Acuminata per 100g fresh weight as provided by Kumar et al. 2021.

3.3 Solar-drying of Food

Solar-drying of food is a technique to dehydrate food items by maintaining their quality at low environmental cost. Several techniques and solar dryer designs exist in which solar light is used in order to raise the temperature of air which will then be used to off transport moisture from the food. (Bennamoun and Li 2018)

Solar-drying of food in a cabinet or chamber emerged from the method of open-air sun drying of food. Open-air sun drying is one of the main types of food drying for farmers. Especially in countries with warm or hot climate and during seasons with lower humidity it becomes easy to sun dry harvest surpluses. (Esper and Mühlbauer 1998) Open air sun drying is predominantly applied due to its low cost. However, a major drawback of open-air sun drying is the susceptibility of the food to external factors like dust, insects or birds. These enhance the spread of microorganisms on the food through physical contact or create losses by food being eaten.

In particular, microorganisms and the microbial load on the food will affect its final quality. (Esper and Mühlbauer 1998)

Nowadays, there exist many solar dryer models in which the food is not directly exposed to the sun in open-air conditions. These models usually function more time and energy efficient, drying the food in a more protected and thereby in a more hygienic way. (Mohana et al. 2020)

Different types of solar dryer models exist, usually being categorized in direct, indirect or mixed dryer models and systems with heat storage. (Mohana et al. 2020)
In Direct Solar drying models the item to be dehydrated is stored underneath a transparent shelter, like glass, but with direct exposure to incoming sunlight. (Dorji and Lungten 2023)
Indirect solar drying provides a drying chamber in the dryer design, where the item to be dried is stored, and an absorber area where air flows through and becomes heated. Water from the food will be removed by the heated air in the drying chamber and is off-transported through an outlet of the dryer. (Mohana et al. 2020; Om 2023) A mixed type of model therefore combines both systems of direct and indirect drying. The dryer model with heat storage is aimed to function even without sunlight, as the heat storage serves as source to heat the air for example during the night.
Furthermore, a division can be made between passive and active solar drying, where passive refers to air circulation in the chambers without external ventilation system and active includes the use of fans or pumps, creating a directed airflow. (Mohana et al. 2020)
Active solar drying systems are found to be more efficient concerning heat supply and drying rate. (Gilago, Mugi, and Velayudhan Parvathy 2023)

In food drying, a balanced temperature to prevent microbial growth and cooking of the food is important. A desirable temperature in food drying is therefore around 60°C, as it is high enough that food spoilage due to microorganisms won't occur faster than the drying process itself. (Döhlen 2016; Schmutz 1999) Further, around 60°C food still does not start to be cooked, which will decrease surface reactions of the food that could lead to the formation of a barrier due to structural deformation. An outer barrier could result in a lower removal of water from the food. (Schmutz 1999)
The dehydration of food through solar drying is a natural way to increase the shelf-life of a food item over a longer period of time, making it more convenient. This mean of preservation is an effective way to decrease the water content of the food, thereby decreasing its water activity which reduces the risk of microbial growth and spoilage. For now, dehydrating food open-air by using sunlight has shown to not fulfill international quality standards due to previously mentioned reasons. (Esper and Mühlbauer 1998; Sancho-Madriz 2003) Often, sensory characteristics are changed to the better when a food is being dried, as the flavor intensifies, making it more appealing and easier to sell. The weight of dried food products makes transportation more easy and affordable compared to their fresh version. (Sancho-Madriz 2003)

In addition, a solar dryer comprises some specific equipment which is needed, making it more costly for farmers. A fan system, consisting of an outer and interior fan, is usually needed. Therefore, access to electricity to run the fans during drying times is required and contributes to higher financial costs. (Mohana et al. 2020) Moreover, to be able to monitor the drying process from outside the dryer, the cabinet and different chambers can be equipped with thermocouples. In this way, abnormal temperature fluctuations within the dryer are visible to farmers without the need to open the dryer and causing heat losses. This monitoring requires special equipment like dataloggers and a multiplexer, which will be costly but can help farmers to indicate and compare the efficiency of drying between several days.

3.3.1 Types of heat transfer

In solar drying of food, thermal energy (or heat content) plays a fundamental role in the dehydration of the food. The heat content is set by the mass of the food, specific heat and temperature and set in relation with a reference temperature. (Singh and Heldman 2014) The process of dehydration does only take place following a heat and mass transfer within the food item. (Singh, Heldman, and Erdogdu 2024)

Heat transfer generally occurs in three different modes. Conduction takes place in a solid material wherefore direct contact is needed and energy transmission takes place between molecules. No motion of the material is happening while heat is transferred. Depending on the substance, the thermal conductivity can differ. A higher thermal conductivity means a faster heat transfer within the materials in contact. (Singh and Heldman 2014) Each food item has their own thermal conductivity. During solar drying of food, conductive heat transfer takes place within the food item. Moreover, conductive heat transfer occurs in the heat exchanger within the aluminum sheet.

Convection is the type of heat transfer occurring in liquids and gases together with a solid material. If a temperature gradient exists, a transmission of thermal energy takes place. (Singh and Heldman 2014) In the case of solar drying this type of heat transfer occurs in the absorber area, with the air as gaseous medium being heated by having direct contact with the black metal surface. Furthermore, the heated air will heat the food item at its surface, being the initial point for the dehydration of the food. This happens similarly in the heat exchanger area, where hot air on the one side gets in touch with the metal. The metal surface being heated, conduction within the material takes place and finally cold air on the other side of the exchanger will become heated as well.

Radiation is the release of electromagnetic rays by an object, leading to heat being transferred between the surfaces of two objects. The transmission of rays does even take place in a vacuum. Therefore, a gaseous medium is usually not affected by radiation whereas liquids and solids are significantly heated through electromagnetic rays. (Singh and Heldman 2014)

In the case of solar-drying, solar radiation plays the essential role in the dryer setup. The creation of heat through solar radiation is directly affected by the absorber area. Solar rays penetrating the glass to reach the absorber, however, will partly be emitted back, wherefore the glass is responsible for a small decrease in thermal radiation and thereby less efficient in heating. (Rissler 2023)

As can be seen, all types of heat transfer are relevant in solar drying. However, on all levels losses have to be considered. Solar-drying is first and foremost relying on the rate of solar irradiation within a day of drying. This rate determines the remaining overall heat transfer happening within the dryer and consequently also the mass transfer leading to the dehydration of the food.

3.3.2 Drying Rate

An important parameter in this research work is the rate of dehydration (drying rate) which shows the amount of water in kilogram evaporating every hour per square meter of surface area. (Singh, Heldman, and Erdogdu 2024)
Generally, the drying of a food item is characterized by different drying rates, as water is not removed in a consistent way at all times throughout the dehydration process. The first stage is when the temperature within the food item starts to rise, and moisture starts to evaporate and leave the food. Followingly, a larger amount of water will leave the product at persistent rate and temperature. This stage is called the constant rate drying period and will proceed until the water content of the food is lowered to the critical moisture content. Over time, this rate slows down as water loss occurs to a fewer extent. Still, after the slow down some falling drying rates may occur. Drying rates depend on the characteristics of the food item, properties of the equipment and process conditions used to dry the food, which makes the drying rate a highly variable parameter. (Singh, Heldman, and Erdogdu 2024)
The formula used to determine the surface area and rate of drying is introduced in section 4.2.2 Rate of dehydration.

3.4 Food quality aspects

Food items show different attributes which determine their overall quality, safety, and general perception by consumers. Various factors strongly influence the characteristics of a food, and these factors differ according to the present food item. In the case of drying bananas, especially the moisture content and water activity become relevant as quality and safety aspects. Furthermore, naturally occurring oxidation should be taken into account as influencing the food quality of bananas in several ways.

3.4.1 Oxidation

The term oxidation describes a series of reactions that is taking place in the presence of oxygen and may be promoted by external factors like high temperatures, light or metal ions. Oxidation generally leads to a reduction in food quality by affecting specific components of a food item as for example fats. In the case of bananas, oxidation may cause a change of colour due to a decrease of pigments. Further, vitamins and flavour compounds can be affected and reduced, potentially leading to an overall lower nutritious value and the creation of off-flavors in the food item. (Man 2015)

The browning reaction of especially fruits can derive from both enzymatic and non-enzymatic origin. As bananas are susceptible towards color degradation, both browning reactions are important to take into consideration when banana slices are dried. (Martinez and Whitaker 1995)

When freshly cutting tropical fruits, after some time often a change in color can be observed. This change in color is often showing a darkening and browning of the freshly cut side. Responsible for this browning reaction is mainly one enzyme, PPO (polyphenol oxidase) that is released when the cells are damaged through the cut. (Yildiz 2018)
As bananas are a fruit that is highly susceptible towards enzymatic browning, this reaction may especially influence results concerning color and off-flavors in the focus group discussion. Furthermore, enzymatic browning can have effects on the duration of storage and deteriorate the shelf-life, leading to early spoilage. (Yildiz 2018)

3.4.2 Moisture content and water activity

Water is a main component in various foods. Especially fresh fruits and vegetables have a high water content, on average between 90 and 98 percent. (Derossi, Severini, and Cassi 2011) Water is essential for enzymes to function and microorganisms to grow and thereby determines the shelf-life and microbial stability of a food over time. (Scott 1957)
It has been discovered that foods containing the same amount of water can have varying shelf stability. This suggests that the spoilage of a product is not solely determined by the quantity of water present, but rather by its effective concentration in the food, known as water activity (a_w). (Tapia, Alzamora, and Chirife 2020) Several definitions of water activity exist. The a_w can be seen as the “free” water in a food, which takes part in chemical reactions as it is not bound to other molecules in the food. Consequently, water activity determines microbial growth and the onset of reactions particularly influenced by certain microorganisms or enzymes. Thus, food safety and its shelf-life are affected by the level of water activity the food is underlying. Out of microbial perspective, an a_w of 0.6 is the limit, which should be undercut for a food to be considered as safe. A_w values higher than 0.6 indicate that microorganisms are still able to grow. (Sancho-Madriz 2003; Troller 1983; Isengard 2001)

In addition to food safety, the water content of a food directly influences its texture. The more water a food contains the softer it is, since water as a component increases the deformability. (Blahovec 2007) For the aim of drying banana until a state that they become crispy, a water content of 10% or less is desirable, as food items then tend to become brittle. (Blahovec 2007) To prevent sogginess and microbial growth, the moisture content and water activity are important parameters to look at in this project.

3.4.3 Maturity Stages

3.4.3.1 Ripening process

The ripening process of fruits and vegetables is taking place naturally and in different pace for each food item. It occurs pre- as well as post-harvesting and influences for example the flavor composition or color of a food, due to chemical processes happening along with the ripening. During storage, fruits and vegetables can undergo a post-harvest ripening process. The main chemical compound initiating this process is the ripening gas ethylene (C_2H_4). Therefore, the post-harvest ripening process and its pace is determined by the surrounding, fruits and vegetables are stored in. Some food items are known for releasing C_2H_4 to the air more than others, thereby contributing to a faster ripening of fruits and vegetables around them. Such

sources can for example be apples and tomatoes. It is therefore essential to consider storage conditions and surrounding food items of a fruit/vegetable in order to control its pace of ripening. (Saltveit 1999)
Especially bananas are fruits that go through several maturity stages as they ripen. Each stage is characterized by distinct changes in color, texture, flavor, and chemical composition. Understanding these stages and setting up a uniform scale is essential for selecting bananas at the desired level of ripeness for processing, as the changing characteristics further influence the results of present experiments. Consequently, different maturity stages were identified according to their outer appearance and the refractive index of each stage was measured.

3.4.3.2 Refractive Index (%Brix)

Another parameter that can be measured and used to define different maturity stages of a food item is the refractive index. Generally, the refractive index of a medium indicates how much the direction of light changes as it enters and passes through the medium. Thus, it is an optical property and defined as the ratio of speed of light in a vacuum and speed of light in an analyzed medium. Values of the refractive index differ according to the substance measured which is again influenced by its density, composition and temperature. (Gallegos and Stokkermans 2024) In the food industry, especially the %Brix is a valuable parameter of a medium analyzed, as it is indicating the number of soluble particles in substances like fruit juices. Soluble solids in the analyzed medium are mainly sugars, wherefore the %Brix can give an indication on the sugar content of a sample. The measurement is done by light passing through the substance and being scattered in accordance with the amount of soluble solids. The Refractive Index can be measured by using a refractometer, which directly transfers the index in a %Brix value. Specific refractometer model analyses the content of sucrose in the pressed out juice of a food item and thereby be used for grouping them in maturity stages. (Hanna Instruments 2024)

4 Materials and methods

4.1 Raw material

4.1.1 Sourcing

For a high reliability in results, the receiving, handling and preparation of banana samples was done according to the following description.
The banana samples were delivered to JNEC, the college where solar dryer experiments were conducted, from a local fruit and vegetables shop, which sourced the bananas from Samdrup Jongkhar. Expected transportation distance was therefore about 17km. Delivery at JNEC took place every week and in required amount for the planned experiments. Bananas were transported in a cardboard box or plastic bag and stored in a medium cool (~15°C), dry and dark space in the College's Guest House throughout the week, until being used. No other food items were stored in the near surrounding, wherefore the ripening took place naturally not being influenced by external sources.
Salt was bought in a local shop and stored at room temperature (~18°C) in a dry and dark space.

4.1.2 Characteristics of “Jazi Kela” *Musa Acuminata*

4.1.2.1 Weight and size

Prior to their use, banana samples were randomly chosen from each batch and analyzed according to their weight and size. This was done to receive average values symbolizing uniform characteristics that were further used for i.e. calculating the surface area during drying. For setting up Table 1, ten bananas per batch were measured after receiving and different locations of the bananas were measured.
As can be seen in Table 1, the minimum and maximum values show that banana samples highly differed and were rather inconsistent in their characteristics. Values did strongly differ between but also within batches. Deviations to the calculated average in weight or size may indicate issues such as uneven drying or variations in sample composition.
Therefore, the table just reflects an approximation of the actual sample characteristics. However, approximate values help to evaluate and interpret results during dehydration and of further analysis.

Table 1: Sample measures pre-drying, their minimum, maximum and average value observed.

	Weight Banana - including peel [g]	Length unpeeled [cm]	Banana weight - peeled [g]	Length peeled [cm]	Weight - middle slice 2mm [g]	Diameter middle slice [mm]	Weight - end slice 2mm [g]	Diameter end slice [mm]	Surface Area - 2mm middle slice [mm^2]	Surface Area - 2mm end slice [mm^2]
Minimum	81.0	15.0	50.0	11.0	0.2	10.0	0.0	21.0	824,250	219.8
Maximum	123.0	20.0	76.0	17.0	1.6	18.0	0.2	27.0	1314,090	621.7
Average	98.8	17.2	60.0	12.7	1.1	23.9	0.1	14.2	1043.022	407.5

4.1.2.2 Moisture content determination

A commercial scale bought in a Swedish supermarket was used to measure the weight of the samples before and after dehydration.

Initial Moisture content

A conventional oven was used to dry banana slices of 2mm thickness. The oven provided by JNEC is usually operating the drying for welding rod and therefore had no air circulation option. Samples were weighed before being placed on the trays and followingly dried at a temperature of 100°C. Further weight measurements were conducted after 12h, 16h and 20h until no weight fluctuations occurred anymore. By using a mass balance formula, the amount of evaporated water was calculated and thereby the initial moisture content of the samples was determined. In this method of moisture determination, the assumption is made that every difference in weight comes down to evaporated water. The following equation was used to calculate the initial moisture content:

$$Total\ mass = mass\ water + mass\ dry\ substance$$

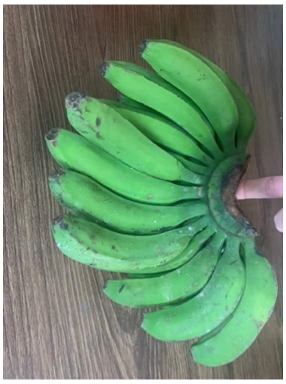
4.1.2.3 Maturity Stages and Refractive Index

A grouping into different maturity stages was based on the outer appearance and color of the banana samples and proceeded subjectively. As bananas ripen, their peel color shifts from a dark green color to a yellow-brown color. There has been done a classification of them maturity stages by Soltani Firouz, Alimardani and Omid, which was seen as guideline for setting up the maturity index. (Soltani Firouz, Alimardani, and Omid 2010)

The Maturity Stages can be seen in Table 2. Pictures of each stage were taken. In section 5 Results, the %Brix Values of each stage can be found.

One observation made is that the more ripened the banana was, the more soft, sweet and yellow (peel and flesh) it became.

Table 2: Maturity Stages and their outer appearance of "Jazi Kela".

Outer Appearance			
Maturity State	1	2	3
Description	all green	green with traces of yellow	more green than yellow

			
4	5	6	7
more yellow than green	yellow with traces of green	all yellow	yellow with black spots

The refractometer model HI 96801 by Hanna Instruments, Inc. was used to measure the %Brix in order to determine the amount of soluble solids for each maturity stage of the bananas. This specific refractometer model analyses the content of sucrose in the pressed out juice of a food item. (Hanna Instruments 2024)

In order to measure the %Brix of the bananas in each maturity stage, several raw material batches were measured. Five bananas of each maturity stage were mashed, and the fruit juice extracted as much as possible. For each maturity stage five drops of the juice were measured on the refractometer and the average of all values was determined. As reference temperature during the measurement, room temperature was taken which lies around 20°C. Final results of the %Brix do not only indicate changes in the amount of sugars during the ripening but display if the classification into the stages based on the outer appearance is reasonable.

As final results the overall average value and standard deviation were determined.

4.1.3 Sample preparation

To keep the microbial load on the food as low as possible, a specific way of handling the samples was followed. Firstly, all equipment was sanitized before use and on a daily basis, before banana slices were prepared. This includes the drying trays in the dryer, further the plates and bowls needed to collect the banana slices before and after drying, and the knives of the slicer equipment. Secondly, hands were washed and sanitized and gloves were worn before preparing the samples. For the preparation of the samples, a commercial food slicer was used to create slices of 2mm thickness, which were gathered on a regular plate and weighed before being placed on the drying trays. The placement on the drying trays was done manually with the aim to equally spread out the slices on the whole drying area, without them touching or overlapping each other. Trays with the banana slices were finally weighed again, before being placed in the dryers. Figure 2 shows a close-up picture of the spread-out samples on a drying tray from the ODM before placing them in the OD.

Figure 2: Distribution of banana samples on a drying tray.

Difficulties faced during the sample preparation included the breaking apart of banana slices, most likely in three pieces. This can be seen in Figure 2 as well. If slices broke, they were still placed on the tray forming a whole slice, if possible.

4.2 Dehydration Process

In the process of dehydration, moisture is easily taken up by the surrounding air from the surface of the food. This moisture will be replenished by water migrating from within the food to the outer layer in various ways. This process leads to an overall decrease in water content and water activity of the product. (Sancho-Madriz 2003) A practical way to determine how much moisture was taken up by the surrounding air is to do frequent weight measurements of the sample, set up a drying curve and calculate the rate of drying over specific time intervals.

4.2.1 Food-Dryer models in Bhutan

For the drying of bananas in Bhutan, two different solar dryer models were used. The "Old Dryer Model" (from now on referred to as ODM) is the model that was already used and analyzed in two Master thesis projects within the past years (Rissler 2023; Mahmoodi 2023). The "New Dryer Model" (from now on referred to as NDM) is an improved version which was newly built in Bhutan to implement the findings that were recognized by experimenting with the old model.

Generally, both food dryers comprise equal elements in a different set-up or dimensions. These elements are a heat exchanger, an absorber area, a drying chamber with different amounts of drying levels, an internal and an external fan.
Concerning the functioning in principle, surrounding air flows into a round pipe, the inlet where an external fan is located contributing to the suction of air. From there it travels over a flat aluminum sheet which is acting as a heat exchanger. The heat exchanger is a so-called counter-flow heat exchanger as cold and hot air flow on both sides in opposite directions. Cold air thereby begins to be heated. It then flows across the absorber area, which consists of a black painted aluminum sheet and a glass. The air moves in-between the black surface and the glass, where its' temperature is raised. From here, the air enters the drying chamber and is coming together with interior, cooler air that circulates within the dryer due to an internal fan. Air leaving the drying chamber flows on the opposite side of the heat exchanger before being released back into the surroundings through the outlet, an opening below or at the back of the dryer.
Major differences of both models are explained in further detail in the sections below.

4.2.1.1 Old Dryer Model

As for the ODM, a sketch is shown in Figure 3 whereas Figure 4 shows the food dryer in reality. The airflow is described by blue, purple and red arrows in Figure 3. Blue arrows depict ambient air which typically shows the coolest temperatures in this system. Purple arrows describe a medium warmed air that was either slightly heated ambient air or cooled down warm air. Red arrows depict the warmest air in the process. The light orange crosses symbolize thermocouples that are installed in the dryer to investigate the air temperature at different locations over time.

All previously mentioned structural elements of the dryer are labeled in the sketch according to their location. The sketch further shows a heat storage. This one was removed from the cabinet dryer before the experiments and is therefore to be neglected. In the ODM, the absorber area accounts up to $0.5m^2$, where the air becomes heated up.

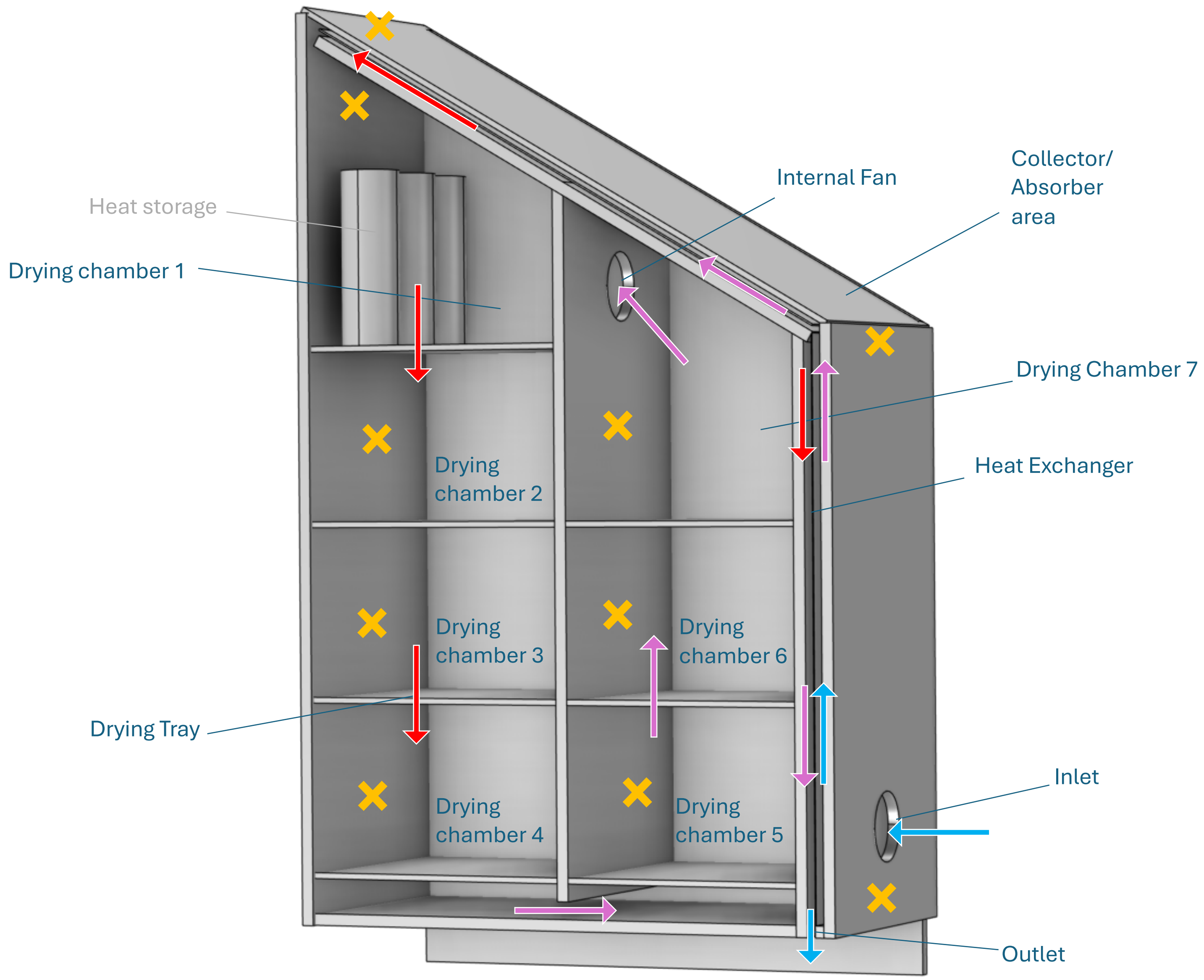


Figure 3: Old Dryer Model Sketch with its main structural elements.

Warmed air Medium warmed air Ambient air	Location of Thermocouple

During the conducted experiments, the fans ran at a voltage of 12. Air velocity and airflow were measured with an anemometer.

Figure 4: Picture of ODM.

4.2.1.2 New Dryer Model

For the NDM, a sketch is shown in Figure 5 whereas Figure 6 shows the food dryer in reality. Similar as in the ODM, the airflow is described by blue, purple and red arrows in Figure 5. Blue arrows depict ambient air which typically shows the coolest temperatures in this system. Purple arrows describe a medium warmed air that was either slightly heated ambient air or cooled down warm air. Red arrows depict the warmest air in the process. The light orange crosses symbolize thermocouples that are installed in the dryer to investigate the air temperature at different locations.

All previously mentioned structural elements of the dryer are labeled in the sketch according to their location. Moreover, a heat storage is shown. However, this one was not present during the drying sessions and can therefore be neglected.

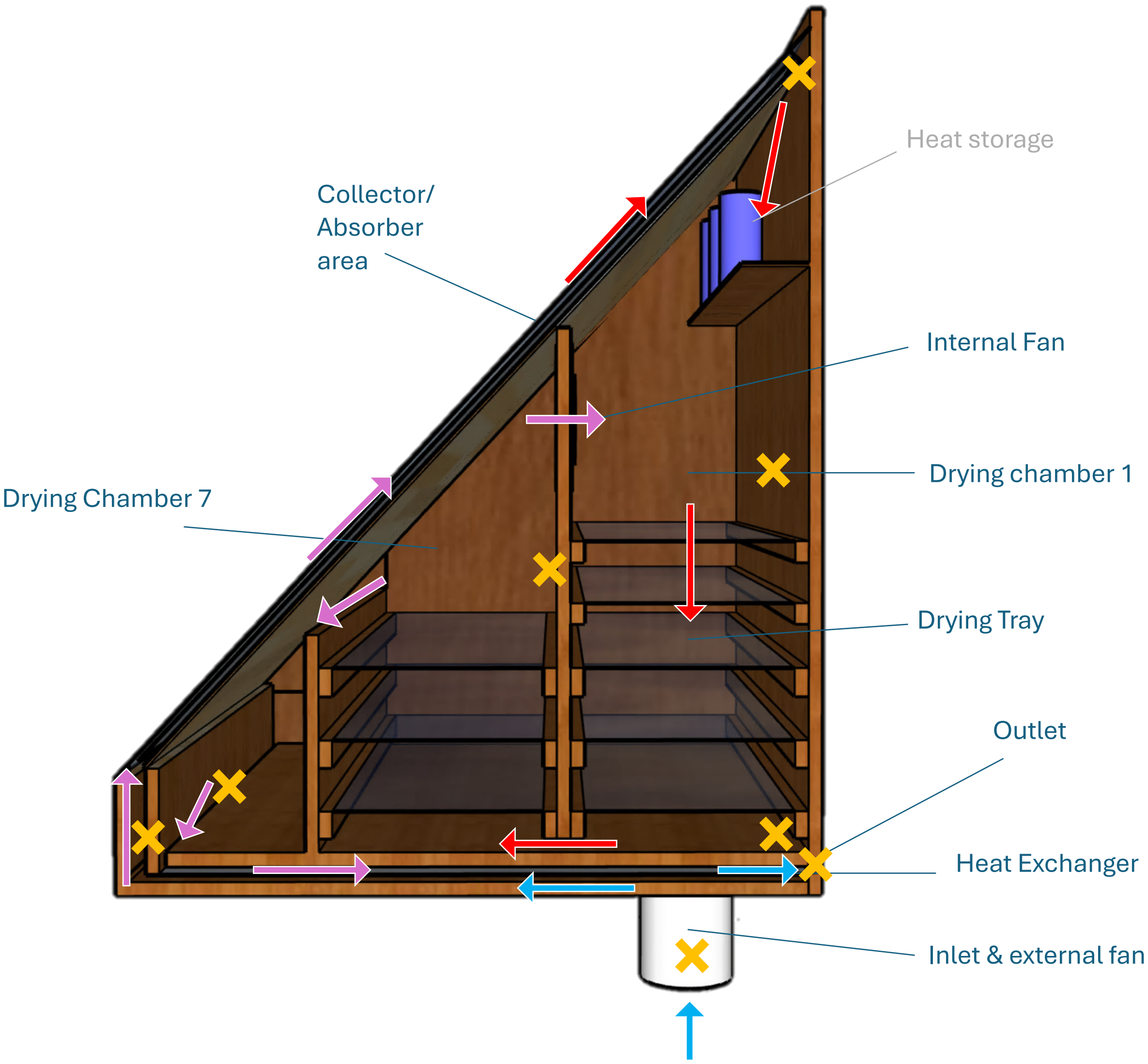
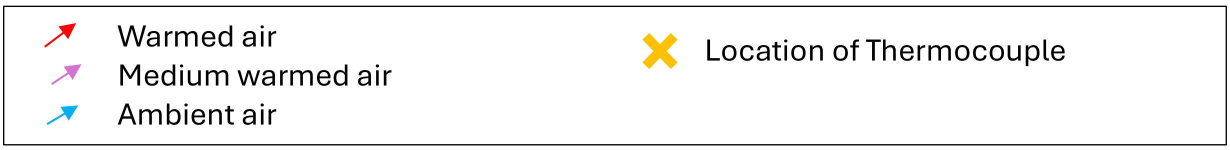


Figure 5: New Dryer Model Sketch with its main structural elements.



In the NDM, the absorber area where air is heated up accounts up to approximately 1.5 m^2. This area is three times bigger than the absorber of the ODM, allowing more air to pass through and being heated at the same time.

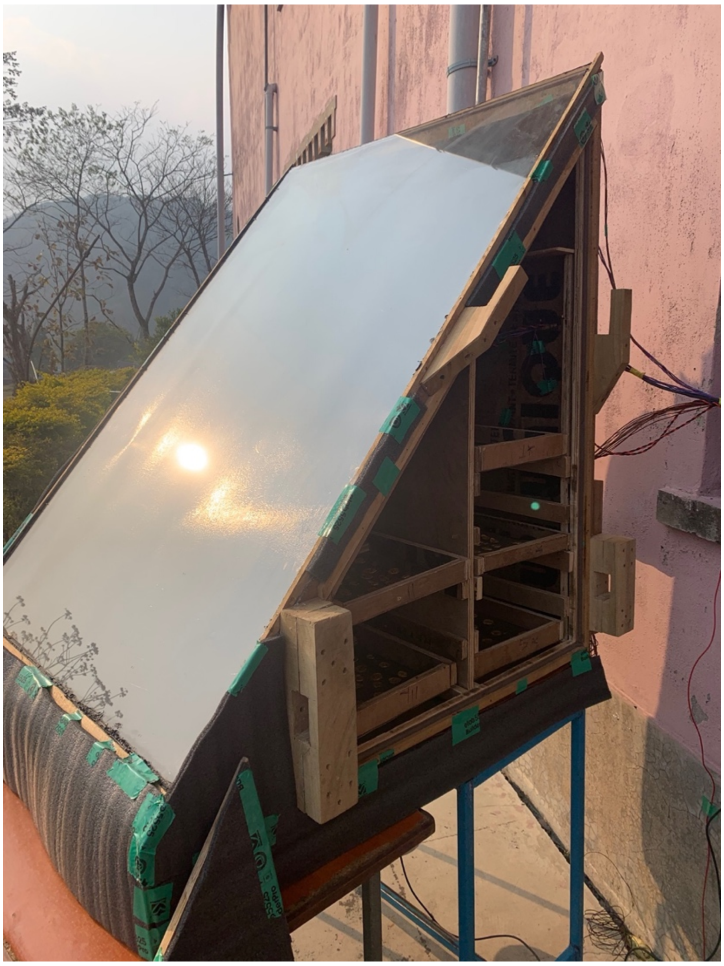


Figure 6: Picture of NDM.

4.2.1.3 Open-Air Sun Drying

In addition to the experiments that were conducted in both food dryer models, an open-air sun drying (OAnF) was carried out as control experiment, shown in Figure 7.

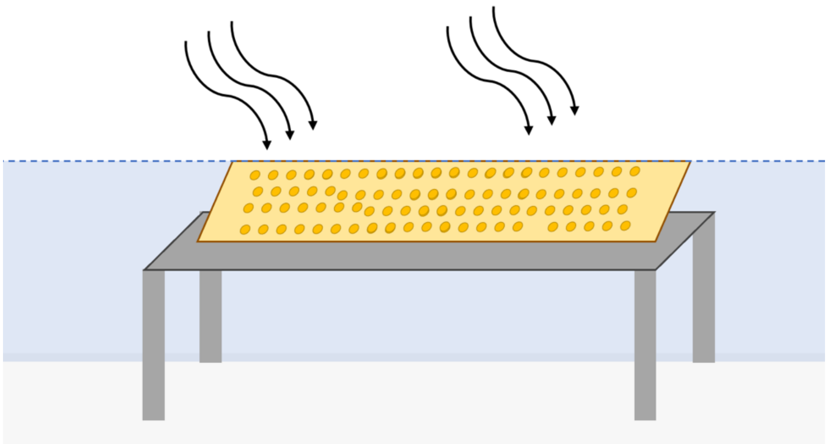


Figure 7: Sketch of OAnF.

Furthermore, the open-air sun drying was performed with the addition of a commercial fan

(OAwF). The fan was directed towards the bananas from about one meter distance, displayed in Figure 8.

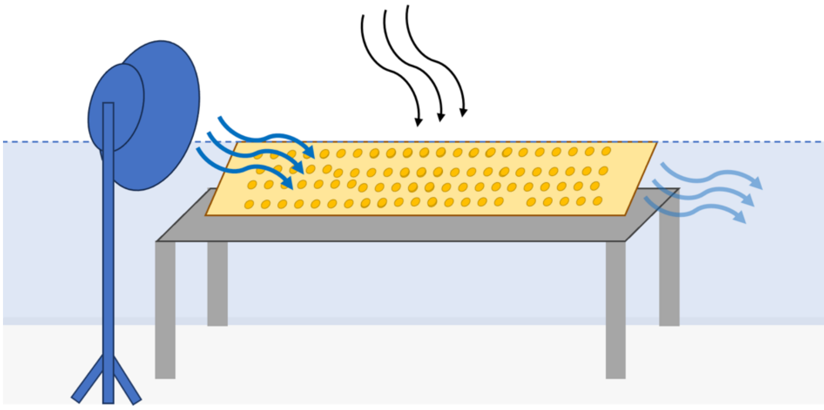


Figure 8: Sketch of OAwF.

Generally, the open-air drying was set up on a 50cm high table located next to a wall. Drying racks were placed half on the table and half leaned against the wall so that ambient air could pass also underneath/behind the trays. No physical shelter was given to the food samples, such as a protection through glass or transparent foil.
The black arrows are symbolizing rays of sun light to which the food samples are directly exposed to. In Figure 8 the blue arrows depict ambient air that is flowing onto the food samples in a directed way due to the fan. Light blue arrows make visible, that ambient air is able to pass through and behind the drying rack as well.
A total comparison experiment was conducted over a period of two days. All dryer set-ups of this one-time experiment can be seen in Figure 9.

Figure 9: Four drying set-ups in comparison. Shown from front to the back: OAnF, OAwF, ODM and NDM.

4.2.1 Drying Curve

To be able to set up a drying curve for each solar-drying model, banana samples were placed in the dryer and weighed regularly. For some drying curves, the samples were weighed each hour, whereas for others they were weighed every two hours. By noting the weight changes and putting them in relation with the initial weight of the samples, a drying curve was set up which visually displays the change of weight over time.

4.2.2 Rate of dehydration

The rate of dehydration or drying rate was calculated by determining the total surface area of the banana slices in one drying session and the evaporated water in kg over a specific time interval.
The formula used to determine the drying rate is as follows:

$$Drying\ Rate = \frac{m_{water}}{t\ \cdot A}$$

in which A is the surface area, m_{water} is the amount of evaporated water and t is the time interval. (Singh, Heldman, and Erdogdu 2024; Rissler 2023)

In the case of banana slices of 2mm height, the assumption was made that the slices show a perfectly cylindric shape. Thereby, the surface area per slice was calculated accordingly:

$$Surface\ Area\ Cylinder\ A = 2\,\pi\,r\,h + 2\,\pi\,r^2$$

Figure 10 shows the division of whole peeled banana in middle and end slices. Per banana, approximately two slices from each end were counted as end slice due to their comparably smaller diameter and therefore surface area. A total of four end slices per banana were used for the surface area calculation. The rest part of the banana was cut in middle slices, characterized by a bigger diameter. Consequently, this division of the banana in end and middle slices helped in the calculation of the surface area for drying.

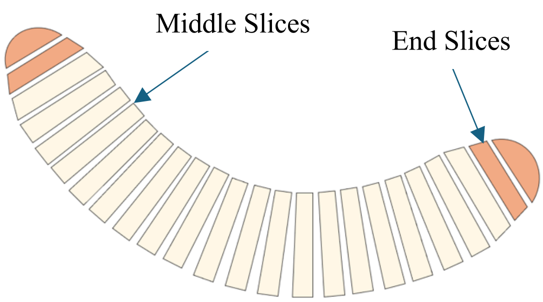


Figure 10: Banana sketch. Division of banana in four end slices (orange) and the rest being middle slices (yellow), due to differing diameter between the ends and the middle part.

4.2.3 Sample handling

During the dehydration process of the banana slices, after a drying time of approx. 8h the samples were stored overnight, by remaining on their trays, in a plastic bag in a dark, dry and cool space (~15°C). The average amount of time in these conditions was about 14h. These storage conditions are necessary to reduce reabsorption of water from the surrounding, as well as prevent oxidation through light and oxygen exposure. At the beginning of the second day, trays were taken out of the plastic bags and weighed again before the second day of drying was started.

4.2.4 Evaluation of homogeneity of drying

4.2.4.1 Within a dryer

For both Solar dryers models each tray was weighed and the moisture loss per hour of the banana slices on this tray determined. In the NDM a total of 5 trays were used for the drying, while in the ODM a total of 4 trays was used. The drying was conducted for 2 days, while weight measurements for the ODM were only taken every 5 hours and for the NDM weight measurements were taken every hour.

4.2.4.2 Within a tray

To see whether drying withing a tray took places homogenously, for the OD, single slices of each tray were weighed to see if the drying on the tray was uniform or for example slices in the back of the dryer dried faster than slices in the front.

For the ND, trays are divided into 3 parts, a front, middle and back section. Slices of each section were weighed to see if the drying on the tray was uniform or for example slices in the back of the dryer dried faster than slices in the front.

4.2.5 Additional Experiments

In order to determine if there was an influence in drying time and efficiency due to the maturity stage, general drying experiments were conducted with bananas of different maturity stages. The maturity stage within an experiment did not differ, solely between experiments.

Furthermore, a one-time experiment was performed which included a pretreatment of banana slices with salt. As salt is an osmotically active compound, the reason for applying salt was to find out whether drying time would be reduced and if so, to what extent. The banana slices were dried open air in the sun together with reference banana slices with and without fan in the sun.

4.3 The food sample – post-drying

Banana slices were fully dried after approximately 16h in the dryer. When the samples were dried from an initial moisture content of about 75% to a final moisture content between 15-25%, samples were taken out of the dryer. Gloves were used to collect the banana slices from the trays, place them in transparent plastic bags and finally vacuum seal them. By vacuum sealing, air and thereby oxygen from the bag is removed as much as possible which becomes beneficial for storing them over a long period of time. The vacuum sealed transparent sample bags were then stored in a black, intransparent plastic bag at an ambient temperature of about 18°C until being used for analysis. Storage conditions were chosen to reduce oxidation through oxygen, light and temperature.

4.3.1 Water activity

Water activity was measured in the laboratory at Lund University by using AQUA LAB Series 3 TE by Decagon Devices, Inc. The water activity can be defined as "the ratio of the vapor pressure of water in food to the vapor pressure of pure water at the same temperature" (Sancho-Madriz 2003). The instrument measures the water activity of food with an accuracy of ±0.003. (Decagon Devices 2007)
Four control measurements with distilled water and specific solutions were carried out before analyzing the food samples. Three measurements of food samples were performed, and their average water activity value calculated. Water activity was solely determined for food samples which were dried in the NDM for two days.

4.3.2 Moisture content

After the determination of the initial moisture content (see section 4.1.2.2) any weight reduction during the dehydration process can be put in relation with the initial moisture content. Banana samples in Bhutan were weighed before and after the dehydration by using a commercial scale

bought in a Swedish supermarket. The moisture content of solar-dried samples was then calculated by using the previously introduced mass balance equation.
For the determination of the final moisture content of dried banana slices brought to Lund, a vacuum drying oven in the laboratory of Lund University was used. The sample was placed overnight in the oven and the final moisture content measured according to 4.1.2.2. Moisture content determination.

4.3.3 Nutritional Analysis

A nutritional analysis was carried out by the Food Science and Technology Department at the College of Natural Resources, the Royal University of Bhutan. Investigated macronutrients include total carbohydrate, crude protein and crude fat content. Investigated micronutrients include total nitrogen, phosphorus, potassium, calcium and iron content.

4.3.4 Focus Group Discussion

A focus group interview was conducted with the purpose of testing consumer acceptance of the dried banana slices. Furthermore, the overall perception of the samples regarding sensory characteristics and visual appeal was investigated throughout the discussion. (Krueger and Casey 2009) The results of this discussion may indicate how popular the dried banana slices could be, when commercialized in Bhutan or India. Panelists tried banana slices of the 2-day drying session in the ND.

For the focus group discussion, five students (four female, one male) with an average age of 23 years and an Indian/South-East Asian background were asked to participate. Each of the students was not allowed to eat or drink anything other than water one hour before the discussion. This time frame of fasting was set in order to ensure a clearer taste for the participants during the discussion. The participants tasted the dried banana samples and were asked to answer and discuss a total of 8 questions about the product. All questions that were discussed can be found in the appendix.

4.3.5 Statistical Evaluation

A one-way ANOVA (Analysis of variance) test was done. This type of test identifies whether variations of results between several experiments are significant or not. For this procedure, a p-value of the measurements is calculated and used to evaluate the significance. If the p-value is lower than 0.05, a significant difference exists between the values of the experiments. If the p-value is higher than 0.05, the results are not significantly different. Outcomes of the ANOVA can thereby show whether a change in variables between two series of experiments has a significant impact on the outcome. (Ståhle and Wold 1989)
In the case of banana drying, the ANOVA was made to see whether the maturity stages of the dried banana had a significant impact on their drying time. The online program "Good Calculators" was used to determine the p-value for the experiments of interest. (Good Calculators 2024)

5 Results

The section will display all outcomes of the data collection. Several experiments were conducted with all introduced solar-dryer set-ups. A total comparison between the set-ups was made and some additional experiments were conducted. Moreover, the food samples post-drying were analyzed regarding moisture content and water activity and a focus group discussion about sensory characteristics and overall acceptance was held.

5.1 Dehydration Process

The findings of a total comparison between the set-ups and findings of additional experiments are shown displaying results from the dehydration process.

5.1.1 Technical Comparison

The following Table 3 sums up some key measures and measurements of the ODM and NDM in comparison. Differences can be the design and overall layout as well as measurements done in Bhutan as for example highest or lowest temperatures observed.

Table 3: Key measures and measurements of the solar-dryer models OD and ND in comparison.

Characteristic	**ODM**	**NDM**
Pipe diameter	16cm	16cm
Average Airflow In (=Volume air entering at a time)	1.497 m^3 / min	1.497 m^3 / min
Absorber area	0.5 m^2	1.5 m^2
Total volume of dryer	0.5m x 1.1m x 0.94m + 0.94m x 0.55m x 0.5m / 2 ≈ 0.65 m^3	1m x 1m x 1.3m / 2 ≈ 0.65m^3
Total area of drying trays	0.3m x 0.25m = 0.075m^2 x 4 trays = 0.3m^2	1m x 0.35m = 0.35m^2 x 5 trays = 1.75m^2
Minimum Temp. Absorber in	18.81°C	18.15°C
Maximum Temp. Absorber in	53.49°C	33.22°C
Minimum Temp. Absorber out	18.5°C	21.89°C
Maximum Temp. Absorber out	50.47°C	61.48°C

As can be seen in Table 3, the absorber area of the NDM is three times bigger than the absorber area of the ODM. Considering that the fans ran at the same voltage, the amount of air entering at a time is the same for both models due to the pipe diameter being the same. The maximum temperature of the ODM Absorber in is marked as red because it is ambient air entering absorber. The deviation to the maximum temperature of ambient air of the NDM in this case is very high and even exceeding the maximum temperature after the absorber area in the ODM. For this reason, the recorded value will be considered as incorrect.

5.1.2 Drying curves

A total comparative drying session with all four drying set-ups was carried out. The comparison of dryer set-ups is done by looking at the moisture decrease over time and the rate of drying in each set-up.

One 2-day experiment trial was carried out to compare the different dryer set-ups: Old Dryer (OD), New Dryer (ND), Open Air Sun Drying without Fan (OAnF) and with Fan (OAwF). This experiment was done in order to identify the efficiency of these dryer set-up.
For both dryer models, OD and ND, the fans were identical and all running at 12 volts. Therefore, the assumption was made that the same amount of energy was required for each model throughout one day of running the dryers. The commercial fan for the Open-Air Sun Drying ran at their maximum speed. For all set-ups the banana samples had a maturity level of 5 and 6.

The following 2 figures display the drying curves of all set-ups in direct comparison, and the temperatures of all set-ups in direct comparison with the solar irradiation over the 2 days of drying. Figure 11 shows the moisture content wet basis (MCwb) in percent over time. The starting time of the experiments each day was 8.00am.

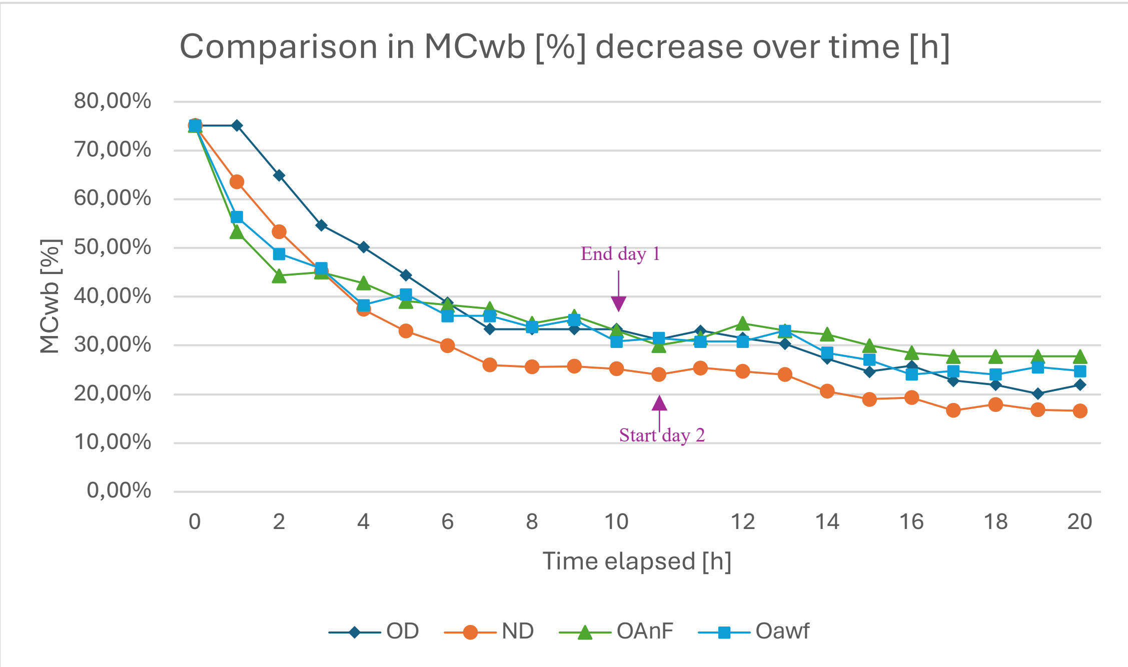


Figure 11: One-time total comparison experiment between a 2-day drying session in the OD (Old Dryer), ND (New Dryer), OAnF (Open Air no Fan) and OAwF (Open Air with Fan).

As can be seen in the figure, the food samples dried in the ND show the lowest final moisture content after 20h of drying, of about 16.63%. The second lowest moisture content is achieved in the ODM with 21.94% moisture left. Both OA Drying set-ups show higher remaining moisture contents with 24.79% with fan and 27.79% without the fan. Furthermore, moisture loss for all drying set-ups is highest in the first four hours. Then, the drying slows down.

Figure 12 shows the temperatures in the OD, ND and ambient temperature over time, just as the solar irradiation measured by the pyranometer, a solar radiation sensor placed on the NDM. The temperature sensors in the dryer models are located at the absorber outlet, which means they display the maximum heated air that is about to flow towards the food.

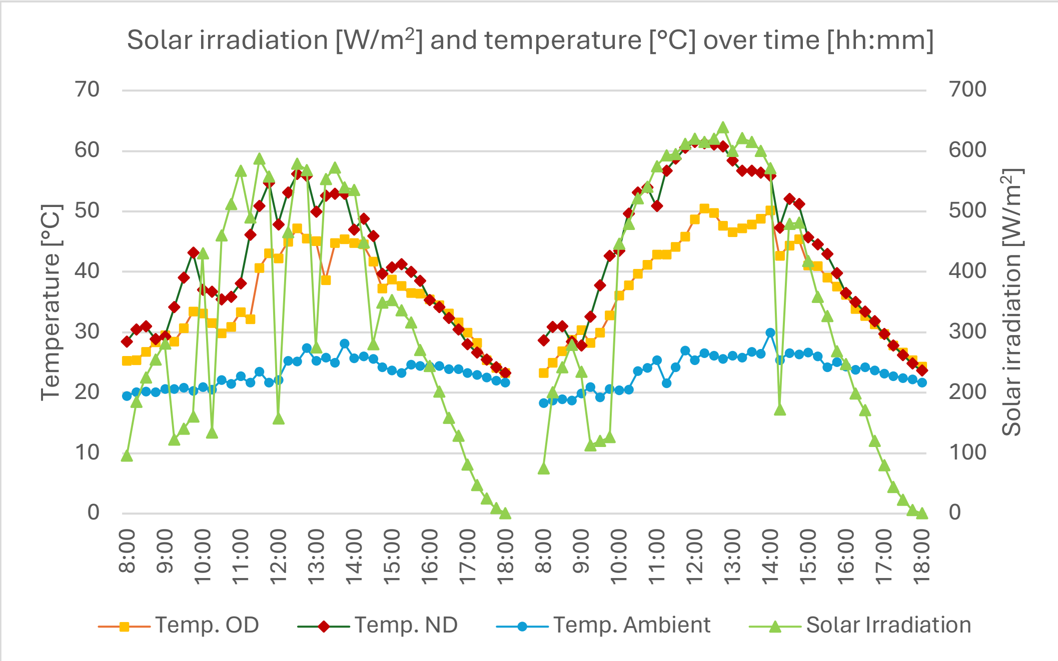


Figure 12: Solar Irradiation, temperature in the Old Dryer, temperature in the New Dryer and ambient temperature over a period of 2 days.

Highest values in solar radiation that were recorded are between 11 and 14:00 o'clock. Out of a possible 1000 W/m^2 solar radiation, the recorded maximum was 639.8 W/m^2 during the second day. Ambient temperature was the lowest of all three set-ups, with values between 18.26°C and 29.89°C. The NDM showed the highest temperature changes during both days. Temperatures in the ND went up to 61.48°C whereas the maximum temperature of the OD was 50.74°C.

5.1.3 Rates of dehydration

For an even better comparison, the rate of drying can be calculated from total surface area, the amount of water evaporated per time interval and the time intervals. The rate of drying for each dryer set-up in the total comparison experiment is shown in Figure 13.

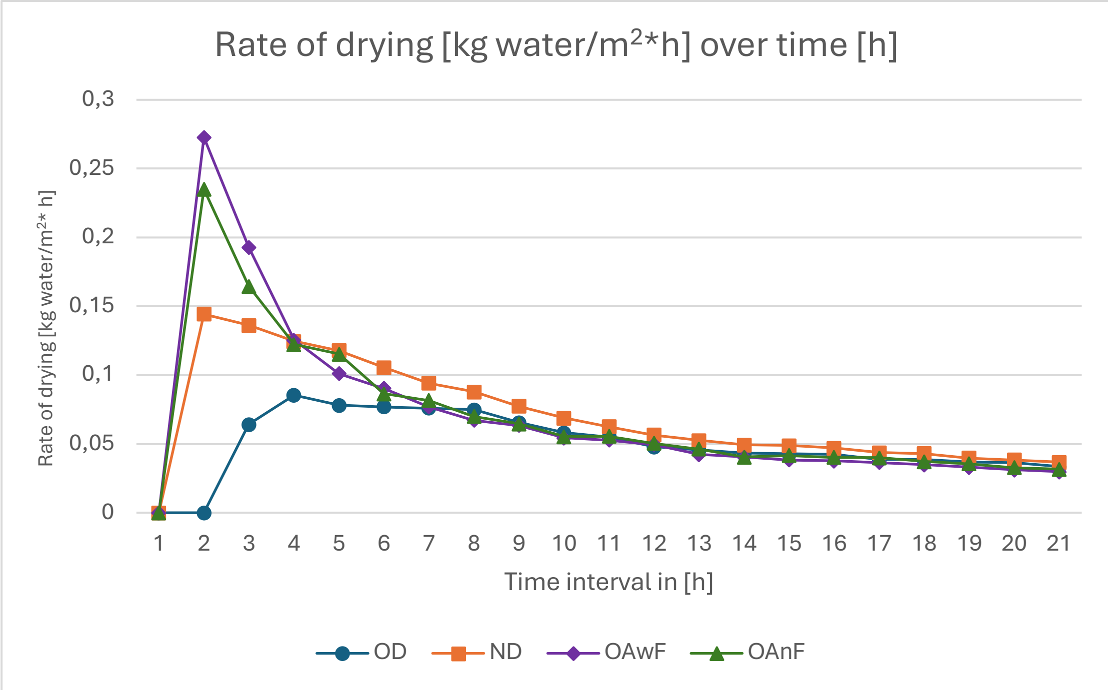


Figure 13: Rate of drying of a 2-day drying session for the OD (Old Dryer), ND (New Dryer), OAwF (Open Air with Fan) and OAnF (Open Air no Fan) in comparison.

The figure shows that the drying rate of both Open-Air drying set-ups is the highest during the first two hours, drying with Fan being even higher. Following this, the ND shows the third highest initial drying rate, while the OD shows the lowest initial drying rate. As high as the drying rate initially is for the Open-air set-ups, as fast it also decreases after the peak of about 0.25kg water per surface area and time. At the same time, the drying rate of the ND decreases rather linearly, whereas the drying rate of the OD at first remains rather constant and slowly decreasing over a period of seven hours, and finally falls in a linear pattern as well. Generally, for all dryer set-ups there are slight fluctuations in drying rate occurring, the highest being in both Open-air set-ups.

5.1.4 Evaluation of homogeneity of drying

5.1.4.1 Old Dryer Model

Homogenous Drying between different trays

Figure 14 shows the moisture loss of bananas slices on each of the 4 trays of the ODM drier. As can be seen in the figure, slices of tray 2 lost the highest amount of moisture during the first 5 hours of drying, whereas slices of tray 3 lost the least moisture at the same time, with a difference of about 10%. Trays 1 and 4 show rather similar moisture loss after 5 hours, in terms of percentage lying between the two other trays. With more time elapsing all trays are aligning in their moisture loss to a roughly same amount of moisture remaining after the 20-hour drying session.

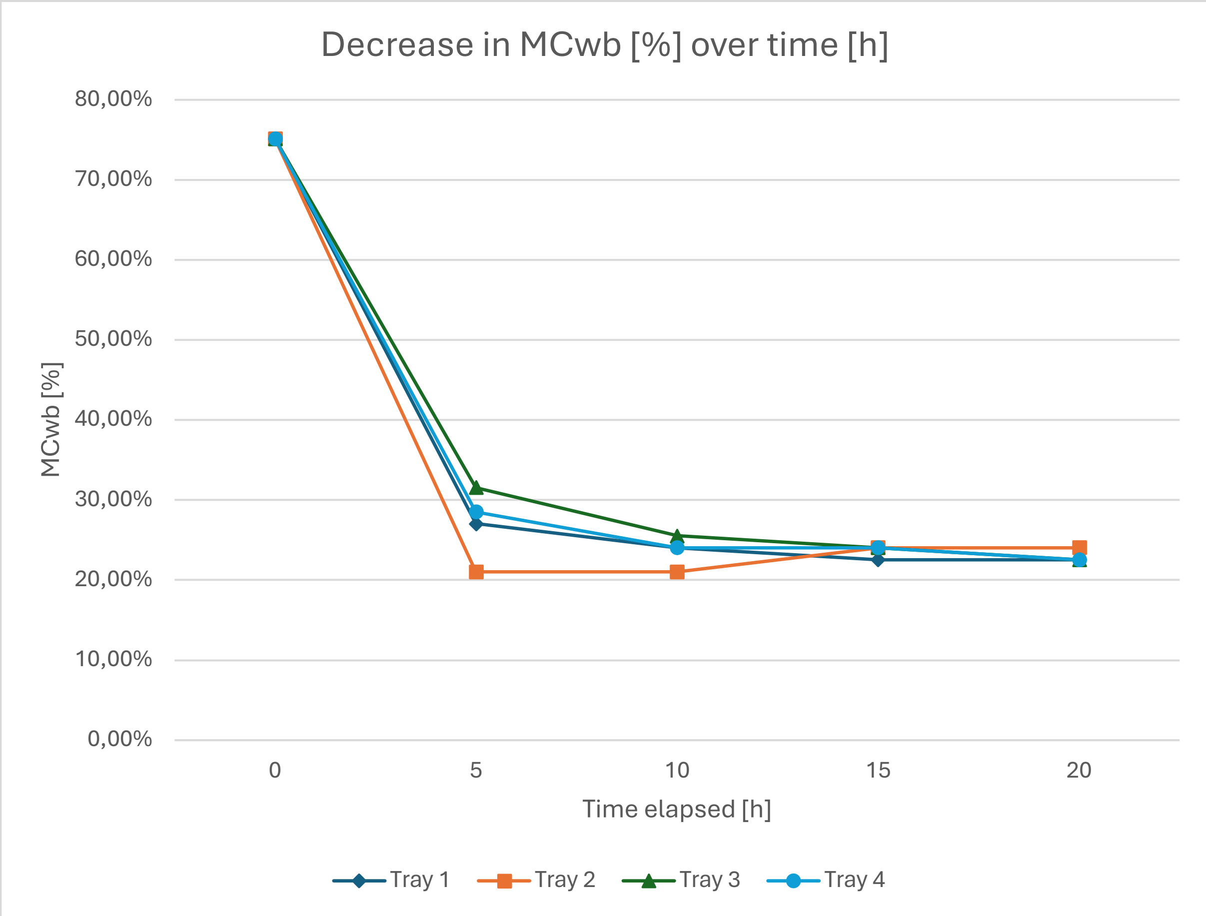


Figure 14: Comparison of drying curves for different trays in the ODM (Old Dryer Model) over a period of 2 days.

The trays were located in counterclockwise order. Tray 1 was located on the upper left-hand corner of the dryer, where the hot air streams in first. Tray 2 was located below, tray 3 on the lower right-hand corner of the dryer, and tray 4 was above tray 3, on the upper right-hand corner in the dryer next to the internal fan.

Homogenous Drying within a tray

The observation was made that no weight differences existed when comparing between the slice's location on the tray themselves. Therefore, it can be assumed that the drying of banana slices within each tray happened equally.

5.1.4.2 New Dryer Model

Homogenous Drying between different trays

As can be seen in Figure 15, the initial moisture decrease within the first hours of drying happened the slowest on Tray 2 while it was fastest on Tray 4. After about 6 hours of drying however the moisture content of banana slices on all trays is slowly assimilating to roughly same values. Consequently, it can be noted that the slices might dried inequal throughout the initial phase of the drying session, but the final result and moisture content did barely differ between the trays.

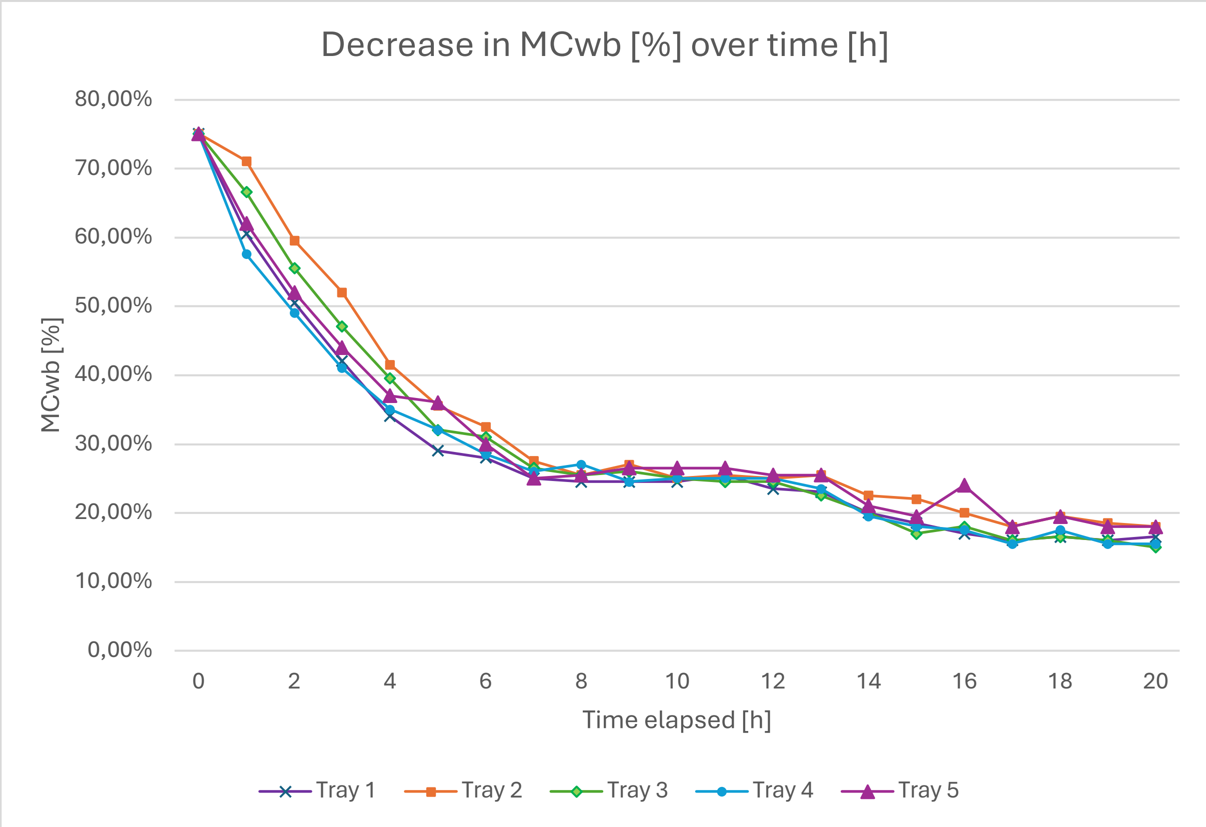


Figure 15: Comparison of drying curves for different trays in the NDM (New Dryer Model) over a period of 2 days.

The trays were located in clockwise order. Tray 1 is in upper right-hand corner of the dryer, 2 is below, 3 is below, 4 is lower left-hand corner of dryer and 5 is above.

Homogenous Drying within a tray

Weight differences were rarely observed and seemed to be rather out of coincidence that due to unequal drying. Therefore, it can be assumed that the drying within one tray happened uniformly.

5.1.5 Additional Experiments

5.1.5.1 Drying and the Maturity Stages

As several experiments were conducted, a difference between the sample handling and the drying characteristics of different ripening stages of bananas was observed. Figure 16 shows the moisture decrease over a span of 10 hours for the maturity stages 1, 3, 5 and 7. The initial moisture content differed slightly according to the ripened stage, which was determined as described in section 4.1.3. It should be noted that the different ripening stages were dried on different days, wherefore solar irradiation and temperatures change. Both ODM and NDM were used for the experiments. For each maturity stage 2 replications were measured, the curves in the figure show an average value for each maturity stage.

The figure further shows that the initial moisture content between different maturity stages slightly varied. This was found out by determining the initial moisture content of samples at a maturity stage of 1 and 7. Overall, an average value of initial moisture content is considered for all experiments except this one. Therefore, the starting points of MS1, MS3, MS5 and MS7 differ in the graph.

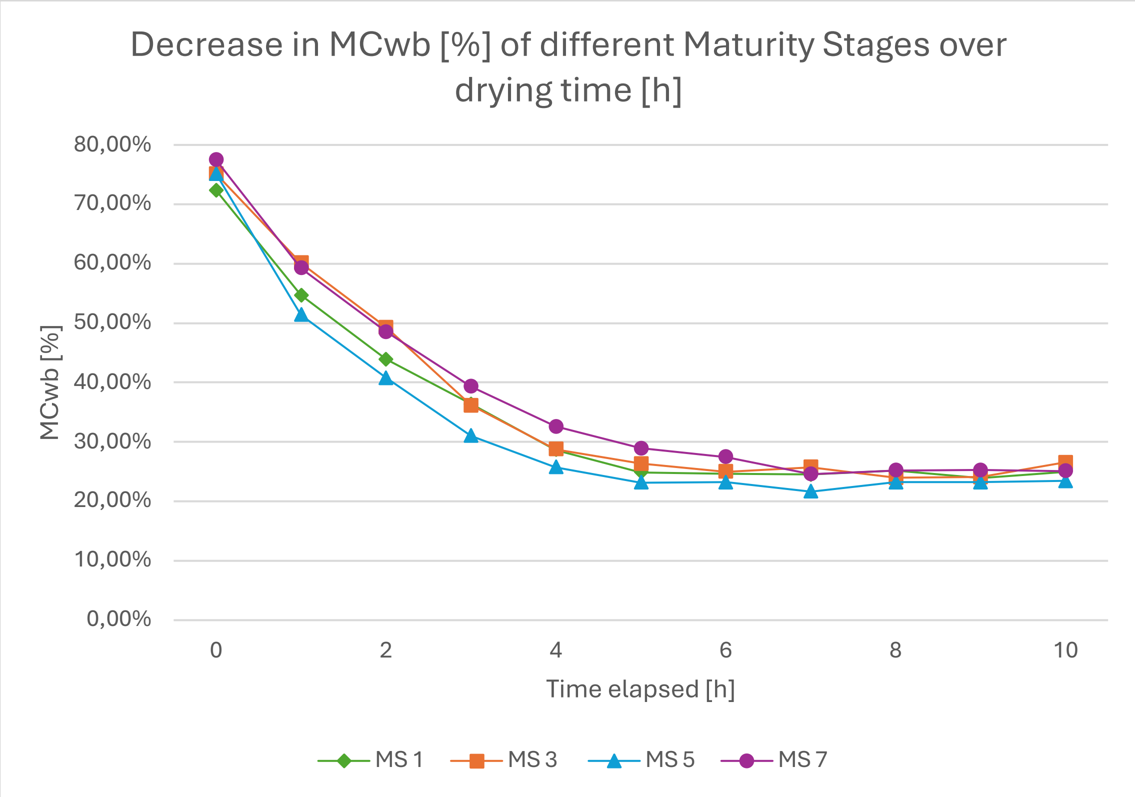


Figure 16: Different Maturity Stages and their drying curve, average values taken.

Two replications per maturity stage were measured. Therefore, ANOVA analysis was conducted in order to evaluate if the moisture loss during 10h of drying differed significantly between the maturity stages 1, 3, 5 and 7. However, results showed that there are no significant differences as the P-value of the four compared groups was quite high with 0.2848. Detailed results concerning the ANOVA can be found in the appendix.

The rate of drying was calculated for a better comparison of the maturity stages and their drying kinetics. Figure 17 shows the rate of drying for the maturity stages 1, 3, 5 and 7.

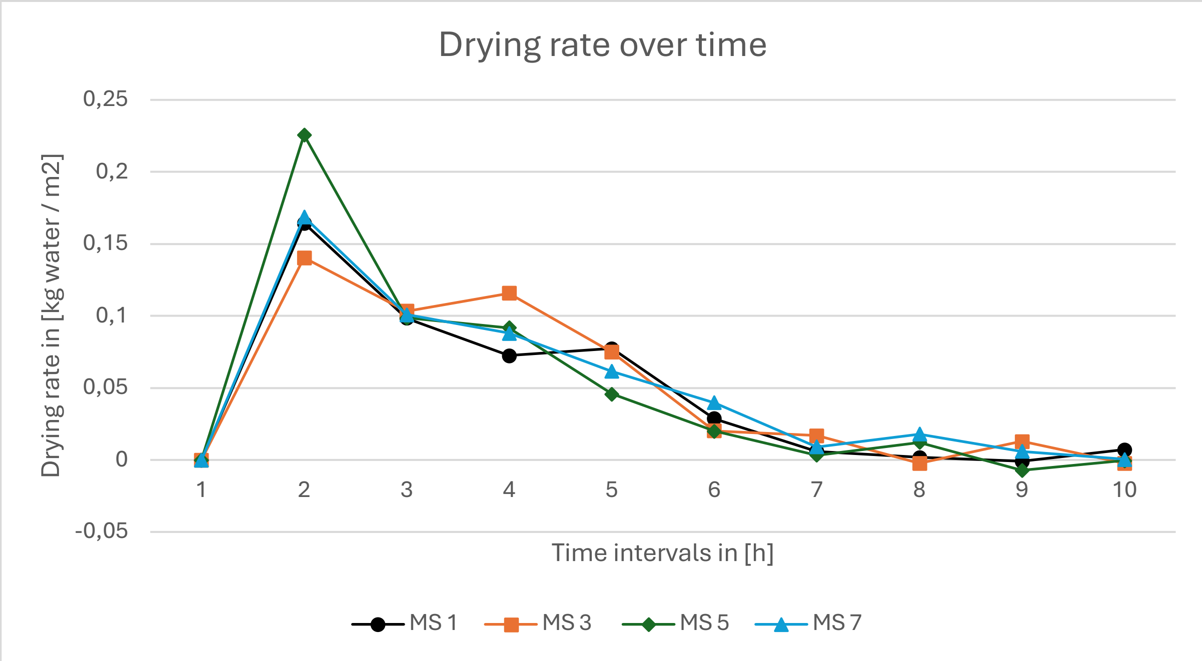


Figure 17: Drying rates of bananas with different maturity stages (MS) in comparison over a period of 10 hours.

It becomes visible that stage 5 had the highest initial drying rate and also the highest decline instead of constant drying rate right after. Maturity stage 3 had the lowest initial drying rate but therefore the most constant rate within the first three hours amongst all maturity stages. After 4 hours of drying the drying rates are all showing increasingly similar values and a linear decrease with final stagnation over longer time.

About the different maturity stages it was further noticed that the handling was much easier with less mature banana samples than mature ones, due to the changes in texture over ripening. Texture was not able to be analyzed on site, wherefore no objective results can be brought forward to show the changes in texture among ripening. Still, it was observed that the maturity stages 2 and 3 seemed best for sample handling and slicing.

Figure 18 shows the measured %Brix values of the different maturity stages introduced in section 4.1.2.3.

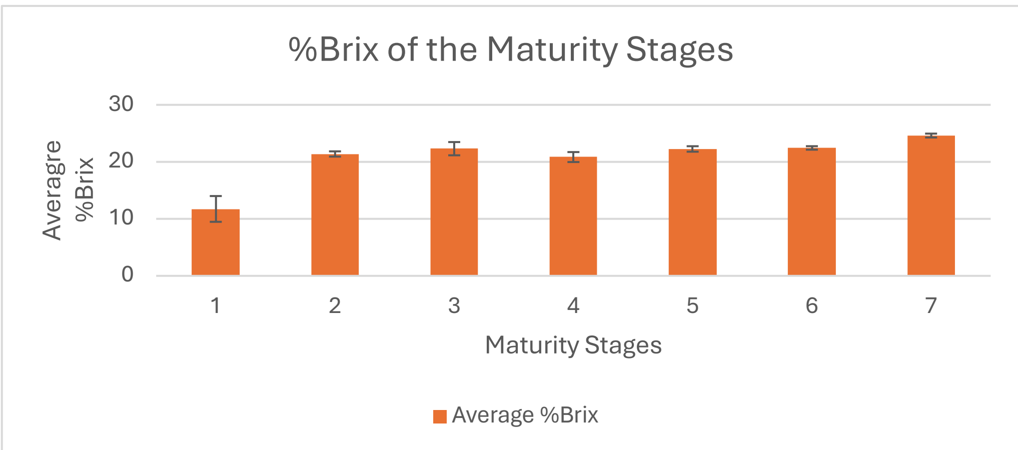


Figure 18: Measured %Brix average values for each Maturity Stage.

As mentioned above, the maturity stages 2 and 3 were recognized as best in sample handling due to their rather firm texture. In line with Figure 18, the %Brix does not change much over the maturity stages 2, 3, 4, 5 and 6. Therefore, the sugar content will be quite similar among these stages. The standard deviation for each maturity stage is shown, whereof the one for stage 1 and stage 3 are the highest.

5.1.5.2 Drying with salt as pre-treatment

Apart from the comparison between different dryer models and their efficiency for drying, some additional experiments were conducted.

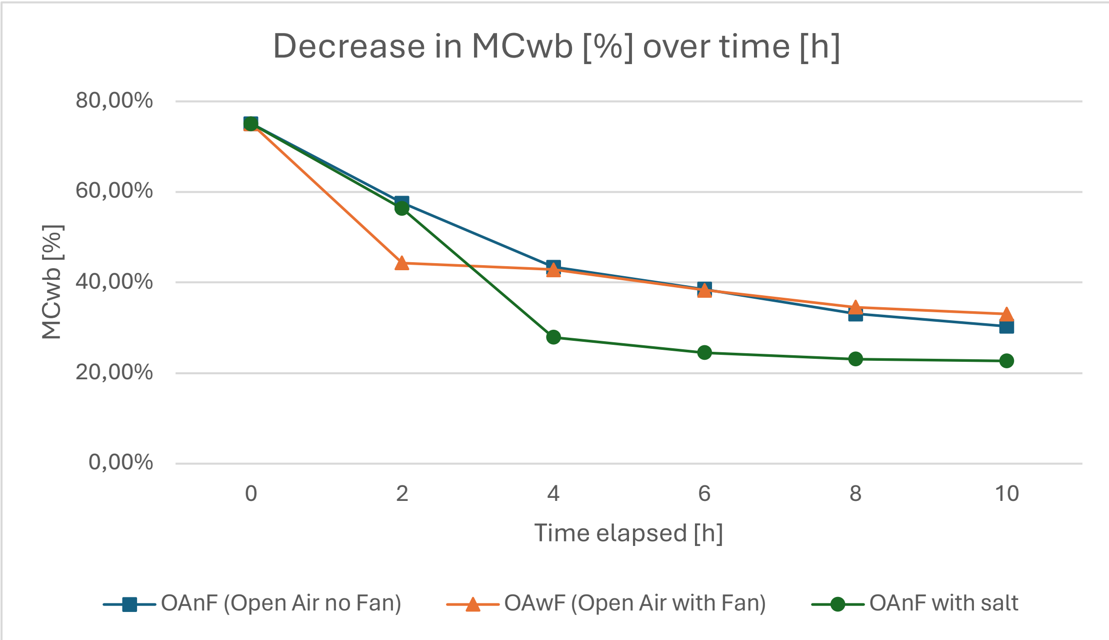


Figure 19: Different types of sun drying in comparison.

Figure 19 shows a comparison of all open-air sun drying set-ups including the salt-pretreated banana slices without fan. An ANOVA test could not be conducted as this experiment was only carried out once out of curiosity.

5.2 The food sample – pre- and post-drying

The food samples were analyzed after drying regarding moisture content, water activity and their nutritious value.

5.2.1 Moisture content and water activity

The initial moisture content of the banana samples was found to be 75.12%, as this is the percentual amount of initial and final weight, which left the sampled during complete dehydration. Lowest measured moisture content for different food samples are shown in Table 4. Furthermore, measured water activities of the 2-day dried banana samples from the ND are shown.

Table 4: Values for measured moisture content pre- and post-drying and water activity. For the water activity an average value was determined from 3 replicates.

Measurement	Moisture Content	Water activity
Sample pre-drying, average value	75.12%	–
Sample post 2-day drying in OD, Bhutan, minimum value recorded	21.03%	–
Sample post 2-day drying in ND, Bhutan, minimum value recorded	15.02%	–
Sample post 2-day drying in ND, Lund laboratory	7.58%	0.386 ±0.003

5.2.2 Nutritional analysis

All results of the food analysis conducted by CNR (College of Natural Resources), Royal University of Bhutan can be found in the appendix. Values of interest for this research are shown in Table 5.

Table 5: Nutritious value of dried banana, as provided by CNR.

Sample	Moisture content	Crude Protein	Crude Fat	Total Carb	Energy	Phosphorus	Iron	Calcium	Potassium
After 2-day drying session	6.00%	5.49%	1.68%	68.7%	~312kcal	3.4ppm	4.27ppm	14.0ppm	20.35ppm

5.3 Focus Group Discussion

Results from the focus group discussion comprise some general questions about the panelists' eating behavior, the evaluation of the outer appearance of the food sample, its sensory characteristics and overall acceptance and likelihood to buy the dried banana. Furthermore, participants were asked about prior expectations, based on the invitation to the tasting of "dried banana".

All participants mentioned they consume snacks rather frequently, between twice per week and on daily basis. The majority of participants furthermore mentioned to be aware of consuming more healthy snacks, like fruits.

Expectations about the food sample "dried banana" mainly included an image of a crispy texture, a strong and fruity banana taste and thin slices of banana.

Concerning the outer appearance, all five participants stated the color of the product to be according to what they expect dried banana to look like, a dark yellow. One person described the color to look dull. Apart from the color, the outer appearance was not liked by 5 participants, as slices were sticking together, the samples looked moist, "waxy and plastic-like". It was discussed that the samples should show a more uniform shape to be more appealing, rather in stripes or circular. Generally, the outer appearance was rather unappealing to the participants (four out of five).

Observed sensory characteristics were a high level of sweetness, described as being too high. Caramel and honey were used to describe strong sweetness. Participants compared the banana sample immediately with dried jackfruit. Only three of the participants noticed a fruity, fresh banana taste, while the other two participants did not taste any banana. A chemical/artificial taste was observed by two participants. Two participants further noticed some unpleasant bitterness and aftertaste of the sample. Suggestions for the improvements in taste included a slightly salted product or the recommendation to use less ripened fresh banana for drying, in order to balance out the high sweetness.

The texture was described as being rather sticky, but not in an unpleasant way. “Chewy, tender and moist” were further adjectives used by all participants to describe the texture. Participants found it difficult to describe their perception of the food sample being moist and dry at the same time. Three found the texture to be soft while 2 found the texture to be firm and tough. One person noted that the mouthfeel during eating would be very dry.

When participants should indicate whether they would consume the dried banana again, four participants said they would consume it again but in a different shape or combination. For example, the form of granules or small cubes was proposed and the idea of the dried banana as a “food topping” discussed in the group. All participants seemed interested in using the dried banana in combination with something else, only two participants would eat the dried banana singularly as a snack. A consumption frequency of twice per month was given by most participants. Moreover, the dried banana was found to be more accurately described by using the name “fruit leather” or “gooey banana” instead of banana chips or banana snack. Also, a candy-like name was suggested, due to the high sweetness in taste.

Lastly, the participants should rate on a scale from 1-5 again how much they liked the food sample, whereas one indicates a “strongly dislike”, three a “neutral” and five a “strongly like” answer. The average result was a four, assuming that the participants finally rather liked the product.

6 Discussion

To start evaluating the outcomes of this research in a broader context, it becomes visible and was already found in previous research projects in Bhutan that the results are highly weather and especially solar irradiation dependent. (Rissler 2023) As seen in Figure 12 the temperatures in the different dryers behave corresponding to the level of solar irradiation. This behavior is observed even stronger in the NDM, for which a reason can be the greater absorber area. Contrary to these findings, a recent study investigated banana slices that were dried in an indirect drying model and analyzed to see how strong the influence of different conditions like air velocity within the dryer, weather and solar radiation is on the overall performance. In this study it was found that the weather conditions and air velocity within the dryer had less of an impact for the moisture removal performance than the dryer set-up itself. (Mawire et al. 2024) The outcome of this study as well as finding from the present research are therefore to be viewed with caution and in consideration with any sources of error.

The data collection on field brings forward benefits and drawbacks at the same time. It is giving a more realistic view on the use and their performance of the solar dryers, however in the research conducted it showed also a lack of resources and thereby less reliable results. This concerns for example the safety of the food and the initially planned sequence of experiments, which was restructured according to the false assumption of incomplete drying on-site. As the project is still in a developing phase, it can be recommended to invest in more and accurate equipment, in order to analyze the food samples quality along the experiments and adjust the types of tests and variables accordingly.

6.1 Dryer Set-ups in comparison

The overall outcome of the comparison can be based on factors like the dryer design, external factors like weather and solar irradiation and parameters or the equipment used for the measurements. Furthermore, results of the four present dryer set-ups ODM, NDM, OAnF and OAwF can be evaluated based on previous research in this project and by considering potential sources of error and assumptions made.

Comparing the moisture loss over time in all four dryer set-ups, the NDM is drying food samples the fastest. In addition to this, the highest rise in temperature can be seen in the NDM. In line with these findings, also other research shows that when comparing the dehydration of banana slices by using different temperatures, the higher temperatures are more beneficial, dehydrating the samples faster and to a higher extent. (Amer, Azam, and Saad 2023) Previous findings (Rissler 2023; Mahmoodi 2023) in the present project support that drying in the ODM and a control open-air drying do not show high differences in drying time and performance. It was even found that open-air drying seemed to work more efficiently than the ODM (Rissler 2023), however this may be due to the season of drying and weather conditions.
Moreover, a dryer similar in its design to the NDM was tested in Lund under laboratory conditions. Optimal conditions for drying with a solar irradiation of 1000 W/m^2 were used to examine the performance of the dryer, showing comparably successful results with complete drying of the food as in the present work. (Om 2023)

As the control trials of open-air sun drying in the present research show, usage of a fan, meaning creating a forced airflow, shows a higher decrease in moisture over the same time period.

Comparing the drying rate graphs with literature reveals that only the values of the ND and OD come close to a theoretical description of a typical drying rate. As described in section 3.3.2 Drying Rate, the initial phase usually shows a steep increase, followingly remaining a rather constant drying rate and finally a falling drying rate. However, drying rates in literature are often shown with the amount of water on the x-axis, which can lead to a different perception of it. (Singh, Heldman, and Erdogdu 2024) Another reason for this deviation to a theoretical drying rate model can be the choice of timing to take measurements. Moreover, heating up of the surrounding to make an off transport of water possible may be another contributing factor for a clear initial stage with high drying rate followed by a linear decreasing instead of constant drying rate. Therefore, the OD drying rate shown in the graph may come closest to theory, because the initial drying rate is not as high, but the time following it, a rather constant drying occurs over a period of about 4 hours until it decreases. Especially for the new and improved dryer model and Open-Air drying this transition of phases may occur already during the first 2 hours but doesn't become as clear in the graph, because only 2 measurements within this time frame were done.

As water activity is the crucial parameter to identify whether the food samples are fully dried, no statements can be made if complete drying was already achieved after one day, meaning ten hours of drying in the different dryer set-ups. This implicates that no comparison can be done whether all set-ups lead to a complete drying of the food. Solely, the course of drying rates and drying times to achieve a specific moisture loss can be compared, leading to an indication of which set-up is the most efficient.

The presented results demand the consideration of assumptions and sources of error brought forward in sections 6.7 and 6.8.

Regarding the technical comparison, the bigger absorber area of the NDM seems to be crucial for the higher temperatures. However, the extent to which temperatures are higher does not behave linear with the increase of absorber area. Maximum temperatures in the NDM during the comparative experiment were about 10°C higher than in the ODM. Also, the heat exchanger area differs and is enlarged in the NDM design through new dimensions. The assumption can be made that the enlarged heat exchanger area leads to higher temperature increase of the air even before it enters the absorber area. Thus, the overall improved design of the NDM is contributing to the temperature increase in the drying chambers compared to the ODM.

Looking at the drying curves, the NDM results initially and finally in the highest moisture loss in the food samples. The ODM compared to the two control Open-Air drying set-ups, shows initially the lowest decrease in moisture. After the full 2-day drying session however, it results in the second lowest moisture content remaining in the food samples, making it less efficient along the drying procedure but second most efficient when looking at the final results.

6.2 Additional Experiments

Maturity stages and drying

When considering the %Brix values of the maturity stages and the choice of stage 2 and 3 for drying, due to easier slicing and handling, this choice seems like the best alternative. The existing sugars contribute to the sweetness, but a still rather firm texture makes the handling easier. However, considering that the projects aim is to prevent food losses by drying foods that can't be sold fresh on the market anymore, bananas of maturity level 7 would be most likely to be used for drying. Even though the taste can be expected to be very sweet, which may be beneficial, the handling of such bananas becomes difficult as they become mushier with higher maturity.

When comparing the drying of different ripening stages, it needs to be noted, that the drying took place on different days and different solar-dryers, wherefore variables like solar radiation, temperature and the overall performance of the solar-dryer model influences the results. Ambient temperature and solar irradiation are values naturally differing in field work research and are thereby variables which can't be tested singularly or stay fixed in order to test other parameters. The overall results for maturity influencing the drying time therefore have to be regarded critically.
Moreover, the grouping of maturity stages was based on subjective separation according to outer appearance, which implicates that the separation may not have happened uniformly and in line with the actual maturity stage. Human error may have influenced the perception of a banana sample of maturity 4 to being of maturity 5, incorrectly, thereby affecting the overall reliability of the drying curves of maturity 5. Measured %Brix values for each stage with fluctuating values between maturity 2 and 6 may further explain the possibility of incorrectly assigning banana samples to a certain maturity stage due to human subjectivity.

Considering these possible interferences, the outcome of the ANOVA showed no significant differences in drying efficiency in relation to the maturity. From the graphs it seemed like MS5 showed the fastest drying, especially in the beginning. Comparing this result with study outcomes where maturity and drying kinetics of banana were investigated, maturity seems to have very little influence on the overall moisture loss of a banana sample (Nguyen and Price 2007). However, there were not many studies conducted yet, researching on the effect of different maturity for oven- or even solar-drying.

Pre-treatments and drying

For additional experiments carried out, as for example the pre-treatment experiment of banana slices with salt, results serve as indication for further pre-treatment methods. The outcome shows that an application of salt had the highest moisture loss over a period of 10 hours. It should be considered, that pre-treated samples were dried open-air and not placed in a solar-dryer for this experiment. Setting this outcome in further context with the focus group discussion results, a slightly more salty taste was desired by participants which further makes salt a potential pre-treatment. The pre-treatment with salt could not only benefit the drying performance but also consumers' acceptance of dried banana slices.

Another possibility for pre-treatment could be sugar. The assumption can be made that sugar will most likely behave in a similar way as salt when applied to the food samples, since both are osmotically active compounds (Rastogi, Raghavarao, and Niranjan 2014).

Generally, the application of a pre-treatment is an interesting field to investigate in solar-drying of food. Research shows that pre-treatments of food with osmotically active compounds like sugar and salt can enhance the dehydration process and thereby shorten the time and energy demand needed for complete drying. (Rastogi, Raghavarao, and Niranjan 2014) This can be beneficial for farmers using the solar dryers, saving them time and energy as resources. Still, results should however be critically viewed, as only a one-time experiment with a salt pre-treatment was conducted and analyzed, outside of the solar dryer. Therefore, a series of experiments about how osmotic pressure may influence dehydration should be investigated in combination with using different solar-dryer models. Several studies exist where pre-treatments and their effect on drying efficiency and maintenance of food quality is investigated (Adepoju and Osunde 2015; Dandamrongrak, Mason, and Young 2003), however pre-treatments have rarely been brought in combination with solar-drying of food.

6.3 Analysis of food samples

When it comes to food quality aspects, especially the safety for consumption and sensory characteristics can be evaluated.

6.3.1 Oxidation

Concerning the potential oxidation happening with cut open banana slices, the focus group discussion results are the only indication to say whether oxidation appeared to be a problem in this experiment. Results showed that the overall taste and color perception of consumers was rather positive. No or few off-flavors and aftertaste was discovered which leads to the assumption that oxidation did not seem to be problematic in this experiment, even with the food item bananas which are seen as very susceptible to unpleasant color changes when cut open. A more detailed summary of the overall outer appearance and sensory perception is discussed in section 6.4 Focus Group Interview. One suggestion might that temperatures in the dryer models, especially in the NDM, were actually high enough to inactivate the PPO enzyme, which takes place at temperature of above 50°C. (Martinez and Whitaker 1995) Another suggestion can be the chemical composition of the present banana species and a lower concentration of browning enzymes. These hypotheses, however, would need further analysis to be confirmed or rejected, which was out of scope of this thesis.

As additional point it can be noted, that a study found that the application of osmotically active compounds like salt did not influence color, meaning it could prevent oxidation (Rastogi, Raghavarao, and Niranjan 2014). This outcome is interesting to put in context with the sensory evaluation in the Focus Group Discussion.

6.3.2 Moisture content & water activity

Out of food safety and shelf stability reasons, it was important to analyze the moisture content and water activity of the samples. Results show that the food samples of the NDM show complete drying with a water activity of 0.389.
It has to be noted that only food samples of the NDM were analyzed regarding water activity. The reason for this was an early but most likely incorrect assumption that samples from the ODM and Open-air sun drying seemed incompletely dried and were thereby not brought to Lund for analysis. This assumption was based on their soft and gooey texture in combination with experimentally determined moisture contents above 20%. A crispy and crunchy texture was aimed for or expected at first, which is directly influenced by the amount of water present in the food and should be preferably below 10% as found in literature. (Blahovec 2007) Consequently, the samples were assumed to be incompletely dried and there are no results available on if the ODM or any of the Open-air sun drying set-ups led to complete drying of the food samples, being food safe and shelf stable.

Comparing final moisture content values of the samples of the NDM experimentally determined in Bhutan with the moisture content results of CNR and the ones determined in Lund with the vacuum oven, numbers are quite different. Values differ in a range of more than 10%. This high of a variation may be due to very inaccurate equipment on-site, like the scale used for weight measuring and determining mass losses. In this case, results by CNR and from the vacuum-oven drying in Lund can be seen as more reliable with final moisture content values of 6.00% and 7.58%. The determined water activity seems reasonable in combination with the moisture content determined in Lund or by CNR, especially when comparing it with commercial banana chips showing a moisture content of 3% (Livsmedelsverket 2024).

Followingly, the same can be expected for results of ODM and Open-air dried food samples. The inaccuracy of the utilized scale in determining mass losses throughout drying can be applicable to the final moisture content values. Therefore, the assumption can be made that the actual final moisture contents of the samples in these set-ups was lower than shown in the results.

In addition to inaccuracy of the scale, also the constructing material used for the Solar-dryers, especially their trays, can influence the experimental data. Wood and fence wire are the components used for the drying trays. As banana slices tended to stick on the wire and couldn't be weighed separately every hour, entire trays were weighed to determine mass losses. However, wood is known to be a material which is losing moisture as well, when being dried. Therefore, the ODM and NDM being made from wood, as well as the drying trays themselves need to be considered in the overall drying performance. For calculating moisture losses, trays solely being made from wire would be more appropriate for further experiments. The usage of wood as constructing material must be seen as general source of error in this research, leading to deviating results for the experiments conducted in both solar dryers.

6.4 Focus Group Interview

Concerning the outer appearance, it should be noted, that the evaluated banana samples were packed and transported in a vacuum bag for a time span of 3 weeks before the focus group discussion. Due to the vacuum packing, slices sticked together and could not be separated properly to be evaluated. Therefore, the findings of the group discussion about the outer appearance like shape, slice thickness and color should be regarded critically.

Generally, one can say that within the focus group discussion the opinions on the liking and not liking of the dried banana was highly influenced by the description of other participants in the group. During the start of the discussion, more participants seemed to not like the look of the sample and the texture, especially according to their prior expectations. Throughout the discussion, participants came up with ideas how they would like to consume the dried banana in combination with other food items, therefore finally being more accepting towards the look and consistency of the product. Solely, the sweet flavor was still too sweet from the beginning until the end of the discussion. In regard to the flavor, participants liked the idea of adding some salt to the fruity and sweet banana taste. This outcome can be seen beneficial in combination with the outcome of the pre-treatment experiment with salt, leading to a reduced drying time. Salt as pre-treatment should therefore be further investigated and tested in a sensory evaluation. Instead of adding salt, the suggestion of using less ripe bananas was brought forward, to counteract the high sweetness of the product. The maturity of the bananas was indeed quite high with being at stage 5-6. Therefore, less ripened bananas should be dried and investigated in a sensory evaluation in future, preferably in comparison with salt treated samples.

As main outcome from the focus group discussion, the dried banana samples convinced consumers with their strong, fresh and fruity banana flavor, which participants would consume and buy again, if available in supermarkets. Therefore, a commercialization of the solar-dried banana can generally be seen as possible. Consumers acceptance however is strongly depending on their prior expectations of the product according to its name. Additionally, texture and outer appearance influence consumers acceptance and interest in purchase highly. The panelists of the discussion seemed to be very open and creative in how to consume the dried banana, which is not necessarily the case for all consumers. The number of attendees for the discussion was rather small, wherefore a larger group should be considered for further sensory evaluations.

Color of the banana slices was not criticized in a negative way and described as appetizing. A suggestion can be made that this is related to the local banana type “Jazi Kela” used for drying. However, in connection with an investigation of pre-treatments, one method to reduce enzymatic browning includes the application of acid on the damaged plant cells. Citrus juice could be used and result in a lower pH thereby inactivating the PPO enzyme. (Yildiz 2018) This pre-treatment could potentially have an effect on perceived sensory characteristics as well and would be reasonable for a series of experiments.

Overall, the focus group discussion brought forward that a general acceptance and interest in purchase for the solar-dried banana samples exists, making it an option to commercialize.

6.5 Societal impact

Considering a commercialization of the solar-dried banana samples on regional or national level, the societal impact can be evaluated. Included in this impact can be nutritional benefits and drawbacks, as well as an overall economic effect showing benefits and drawbacks, particularly for farmers.
The nutritious value of the analyzed food samples can be put into context with the overall nutrition status of Bhutan (section 3.1.2).

6.5.1 Nutritional Benefits

Generally, as especially children are concerned of undernutrition leading to wasting and stunting, the dried banana may be a good source of energy for them with ~300kcal/100g. Poverty may be the cause for insufficient food in general but especially of fruit and vegetables. Life circumstances of the Bhutanese population are showing to influence food security and access to fresh and healthy food (NSB 2024). Therefore, banana in a dried condition being more shelf-stable is a good option to include fruit in the diet. Regardless of the duration of transportation or storage, bananas in dried form are a way to make fruit more accessible to the Bhutanese population and depending on the price.

On the other hand, obesity and overweight are problems among the population based on too few consumptions of fresh vegetables and fruit. Even if the banana is dried, healthy components like fiber, minerals and vitamins persist the drying and can contribute to a healthier diet in a similar way as fresh fruit. Furthermore, the dried bananas are very low in fat.
Considering maximum temperatures of 61.48°C within the dryer models during dehydration, it can be assumed that the initial vitamin contents are likely to remain the same after drying still minor losses due to heat and light instability should be considered (Essodolom et al. 2020). In addition to this, the minerals Magnesium, Manganese and Copper for example that are found in fresh *Musa Acuminata* are assumed to not be influenced in their amount due to the temperatures either. (Kimura and Itokawa 1990) Despite these findings, an overall loss of health active substances like vitamins and minerals should still be considered after complete dehydration of the samples, as also light can lead to a degradation. (Essodolom et al. 2020)

Diabetes is a NCD that is quite prevalent in Bhutan especially amongst adults and can develop out of genetic and environmental factors, like diet. Especially high sugar and saturated fat intake is known to increase the risk for diabetes. (WHO 2023) With banana mainly having fructose as sugar, the source of carbohydrate is comparably better than other candy or pastries made from refined sugar, which Bhutanese consume. This also counts for the saturated fat intake, which is very low in the dried banana slices.
As the dried banana for now has not been pre-treated, for example with salt, it is a sodium-low food item. With Bhutanese generally consuming too high amounts of salt (Global Nutrition Report 2024), the dried banana can be a good low-salt food item to be implemented in the diet. According to outcomes from the focus group discussion, dried banana shows a good potential for commercialization and high acceptance by consumers, making it possible to contribute to the nutrition status of Bhutan positively.

6.5.2 Nutritional Drawbacks

Concerning the maintenance of vitamins and minerals in the banana compared to before and after drying, the assumption is made that these were not or very few influenced by heat or the moisture removal. However, as these contents were not experimentally analyzed, and no actual statement can be made about the persistence of health active compounds. Any health benefits awarded to the dried banana could finally be inaccurate and lead to false impressions, for example that consumption of the dried banana is just as nutritious as fresh banana.

Dried banana is a rather energy dense food item due to a high amount of carbohydrates. Even though the sugars in the food item are mainly fructose, being more slowly digested in the human body compared to other monosaccharides (Tovar 2022), dried banana can only be included in the diet of diabetes patients in a limited amount.
Micronutrients found in the food sample per 100g were contained in very low quantity, therefore dried bananas will not be a food item which can cover the daily needs of certain micronutrients for children or adults. With results received by CNR for the dried food analysis, it becomes interesting to analyze the raw material, fresh banana, to be able to compare the nutritional changes due to drying. The assumption that solely moisture left the food with no further chemical changes or losses occurring, the validity of this assumption should be investigated experimentally. Results would thereby help identifying the overall nutritional impact on the nutrition status of Bhutanese.

Consequently, it is to mention that results about the nutritive value of the solar-dried bananas presented in this research work only serve as an indication. Previously mentioned results and their benefits should therefore not be taken for granted but observed more critically.

6.5.3 Economic effect

A prevention of food losses from easily perishable foods like bananas implicates an economic effect, especially for farmers. Generally, the highest share of the Bhutanese population is employed in agriculture, making the topic of solar drying of food very interesting (NSB 2022; UNDP 2024; World Bank 2024). Benefits and drawbacks of the solar drying of food may occur at the same time.

6.5.3.1 Benefits

Regarding the positive impact that the commercialization of the dried bananas could have, it is certain to say that food waste is reduced by drying leftover bananas. Thereby, the income of farmers can be increased with an additional income stream from foods that would have been discarded otherwise.

Selling both fresh bananas on the market and dried bananas in supermarkets, the pricing for both products should be further investigated. Generally, bananas are cash crops which can positively influence the income of farmers (FAO 2023). As dried bananas demand a higher energy and labor input, prices should even be set higher. Considering that in dried condition also the shelf-life increases while the nutritious value is not highly degrading, a higher price is justified. In the price setting, investment costs for the dryer should be included. However, a communal share of solar dryers can be a further option to prevent these high investment costs. Several farmers could use one or several solar dryers together, as they might plant different foods which are harvested at different times. By sharing the solar dryer, it is further prevented that there will be idle times.

Easier storage and transportation of the dried bananas may open new market possibilities for farmers, regional, nationally and even internationally. This possibility again advantages the additional stream of income. It can be noted that due to the high weight loss of dried bananas compared to fresh ones, transportation and storage is not only more easy but also less costly and energy demanding. With India being the main trading partner of Bhutan (World Bank 2024), an international sale of the dried bananas is possible. This is further supported by the focus group outcome, where panelists originating from different regions of Indian were asked to evaluate the dried banana and generally liked the food item, claiming they would purchase it from a supermarket.

Depending on the scale of banana harvest, the establishment of solar drying operations at farms could further create new jobs, contributing to local employment and economic growth. The running of solar dryers itself doesn't demand labor, but the preparation of the food does, for example slicing the bananas. Also, maintenance and repairing, sourcing of raw materials and frequent check-ups of the dryer efficiency require some expertise in this field. Thus, employment rates in Bhutan may be positively influenced with the use of solar dryers on farms.

Out of an environmental perspective, solar drying is very energy efficient with locally sourced materials used for the dryer set-up. Utilizing solar energy reduces reliance on electricity or fossil fuels while using renewable sources. Especially in Bhutan with its climate and weather conditions renewable energy sources are easily accessible and a cost-effective method for farmers.

As last benefit, the sale and consumption of very seasonal foods can be prolonged through drying them. Bananas could be eaten throughout the whole year instead of only during their time of harvest leading to a rather steady than seasonal income. The availability of bananas throughout the whole year can again positively affect the nutrition status of the population.

6.5.3.2 Drawbacks

As mainly overripe bananas will be left over after the sale of fresh bananas on the market, this maturity stage implicates a difficulty in drying which should be considered. The present research shows that the handling of very ripe and often mushy bananas is more difficult than using rather unripe and more firm bananas. Slicing will potentially take more time for farmers when the bananas are sticky or falling apart. Putting the drying of left over bananas and their commercialization in context with the focus group outcome, it is rather undesirable to use the maturity stage with the highest sugar content present for drying. Taste wise, consumers seemed to prefer less sweet, dried bananas. An additional tasting and market analysis could show which maturity stage should be used to result in the highest purchase rates of consumers. Therefore, a simultaneous production of dried bananas along with the sale of fresh bananas can be the best option, to make the products most attractive for consumers and prevent food wastes at the same time. However, this suggestion demands a lot more research.

Moreover, farmers may face investment costs for the establishment of a solar dryer, which they may not be able to afford. Resources needed for using the solar dryer and maintaining it are additional costs that farmers face, as well as the food preparation like slicing is labor intensive. It becomes necessary to balance costs and incomes that arise. Therefore, considering the resources needed, a dehydration of bananas may finally not lead to a high additional income for farmers compared to before.

With the use of solar energy for drying, the process of dehydration becomes also very dependent on the weather, which can be a disadvantage. Drying can only take place in seasons that are showing dry and sunny weather conditions. These seasons may not be synchronized with the time of harvest. Also, a potential planning of drying sessions is restricted by the flexibility farmers have to keep due to weather fluctuations. Solar drying is very climate and weather reliable which makes the overall value that a solar dryer will bring difficult to estimate.

Lastly, dried banana may seem to have a high shelf life and be stored and consumed over a long period of time. The exact duration of this period however is strongly relying on the packaging and storage conditions. Thus, no statements can be made on if the dried banana have a shelf life of one year, for now. It demands further tests and analysis to see how long the seasonally harvested fruit can last in its dried condition and is safe to be consumed. The availability and nutritious contribution throughout the year should therefore not be taken for granted.

Overall, the present research on the use of the solar dryer shows that can definitely be used to dry bananas in a safe way and making them more shelf stable. However, to be able evaluate the economic benefits and drawbacks of using the solar dryers in a more accurate way, a lot more research has to be done. Microbial tests in order to determine shelf stability should be conducted, as well as consumers preferences, cost and price evaluations, packaging options and market opportunities investigated in more detail. Prior mentioned benefits and drawbacks are only assumed. The statement on the economic effect of drying and commercializing banana in Bhutan with the information present, is restricted.

6.7 Assumptions

To interpret the results received from the experiments, it is necessary to include the assumptions made throughout the experiments.
Firstly, all recorded weight changes were assumed to be due to the evaporation or re-absorption of water from the bananas. To ensure the accuracy of these measurements, a control experiment involving the empty drying of wooden racks was conducted. Values obtained from this control were systematically subtracted from the measured weight changes observed during the banana drying experiments.

Furthermore, it was noted that both dryer models demanded consistent energy requirements throughout the experimental period, with two fans consistently operational. An assumption on equal energy consumption across the different dryer models was made in order to compare their overall performance. However, actual energy demand could not be measured so the potential of differing values exists.

There were many studies conducted for drying banana slices, pre-treated or at different temperatures, which help evaluating the outcome of this research. However, it is essential to acknowledge that in most studies different banana species were used, which may lead to variable chemical composition. Thus, in this research work it was neglected if studies used for comparison did analyze different banana species than the local “Jazi Kela” in Deothang, Bhutan.

6.8 Sources of error

Some noteworthy limitations and sources of error were encountered during the drying process. Firstly, it was observed that certain equipment, such as the scale utilized for measurement in Bhutan, showed some inaccuracy, potentially impacting the precision of data collected.

Additionally, the construction of the dryer from wood caused a source of error, as the material itself absorbed moisture, affecting the food drying results. This also included the choice of wooden trays. As full trays had to be weighed to determine the moisture loss of bananas, trays themselves may have influenced the recorded drying kinetics of the bananas. This source of error may be a crucial point why a high discrepancy of about 10% between moisture content determination on field and in the laboratory occurred.

Furthermore, interruptions to the drying process, such as opening the dryer door, highly impacted the systems and their performance. This interruption led to fluctuations in temperature and airflow, affecting the drying curves results and potentially reducing drying times.
One limitation was the availability of the dryer models, restricting the number of experiments and variations that could be conducted.

Concerning the raw material used itself, high variations related to the shape and texture of the bananas themselves were noted, with irregularities in slice thickness arising from the soft tissue of the fruit. The ripening times varied highly, which made it difficult to use a uniform maturity state for all experiments throughout 8 weeks. Diameters of bananas differed in about 1 to 1.5cm per batch and within batches, making the used values for surface in the drying rate calculation a rough approximation.

As external factor the location of the dryers, situated close to a house, resulted in periods of shadow during peak solar irradiation hours in the morning, affecting the drying process. These can be seen in the graphs around the time of 9.00am. The flexibility in location was limited due to the placement of thermocouples and reaching distance to power outlets for the fans.

All in all, the series of experiments provided valuable insights into the drying kinetics of bananas, however with several limitations which naturally occur in field work. These should be considered and improved in future studies on the solar dryers in Bhutan for a higher accuracy and reliability of results.

6.9 Focus for further research

The field of solar drying of bananas in general and especially the project in Bhutan requires more research. As this is the first work conducted in Bhutan analyzing the food samples themselves, more equipment on site will be beneficial to invest in. This includes for example the possibility to measure water activity of food samples along with their moisture loss. Thereby, it can be determined at which moisture level the food underscores a water activity of 0.6, which is crucial to inhibit microbial growth.

In the drying of banana slices, different ways of pre-treating them before drying should be investigated, to see both the influence on drying behavior and consumer acceptance in the scope of a sensory evaluation. Substances with osmotic dehydrative effect are, in particular, interesting to investigate in terms of the dehydration process.

Pre-treatments should then also include the results of the present research, lowering the sweetness and maybe adding a salty component. Participants for this sensory evaluation may be students of JNEC where the dryer is located, as they could be the potential target group eating the dried fruit as snack. Including more participants would be recommended in order to receive more reliable results. Depending on whether a commercialization is planned on regional, national or international level, participants from the according regions should be considered for a tasting.

Based on consumer's perception, texture and color analysis should be conducted in a laboratory and results can be brought in line with what consumers desire.

Apart from bananas, different food items should be analyzed in the dryer to see how uniform the dryers' performances are. As banana slices were cut open, fruit or vegetables in their whole may be interesting to look at, especially those with a protecting outer layer like bell pepper, making moisture loss potentially more difficult.

In this project it was already found that the NDM is drying food samples faster by achieving higher temperature in the chambers, leading to a complete drying of the food. By focusing on food safety and quality aspects in further experiments in the project, a better evaluation of the NDM can be made in regard to a commercialization of the food. Also benefits and costs both for farmers that are intended to use the solar dryer, and the societal impact including economical and nutritional benefits in detail are essential to look at.

7 Conclusion

From the present thesis work some main conclusions can be drawn. Drying curves of the different dryer set-ups showed that the NDM led to the most efficient drying. This is due to reaching the lowest moisture content in the food at the same time. It is suggested that the main reason for this outcome is the overall design of the dryers. Another result found, was that the use of a fan, even in an open-air sun drying setting, showed a faster dehydration of the food than the set-up without any fan. Contrary to previous findings in the project in Bhutan, in the present research the ODM showed faster drying than both Open air control set-ups. This is a positive outcome which should be further investigated in terms of water activity of food samples dried in the ODM. As additional experiment, the effect of pre-treatments should be investigated in more detail, as especially osmotic active compounds seem promising in decreasing drying times and thereby energy demand.

Concerning the influence of the maturity stage on the drying, no significant differences in drying curves were found between the four investigated maturity stages. However, differences in handling of the banana samples were observed during the experiments. These support the choice of less ripe bananas for drying due to their texture. Concerning the effects of maturity on drying, new tests should be performed on the same day so that most variables (such as ambient temperature and solar irradiation) stay constant, and a better comparison can be made. Considering the initial idea to use the solar dryer to prevent food losses after market sale, a conflict exists between easy sample preparation and consumers taste preferences, and the use of left over and overripe bananas. Therefore, the final aim and application of a solar dryer in Bhutan should be revisited.

Main nutritional components of the dried banana are carbohydrates. It can be assumed that during the dehydration process only water leaves the food item, wherefore the nutritional composition does not change in terms of minerals and vitamins. This assumption is made due to the maximum temperatures recorded in all dryer models. However, as the final nutritional value of the food samples analyzed by CNR was compared to a nutritional value pre-drying found in literature, no clear conclusion can be made in how far the overall nutrition of the product is influenced. Tests on the vitamin and mineral content should be conducted with several batches of the raw material and several batches of the dried sample.

The focus group discussion showed that a commercialization of the solar-dried banana slices is an option in Bhutan and further in India. Participants with an Indian background seemed to have clear ideas on how to commercialize and in which context to consume dried banana in their country. Prior expectations of consumers on “dried banana” however need to be considered and put in balance with the actual food item. Concerning the consumers acceptance, a sensory evaluation including more participants would be recommended in order to receive more reliable results. Depending on whether a commercialization is planned on regional, national or international level, participants from the according regions should be considered for a tasting.

Societal impacts of a commercialization of dried banana on the Bhutanese population can both be economic and nutritional. Moreover, positive as well as negative impacts can be found in both fields. The commercialization of solar dried banana can contribute to a healthier nutrition status of Bhutan when being substituted with refined sugar items, as the present fructose is raising the blood sugar less slowly. However, major nutrient deficiencies of the population will not be solved with this food item. Out of economic perspective, solar dryer may deliver a solution to reduce food wastes in Bhutan’s agriculture, which forms the biggest sector of its economy. On an individual level, costs and incomes of solar drying food crops have to be weighed up against each other. Generally, a communal use of the solar dryers (new design) can be a good option to reduce costs per farm/farmer and prevent idle times of the dryer.
As a summary, further research should be conducted in this project with special regard in analyzing the food samples throughout their drying.

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Appendices

Appendix A

Calculations Moisture content
Mass Water = Total Mass – Mass Dry Substance
100% - 24.88% = 75.12%

Appendix B

Calculations Drying Rate

Surface area determination:
2mm thick slices

New dryer – 14/15th:
→ average weight of banana was used
750g banana slices = 750g / 60g/banana ≈ 12.5 bananas

$$amount\ bananas = \frac{total\ weight\ banana\ slices\ before\ drying}{weight\ per\ peeled\ banana}$$

12.7cm length banana on average → 2mm thick slices
12.7cm / 0.2cm = 63.5 slices per banana
12.5 bananas x 63.5 slices/banana = 793.75 slices
→ assuming that there were 4 slices with the end measurements per banana → 50 end slices

$$amount\ slices\ per\ banana = \frac{length\ banana\ peeled}{2mm\ thickness}$$

→ input of surface area, water evaporated over time and time put in the Drying Rate equation

Appendix C

ANOVA test on maturity stages: test if difference between drying curves and maturity stages are significant or not

Analysis of Variance Results

F-statistic value = 1.81127

P-value = 0.28483

Data Summary				
Groups	N	Mean	Std. Dev.	Std. Error
Group 1	2	24.45	0.7495	0.53
Group 2	2	25.315	1.7324	1.225
Group 3	2	23.34	0.1414	0.1
Group 4	2	25.17	0.1131	0.08

ANOVA Summary					
Source	Degrees of Freedom DF	Sum of Squares SS	Mean Square MS	F-Stat	P-Value
Between Groups	3	4.8846	1.6282	1.8113	0.2848
Within Groups	4	3.5957	0.8989		
Total:	7	8.4804			

Appendix D

Focus Group Discussion – main questions

1) How do you like the overall appearance of the product? Why?
2) How do you like the overall taste of the product? Why?
3) Do you perceive any negative tastes?
4) How do you like the consistency/Texture of the product? Why?
5) Would you buy this product in the supermarket?
6) What name description fits?
7) How often would you buy or consume this product?
8) Would you prefer any additions in taste, for example through pretreatments of the sample?

Appendix E

Nutritional Analysis conducted by CNR

Royal University of Bhutan

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Royal University of Bhutan, College of Natural Resources

1.3.(Table 3), Details of Parameters analysis and the result

Lab Code	Sample ID	Moisture Content MC	Total solids TS	Total ash TAC	Organic dry matter ODM	Crude Protein CP	Crude Fat	Total Carb	Energy	Nitrogen N	Phosphorus P	Potassium K	Calcium Ca	Iron Fe
	Unit	%	%	%	%	%	%	%	*Kcal/100g*	%	*ppm*	*ppm*	*ppm*	ppm
1	S1	3.76	96.24	8.94	91.06	8.82	4.46	74.02	371.47	1.41	9.329	57.60	25.00	7.0213
2	S2	6.00	94.00	22.90	77.10	5.44	1.19	64.47	290.31	0.87	3.984	22.90	15.00	4.2324
3	S3	6.00	94.00	13.30	86.70	5.53	2.16	73.01	333.62	0.88	2.805	17.80	13.00	4.2993

1 : Chilis
2 : Banana 14/15 March ND
3 : Banana 14/15 March ND

NOTES

The integrity of the sample and results are dependent on the quality of the sampling. The results refer only to the parameters tested of the samples provided/collected for analysis.