Czech University of Life Sciences Prague

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Influence of Glazing of Direct Solar Drier on Final Product Quality

Master's thesis

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DIPLOMA THESIS ASSIGNMENT

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Sustainable Rural Development in the Tropics and Subtropics

Thesis title

Influence of glazing of direct solar drier on final product quality

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Objectives of thesis

Objective of this work is to investigate effects of different glazing on quality of final dehydrated product with use of direct (integral) passive drier

Methodology

The Methodology is based on design and construction of experimental solar dryer with different materials used for glazing layers including calculations and optimization of selected material for construction. Set up several experiments for testing the quality of product (slices of apple) during drying under 4 different glazing layers (glass, polycarbonate, plastic glass, PP foil). During the experiments parameters such as temperature, relative humidity, moisture content and final color of apples will be measured. After experimental part the Data processing part will continue with data analyses using statistical methods, calculations and data publication.

The proposed extent of the thesis

40-70

Keywords

glazing, solar drier, product quality

Recommended information sources

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Prague on 27. 04. 2017

Declaration

I declare that the presented thesis entitled "Influence of Glazing of Direct Solar Drier on Final Product Quality" is done as my own work and effort with use of the referred literature. I agree with the storage of this work in the library of CULS in Prague and making it available for further study purposes.

In Prague ………………

……………………………

Bc. Vojtěch Marek

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ABSTRACT

The Sun has a high energy potential in many disciplines. Over the human history, there is a challenge of food insecurity. Solar drying is an effective way of post-harvest processing to preserve food and increase the storage time of the product. In comparison to the traditional open sun drying, solar drying has many advantages in protection against external factors and allows drying the product faster and more effectively in order to prevent the food from microorganism growth. Nearly 80 % of agriculture production comes from small-scale farmers of so-called developing countries. These primary producers are indeed often struggling with food insecurity. In consequences to deal with the food insecurity, increasing product quality is a key issue for them. That brings us to focus on solar drying technologies, in its simplest way of direct passive solar drier, of economically reasonable effective process. The colour is among primary quality indicators recognized by potential consumers and thus plays crucial role in the drying process.

The colour of indirect passive solar drying technology was measured under different glazing materials (Glass, Polycarbonate, PP foil and Plexiglas of 0, 75 %, 89 % and 75 % of UV transparency, respectively) to determine effect of UV irradiation on colour of apple slices. The measurements were done in the Czech Republic during August 2015 and 2016. The results are showing typical appearance of so-called Maillard reaction related to correlation between temperature and Browning Indicator. Correlation showed that the effect of Temperature on Browning Index is significant, $p = .000$ and strong (Pearson's ρ between 0.84 and 0.96). The PP foil glazing with the lowest inside temperature had the lowest Browning Index difference measured. These results suggest that the UV-B light does not have significant effect on colour change and therefore does not affect the quality of the dried product, in means of colour quality indicator.

Key words: glazing, solar drier, drying, browning index, product quality

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List of Abbreviations

ANOVA	Analysis of variance
FAO	Food and Agricultural Organization
Grnd	Ground
ISO	Isometric projection
OSB	Oriented strand board
Plexi	Plexiglas glazing
PP Foil	Polypropylene foil
SDGs	Sustainable Development Goals
UV	Ultraviolet

Nomenclature

a_w	Water activity, [-]
d	Thickness, [m]
md	dry matter weight, [g]
mw	wet matter weight, [g]
N	Drying rate, [kg m^{-2} h^{-1}]
R	thermal resistance, [m^2K/W]
T	Temperature, [°C]
t	Time, [s, h]

w moisture content, [%]

X Total moisture content, kg water/kg dry solid, [-]

X* Equilibrium moisture content, kg water/kg dry solid, [-]

X_c Critical moisture content, kg water/kg dry solid, [-]

X_f Free moisture content, kg water/kg dry solid, [-]

λ Lambda, [W/mK]

φ Humidity, [%]

List of Figures and Tables

Figures:

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1. Preface

From the history of the human kind, or even before, one of the human challenges is to be food secure during any time of life. Due to uneven conditions during a year (seasonal harvesting and other related obstacles), it is fundamental not only to gather the nutrition resources but also to maintain them for future needs. Food preservation is therefore crucial for the food security of people. Food security has been defined as one of the biggest challenges in the World. Food loses and wastage is about 1/3 (Lipinski et al., 2013) in total production. That is present in our World of 800 thousand of people (by the year 2015) that are food unsecured (FAO et al., 2015; FAO, 2016).

> *"For the man who is extremely and dangerously hungry, no other interests exist but food. He dreams food, he remembers food, he thinks about food, he emotes only about food, he perceives only food, and he wants only food". (Maslow, 1954)*

Malnutrition has a dramatic effect on many other following challenges. It is essential to view the problem in complexity in order to understand economic, social and political aspects of food insecurity. There is a so-called vicious circle of poverty or "cycle of rural poverty" that has explanation on the various links to consequences such as political instability and socioeconomic consequences touching us as a human population. Therefore, food preservation is not only a way of reducing food waste but from the global point of view it is directly linked via food security to the World stability. (FAO, 2015; Trani and Loeb 2012)

Preservation of food has a high potential in terms of food storage. Open sun drying is efficient and independent way of preservation, and in fact does not have any other demand on energy other than the Sun. In comparison to solar drying, the loses of open sun drying are much higher, 30 to 40 % of total production (El-Sebaii and Shalaby, 2011). In addition, about 80 % of agriculture products is produced by small scale farmers mainly in countries of Global South (Graeub et al., 2016). In fact, small scale farmers are the most involved in agriculture production. FAO et. al in report (2015) highlight the diverse definitions of small scale farmer, for example.

An energy independent approach is important, in case of the so-called developing countries, where most of the products are grown and processed. From this point of view, the only suitable way to dry agriculture products for the sake of food preservation is to dry them in a non-forced solar drier. Since the use of a non-forced solar drier is independent from conventional sources of energy, it is most suitable for small-scale farmers to use. In many cases, there is no electrical energy supply in rural areas where agricultural products are produced (Ekechukwu and Norton, 1999; FAO, 2016b).

When we look at a small-scale farmer as the typical farmer producing most of the World's food, there might be case that the raw harvested product is sold for lower price than the price on the market. Drying process improves processing to increase profit of the primary producer (FAO 2013). In case of further high quality processing the farmer would be able to get higher revenue for the already processed product. The practical part is designed to focus on drying of food as a cheap and efficient method with use of direct passive solar drier. In order to focus on quality, we have designed four identical experimental driers each attached with a different glazing layer to analyse the effect of UV light on the quality of the product.

Quality of the food product is defined by various indicators; one important sensory indicator is the colour of the product (Mujumdar and Devahastin, 2006). Therefore, the colour of the product plays a significant role in the market price of product. This should be used in favour of the primary producers. We see the importance of focussing on the higher quality and support of the primary producers, that are rural habitants. These small-scale farmers are indeed facing the highest poverty struggles (FAO 2015).

2. Introduction

Techniques of drying under the sun have diverse ways all using the solar energy as an alternative source of energy. “Drying is the oldest, most common and most diverse of chemical engineering unit operations” (Mujumdar S. and Devahastin S., 2006).

Drying is a controlled process of dehydration and it is possible to measure different parameters of drying behaviour that results in the final dehydrated product with significantly low water content level to prevent the spoiling by microorganisms. Low presence of microorganism is beneficial for the possibility of easy transport, storage and preservation in conditions often not demanding extra energy input. The final quality of the dehydrated product is a result of the drying technique and equipment, it takes in consideration aspects of light spectrum, type of solar drier and its glazing in case of direct solar drying. These aspects of drying will be covered in following chapter.

2.1 Drying Theory

Drying leads to dehydration of the product, it is an exclusion of water content from product to preserve dried product from higher moisture content dangers from the micro-biological point of view. Evaporation of the liquid into vapour phase by heating takes place. Unless the freeze drying is applied, that is done by sublimation of the solid phase (of liquid below triple point) directly into vapour phase to decrease water content.

As drying is a complex process, it has broad limitations that are challenging as follows (Mujumdar and Devahastin, 2006):

- Size of the dried particles vary from microns to decimetres.
- Porosity of the product ranges from zero to nearly hundred per cents.
- Operation pressure scales from hundreds of microbars to twenty-five atmospheres.
- Heat is transferred continuously or immediately (by electromagnetic field, conduction, radiation).

Following table shows common terms and definitions that are important to mention in case of drying process.

Table 2.1: Basic terms and definitions of drying

Term	***Definition / Meaning***
Adiabatic saturation temperature	Equilibrium gas temperature reached by unsaturated gas and vaporizing liquid under adiabatic conditions.
Bound moisture	Liquid physically and/or chemically bound to solid material.
Constant rate drying period	Under constant drying conditions, drying period when evaporation rate per unit drying area is constant (when surface moisture is removed).
Dew point	Temperature at which a given unsaturated air-vapour mixture becomes saturated.
Dry bulb temperature	Temperature measured by a (dry) thermometer immersed in vapour-gas mixture
Equilibrium moisture content	At a given temperature and pressure, the moisture content of moist solid in equilibrium with the gas-vapour mixture (zero for non-hygroscopic solids)
Critical moisture content	Moisture content at which the drying rate first begins to drop (under constant drying conditions)
Falling rate period	Drying period (under constant drying conditions) during which the rate falls continuously in time
Free moisture	Moisture content in excess of the equilibrium moisture content (hence free to be removed) at given air humidity and temperature
Humidity, absolute	Mass of water vapour per unit mass of dry gas
Humidity, relative	Ratio of partial pressure of water vapour in gas-vapour mixture to equilibrium vapour pressure at the same temperature
Unbound moisture	Moisture in solid which exerts vapour pressure equal to that
Water activity	Ratio of vapour pressure exerted by water in solid to that of pure water at the same temperature
Wet bulb temperature	Liquid temperature attained when large amounts of air-vapor mixture is contacted with the surface. In purely convective drying, drying surface reaches wet bulb temperature during the constant rate period

Process of drying is in literature described by moisture of dried material. Therefore, so-called moisture rate is an important aspect measured during the drying process.

2.1.1 Moisture of Drying Material

The following chapter examines the moisture content of drying material from the perspective of diverse phases of drying process. So-called moisture content equilibrium represents relative humidity in equilibrium for any wet solid content with given humidity and temperature of air and solid. We can distinguish between three phases of sorption isotherms A, B and C that differ water content binding. (Andrade et al., 2011)

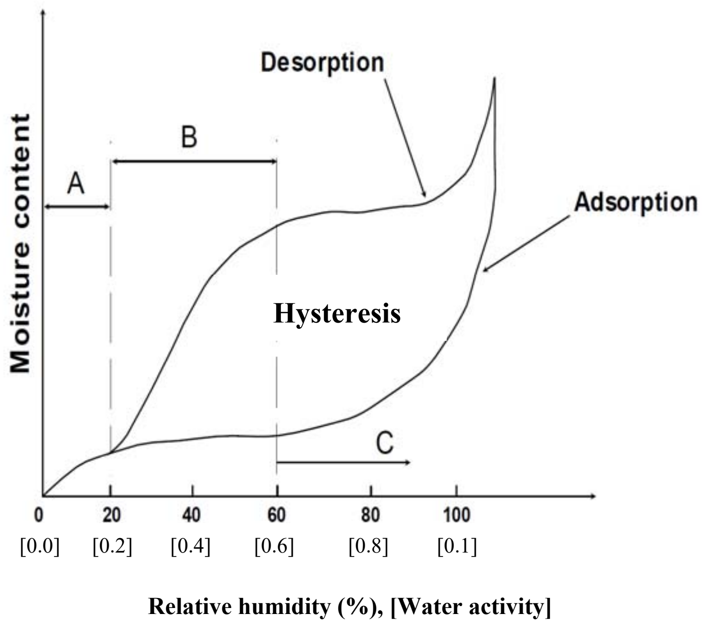


Figure 2.1 Sorption isotherms A, B and C phases for typical food product (model III)

(Source: Mujumdar and Devahastin, 2006)

Relative humidity in Figure 2.1 Sorption isotherms A, B and **C** is expressed in % but Andrade et. al. (2011) are using water activity on x axes as relative humidity dividend by 100 to get values from 0 to 1.

Figure 2.1 Sorption isotherms A, B and C phases for typical food product is showing the relative humidity used by Mujumdar et. al. (2006), in squared brackets is the Andrade et. al. (2011) water activity. Sorption isotherm assumes that the temperature and pressure is constant.

In the first part of graph (A) the relative humidity is below 20 %, the water is bounded. The water is “locked” in the material and is neither freeze-able nor available for chemical reactions. From 20 to 40 % of relative humidity (B) the molecules of water are not bounded that well anymore, as moisture content rises, absorption take of water takes place. This water mostly occurs in small capillaries, it is a transition phase between bound and free water. Finally, relative humidity higher than 40 % belongs to phase (C). The water is already stored in large capillaries and is loosely bonded to material. Last phase is available for chemical reactions. Hysteresis occurs in drying process, the product does “remember” the absorption, than the desorption tends to the initial situation (Yan et al., 2008). (Mujumdar et al., 2006; Andrade et. al. 2011) In case of apple drying (Golden Delicious) the isotherm type III is applicable as a result of Bellagha (2008), see Figure 2.1.

In connection to the drying sorption isotherms, the process of drying is based on drying rate and critical moisture content to estimate the drying time. Earl (1983) says that the general drying process is usually based on (A) initial period of adjustment and linear decrease of moisture content in time. Then, (B) non-linear decrease of moisture content takes place until it reaches its (C) moisture content equilibrium, see Figure 2.2.

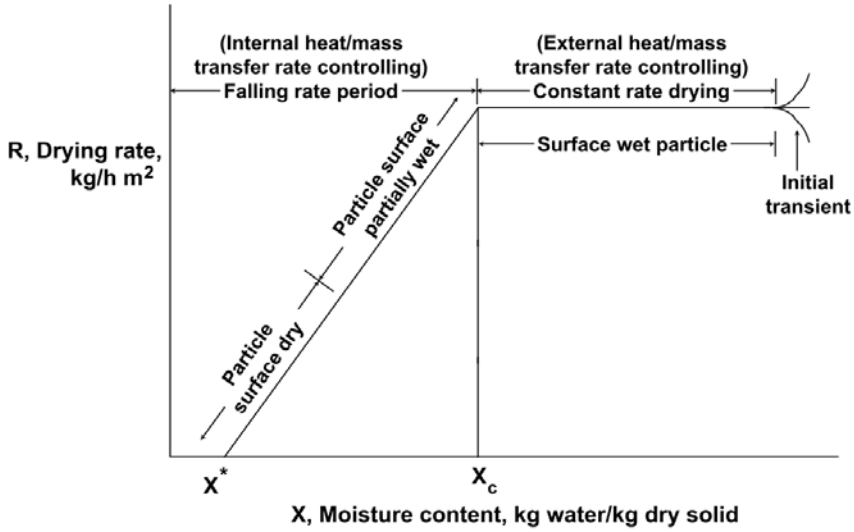


Figure 2.2 General drying rate curve for constant drying conditions (Source: Mujumdar and Devahastin, 2006)

The drying rate shown above is a general "book" scheme of drying process, however, in practice, it differs. There is an aspect of drying temperature, as it is usually not constant and depends on different material thickness and drying techniques. Drying involves heat and mass transfer as well as material science. The drying process affects the quality of the product and has to be taken in account besides the moisture content aspects. (Mujumdar and Devahastin, 2006)

Most microorganisms grow in A and B phase of water activity, see (range 0.0 to 0.6) in Figure 2.1. Water activity (a_w) is equal to surrounding relative humidity and is defined (Equation 2.1).

$$a_w = \frac{p}{p_w}$$

Equation 2.1 Water activity

Water activity safe limit is specified in case of many products. Apples as well as many other food products are at maximum 0.6 of water activity safe

2.2 Solar Drying as a Way of Food Preservation

Direct sun energy known as renewable energy has a high potential in many disciplines. Among any other energy sources, it has advantage in access and sustainability. Drying process undergoes different processes of physical and chemical transformation. Water activity in drying process plays a key role in microorganism growth.

Other following aspects are known as Food quality preservation indicators. Common types of degradation were identified by Heldman et al. (2006), see Table 2.2.

Table 2.2 Factors influencing quality during drying

Chemical	**Physical**	**Nutritional**
Browning	Dehydration	Vitamin
Lipid	Solubility	Protein
Colour	Texture	Microbial
	Aroma	

(Source: Heldman et al., 2006)

Following Figure 2.3 shows minimum water activity for undesirable micro-organism growth in the case of food products such as moulds, yeast, and bacteria. However, other processes are taking place even at the safe level of water activity such as Browning reaction (Mujumdar and Devahastin, 2006; Yan et al., 2008).

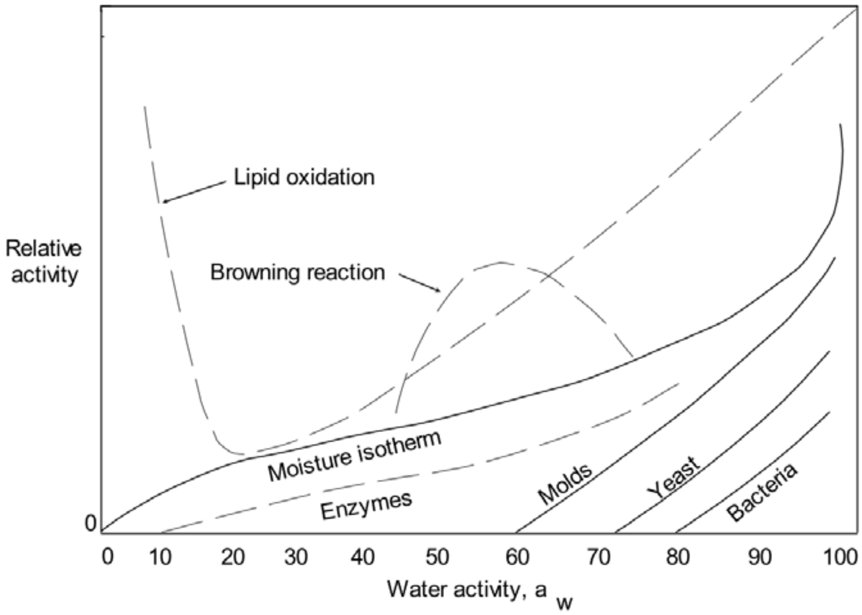


Figure 2.3 Relative activity of natural deterioration

(*Source*: Mujumdar and Devahastin, 2006)

Besides the effect of decreasing water activity to preserve the food from microorganism growth, solar drier plays a role in complete protection from external factors during the drying since the product is protected by its shell against rain, dust, insects and animals, but open to sun drying. That is a competitive advantage, besides the microorganism elimination, compared the open sun drying. To add, the driers are usually equipped with nets against insects and an inlet and outlet for the air. (Esper and Mühlbauer, 1998; Ekechukwu and Norton, 1999)

2.3 Sun Drying of Agriculture Product

Drying under the Sun is a traditional technique used worldwide. Drying itself has many advantages such as elimination of spoilage and microorganism growth. Indeed, when the product is at higher moisture content for longer time period, the spoilage occurs, in case of agriculture harvested goods. Therefore, there is an importance of shortening the drying time, if possible.

Arinze (1987) mentioned that the in case of African countries, referred to Nigeria climate conditions, danger of food spoilage occurs when the goods are harvested at its higher moisture content. Here comes the solution, introduced as applicable for other countries of Africa, to use the solar drying. This insures the production safety as it is applicable to harvest and preserve food goods at any time.

However, initial costs are required for the construction of a solar drying system. A market opportunity survey is done by Voskens et al. (2000) and the potential of drying possibilities worldwide is presented. The potential energy displacement by solar drying is in total between 677 PJ and 1530 PJ. Following Table 2.3 is showing the market segments and indicates the potential of solar drying technology to be used instead of current drying methods.

Table 2.3 Market segment opportunities

Market	**Current**	**Level**	**Desirable**
1	Mechanical	Farm,	Partly
2	Mechanical	Factory	Add
3	Sun	Farm	Replaced

(Source: Mujumdar and Devahastin, 2006)

Voskens et al. (2000) divide the market segment into three analysed categories:

(1st) Mechanical drying below 50 °C applicable for farm, village or factory. The higher degrees are possible to reach but usually more advanced equipment is needed. Therefore, the desirable drying techniques is essentially only partly replaced by solar drying.

(2nd) Mechanical drying above 50 °C applicable for factories. It is possible to reach the higher degrees but usually more advanced equipment is needed. Therefore, the desirable drying technique is essentially only partly replaced by solar drying, as proposed.

(3th) Sun drying done by farm, understanding small-scale farmers using sun drying with very low temperatures limited to sufficient weather conditions due to the open sun drying technique.

The shift towards solar drying is presented as an opportunity to gather higher quality of final product directly by the primary producers. As mentioned previously, there is an essential need of rising the primary producers' income, applied for small-scale farmers (FAO, 2013). The benefits of solar drying compared to open sun drying are for example (Arinze, 1987):

- Over 50 % savings in time can be achieved using solar driers
- Harvesting at higher moisture content is possible without danger of microorganism growth.
- Also the danger of external causes of food degradation is reduced (Esper and Mühlbauer, 1998; Ekechukwu and Norton, 1999), see chapter 0.

In general, the products that are currently open sun dried are suitable for solar drying, but there is often a lack of financial resources in case of so-called developing countries. This would fully apply for solar drying of temperatures below 50 °C. However, if higher temperatures are needed, solar drying may be used only up to certain extent. (Voskens, 2000)

2.4 Classification of Solar Driers

Categories of solar driers will be described to identify diverse possible driers with the special focuss on to the so-called developing countries due to the importance of small-scale family farms. Therefore, we will categorize different solar drier comparing their efficiency, quality, availability and dependency on other source (for example electrical energy).

About four hundred types of driers are found in the literature and about one hundred types are available for use. Most common driers are the ones using hot air as drying medium. (Mujumdar and Devahastin, 2006)

Available literature shows a diverse distribution over the solar drying techniques. There are many different classification groups of the driers and the terminology is not always uniform among the diverse authors. However, there are common signs to classify them. Before starting with the overall classification, it is necessary to exclude the already mentioned traditional drying techniques such as open sun drying and drying by burning of fossil fuels or wood to be more concrete.

The classification is a natural way to generalize and understand more certain objectives In this case, the generalization might seem simple but there are many driers on the edge of one or another group as shown below. Therefore, the aim is to hand out different general models of various drying equipment.

Now, there are only the specified conventional driers to classify. By Sharma et al. (2009) the convention drying technique is so-called “controlled drying”, see Figure 2.4.

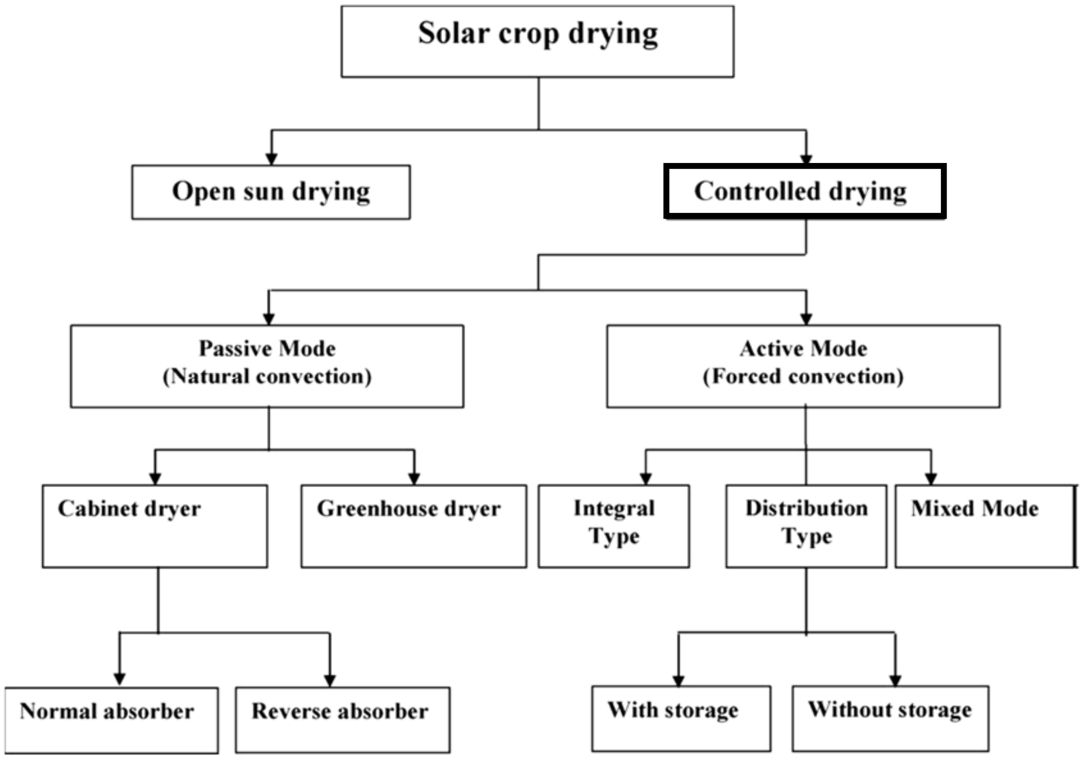


Figure 2.4: Classification of crop drying using solar energy

(Source: Sharma et al., 2009)

Solar driers of controlled drying are classified into two main categories, generally: passive and active (Figure 2.4). The passive convention driers are using the natural air flow of heated air only (typically with the entrance of the air lower than the outlet) and the forced convention drier is equipped with additional technologies. Amer et al. (2010) is using the terminology of non-forced and forced convention solar driers. Forced driers are designed to use an external source of energy to increase the drying efficiency.

Another dimension for the classification is the (a) direct, (b) indirect and (c) mixed drying technique. This classification is to see distinct perspectives of solar drying technology. In general, the drying by (a) direct drier is a more simple way due to the light coming through the plastic or glass cover (roof) straight down on the biomass stored in the drying chamber. On the other hand, (b) indirect drying is more sophisticated by its separated sections of the helio-collector (in the case of direct drying the roof) and the drying chamber.

This is discussed by many authors, among others by El-Sebaii and Shalaby (2012). Here, the author is also taking in account another group of so-called (d) *"solar driers with heat storage media"* where the additional boiler is present (Amer et al., 2010). The exchange of energy is taken in account to reach through the heat exchanger (in many case present after the reversible fan before the air enter the drying chamber) additional heat to decrease drying time, possibly during the off-shine hours.

Information of two-dimension classification, compilation of (a), (b), (c) and (d) with the passive and active category is shown. The present matrix is to see the possible drying techniques derived by the previous classifications, see Table 2.4

Table 2.4: Classification (compilation) of drying techniques

Classification	Passive	Active
(a)	Greenhouse	Integral
(b)	Cabinet	Distribution
(c)	Natural	Mixed
(d)	-	Back-

Table 2.4 there are all the possible types or models of solar drier presented by El-Sebaii and Shalaby (2012) and Amer et al. (2010). The mentioned Back-up model is also presented by El-Sebaii and Shalaby (2012). For the passive mode, the driers with the storage media heater were not found in practice due to its impropriety by already mentioned more simple construction design apart from the active mode. However, in contradiction for example Vijayavenkataraman et al. (2012) is showing the Natural mixed

mode drier in more complex way used for example for drying cassava and other crops of so-called countries of global south. It is suitable to mention the additional heat source driers used in conventional active drying techniques.

As mentioned before, it is generally possible to divide the solar driers can into two broad groups: non-forced and forced or passive and active. The non-forced (passive) driers can be built easily, without any extra materials, and are thus affordable for small scale farmers. For example, raw construction materials such as wood may be used (Sharma et al., 2009).

2.4.1.1 Passive Solar Driers

Non-forced driers are used for the drying of biomass in smaller scale, in general. The passive drying is based on the chimney effect of the rising air flow or it is using the wind speed. There is another diversification of non-forced driers. It is the direct and indirect drying, where the direct drying is common for the passive drying system (Murthy, 2009). The non-forced, also known as natural-circulation, direct driers are shown, see Figure 2.6Figure 2.5. These driers are designed to directly absorb the solar energy to the so-called "greenhouse drier" due to its look are similar to the green house itself using the same heat income for a different purpose. The indirect form of drying system is usually not found in practice. Therefore, the mixed model of drier is presented in the Figure 2.6. The mixed model is a combination of the direct and indirect drying where the drier is basically designed as an indirect drier with at least one or more walls made by a transparent material settled towards the potential sun radiation energy waves (El-Sebaii and Shalaby 2012), see Figure 2.6 .

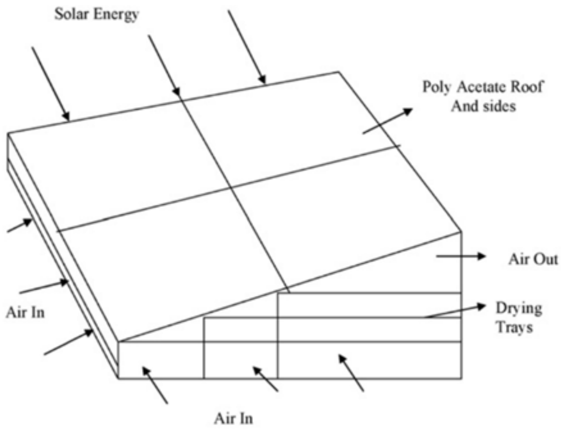


Figure 2.5 Mixed solar drier, non-forced
(Source: Murthy, 2009)

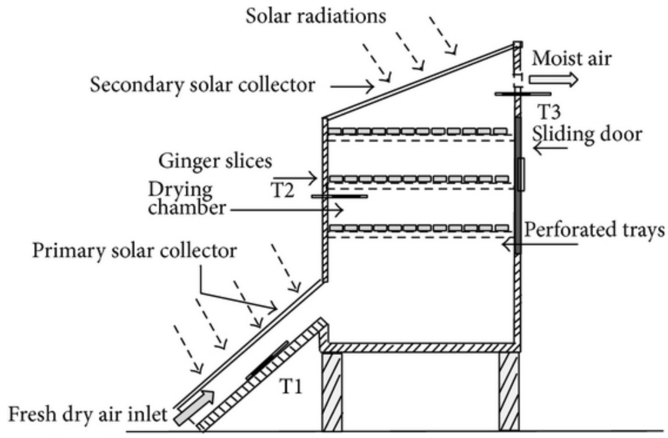


Figure 2.6 Direct solar drier, non-forced
(Source: Deshmukh et al., 2014)

The Figure 2.6 is showing an example of the passive mixed model (direct and indirect drying). In this case, the front view is showing the so-called primary and secondary "solar collector" where the primary collector is playing the role of indirect drying (indirect heating of the inside air) and the secondary collector is playing an additional role with its direct sunlight to support the drying process. That is due to the fact that the one wall with the same direction as the primary collector is transparent.

2.4.1.2 Forced Solar Driers

In general, in the group of indirect driers the active solar driers are used more than the passive ones (Brenndorfer and Kennedy, 1985). But the construction is also more difficult and the following parts are included (for the active-indirect solar dyer), (Figure 2.7):

- Solar collector
- Mixing chamber
- Ventilator (with the additional heat exchanger – if added)
- Grate of the biomass layer
- Drying chamber

This solar drier, shown as an example, is designed with the additional heat source which might be used for example in the off-shine hours. Supplementary heating system is used for drying without heat loses form the separate sun absorber.

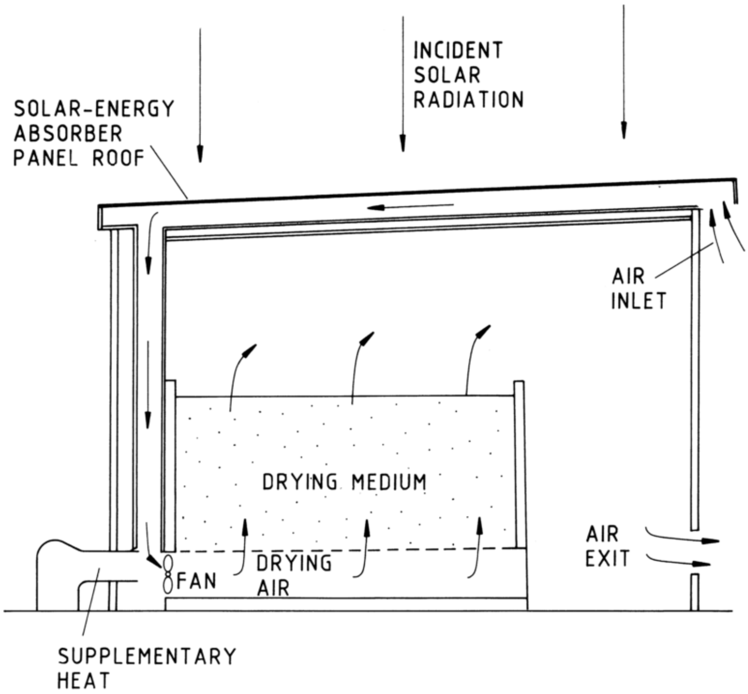


Figure 2.7: Combined drier with the additional heat source

(Source: Ekechukwu and Norton, 1999)

In Figure 2.7: Combined drier with the additional heat source is presented. The scheme shows a practical example of an additional heat source. The uncomplicated way of the additional heater is presented, for example, as a case heat transfer unit. Additional boiler might be attached to heat up water in closed thermo-regulation system. The water is transferred by pipes and pumps to the heat exchanger. In the heater exchanger, the heat energy from the water is transferred by the air to increase the air temperature for further drying process, see Figure 2.7 – Supplementary heat.

Forced driers are designed to use an external source of energy to increase the drying efficiency. The idea of the forced driers is to increase the speed of air flow inside the drier. In different words the same idea is supported by following. "… higher flow rates [of air] increases the overall drying performance and efficiency" (Vijayavenkataraman et al., 2012).

From the point of energy efficiency, the forced solar driers are faster in means of energy efficiency. According to FAO (2016a), conventional forced solar driers can reduce drying time by up to three times and decrease necessary collector area by half. The example of forced solar drier with back up heater is an advanced model, which can cover off-shine sun hours or dry the material even during the night. However, when we consider the often too expensive or unreachable electrical energy sources, the forced driers are not reasonable, especially in case of small scale farmers of the so-called developing countries. (Ekechukwu and Norton, 1999)

2.5 Light from the Sun

After, the presence of UV light will be reviewed to understand better the light and its components for purpose of higher quality dehydrated product. Light spectrum is relevant in case of direct solar drier where the sun light goes directly to the product. That is a case of direct solar drier and its simplest sub-category of non-forced direct solar drier, the most relevant model for rural areas. We will talk about light from the perspective of visible and invisible light, for to use unified terminology.

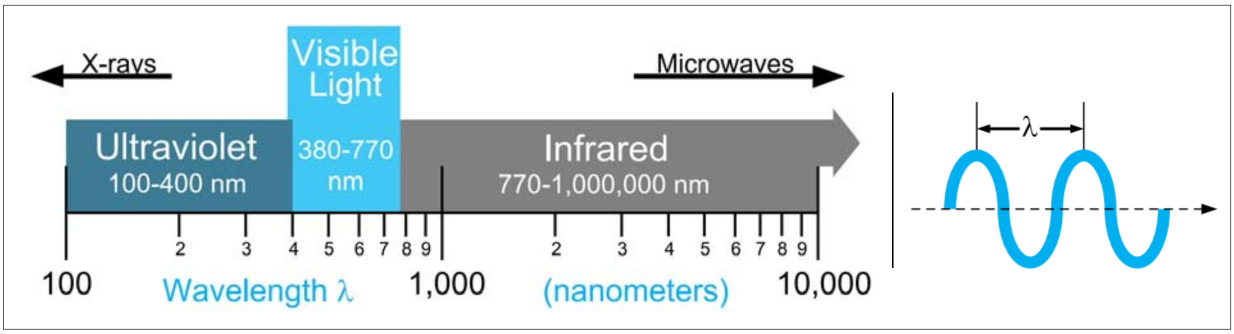


Figure 2.8: The electromagnetic wave spectrum and wavelength

(Source: Ryer, 1997)

According the electromagnetic wave theory, light is formed of various waves of photons flying in space. There is a broad range of waves form the radio waves to the X-rays, see Figure 2.8. The Sun irradiance waves that are forming the spectrum of the light range from about 150 nm (Ultraviolet) to 7,000 nm (Infrared) including the visible light that is just in the range of 380 nm (violet appearance) to 770 nm (red appearance). In energy, it is 1.38 kW/m^2 that is referred as solar constant (Ryer, 1997).

However, the amount of radiation that gets to the earth surface is a fraction of the solar constant depending on latitude, season, specific weather conditions and time of the day. Also, the level of different constant is not proportional. Therefore, per a level of solar irradiation measured in spectrum of one wavelength, we cannot recalculate that fraction for another wavelength. Therefore, the certain wave length of the light needs be measured separately to get the overall picture. For example, the visible light spectrum is seen differently during the sunset or sunrise due to different fraction of the visible light that is passing to the earth surface. From this phenomenon, we can conclude that the light (visible and invisible) is not transmitted equally through the atmosphere and must be elaborated individually and not respectively to the solar constant fraction of the mentioned 1.37 kW/m^2.

The Figure 2.9 shows distribution of the light at (a) of the Earth before entering atmosphere and (b) at the sea level on the equator faced directly to the sun. The figure also shows so-called black body radiation at temperature of Sun (5777 K). The black body radiation is calculated for any object emitting light in the space according the outer temperature. (a) The yellow and orange area is representing the solar constant, the total amount energy of 1.37 kW/m^2. It is measured by the mean distance of the Earth from Sun facing the Sun. The blue represents black body radiation distribution, according the quantum theory. (b) The orange layer represents energy that is measured perpendicularly at the sea level. Orange area is representing the total amount of energy. Typical it is about 1.00 kW/m2 including the energy that is absorbed by the atmosphere.

(MPowerUK, 2015; Johnson, 2012)

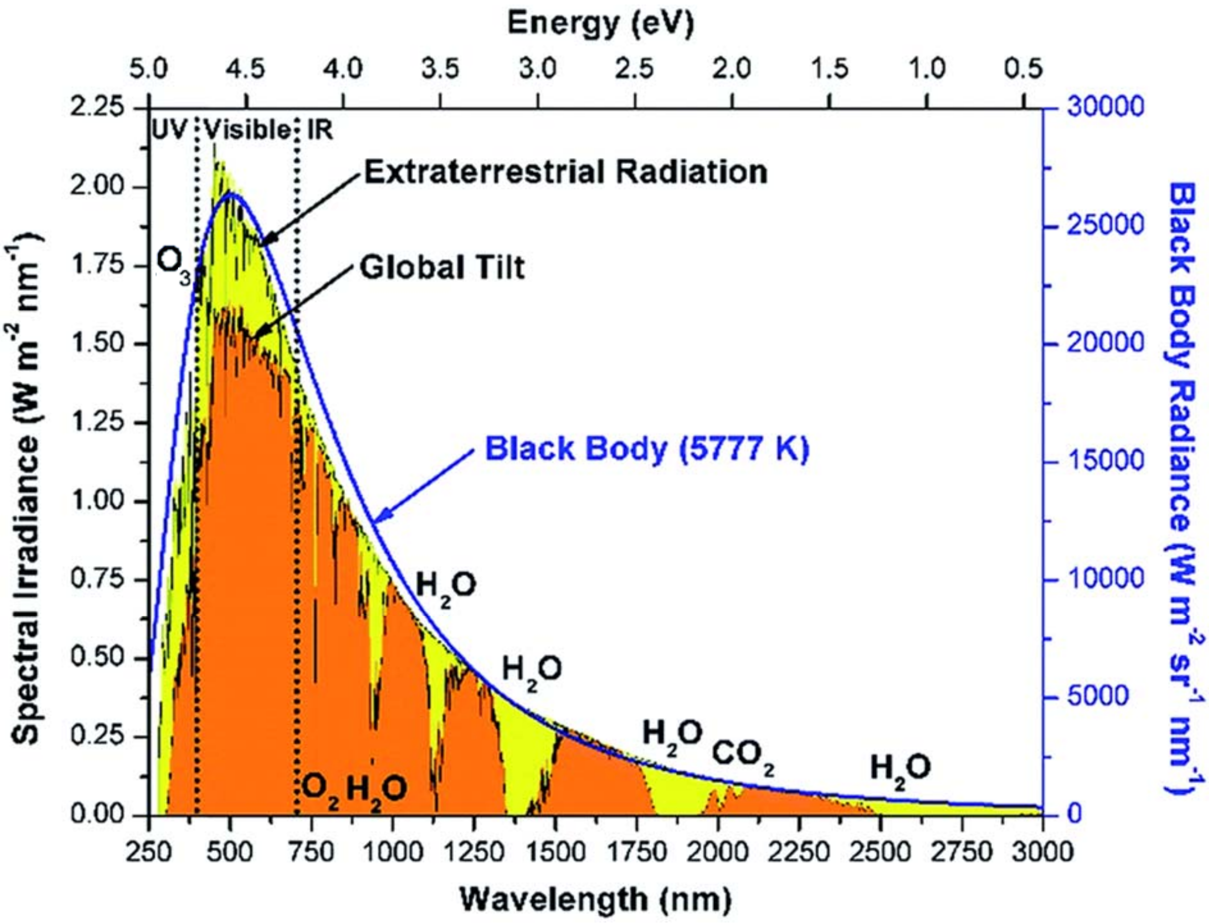


Figure 2.9 Solar radiation spectrum

(Source: Herron et al., 2015)

From the Figure 2.9, we can see that the difference between energy before the atmosphere and on the surface variates over the different light spectrum, see yellow part of the graph. Visually, the visible light and UV light is captured in similar proportion to each other by the atmosphere. In the case of lower length of waves, the proportion is not even due to the fact that certain light is absorbed by water, CO_2, O_3, oxygen and other gases.

2.5.1 Projection of Visible Light

It is possible to quantify the colour using different models and its attributes. A widely used colour model is the so-called HSB model that takes into account the three following attributes; (a) Hue, (b) Saturation, (c) Brightness (also referred as Lightness by Ryer (1997)), see Figure 2.10. (Tilley, 2011)

The CIE colour model was made to be independent of any electronic device or other means of emission to get as close as possible to how the human perceives light. CIE stands for International Commission on Illumination (Commission Internationale de l´Eclairage).

CIE was found in 1913 as an international board and has been a leading force in colorimetry since the colorimetry standards were set in 1931 and 1964 (in Cambridge, England). The CIE colour model was based on observers that set the combination of colours per the reference colour based on black body radiation of 2854 K, see page Light from the Sun17 (Light from the Sun).

There are different CIE models that were developed. The first invented was the so-called CIE XYZ, in 1931. The other models such as CIE LUV and CIE LAB were derived from that. XYZ values are corresponding to red, green and blue, respectively, but are not measured similarly.

The, so-called Munsell colour cylinder is constructed when all three parameters are arranged based on the CIE LAB space, see Figure 2.10 CIE Lab colour space

Note: Presenting Lightness (L*), and colour coordinates (a*) and (b*) are for reddish/greenish and yellowish/blueish respectively; within Hue and Saturation attributes

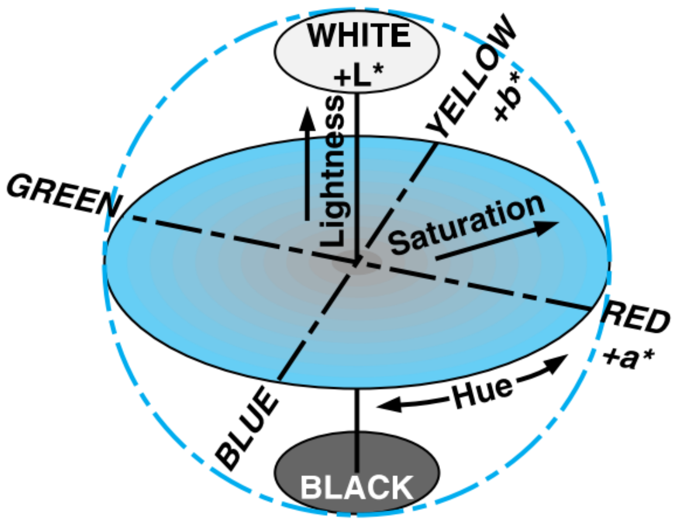


Figure 2.10 CIE Lab colour space

Note: Presenting Lightness (L*), and colour coordinates (a*) and (b*) are for reddish/greenish and yellowish/blueish respectively; within Hue and Saturation attributes

(Source: Ryer, 1997)

2.5.2 UV Light waves

Ultraviolet (UV) light is an invisible fraction of light that partly gets to the earth surface in relatively low amounts. Historically, before the protection ozone layer of atmosphere had developed, the organisms were exposed to the UV light and only the ones that could develop protection mechanism evolved. Due to this evolution step, the UV light contributed to our DNA reproductive controlling mechanisms for correct DNA. (Cooper, 2000)

The UV radiation is divided into four different light spectrum according to Blaustein and Searle (2013); "Ultraviolet radiation (UV) can be divided into four wave bands. These are Vacuum UV (100-200 nm), UV-C (200–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm). At the earth's surface, vacuum UV and UV-C are not present because of their absorption by various gases such as oxygen and ozone." But Ryer (1997) does not take in count the so-called vacuum that is close to the extreme of the X-Ray waves below 100 nm.

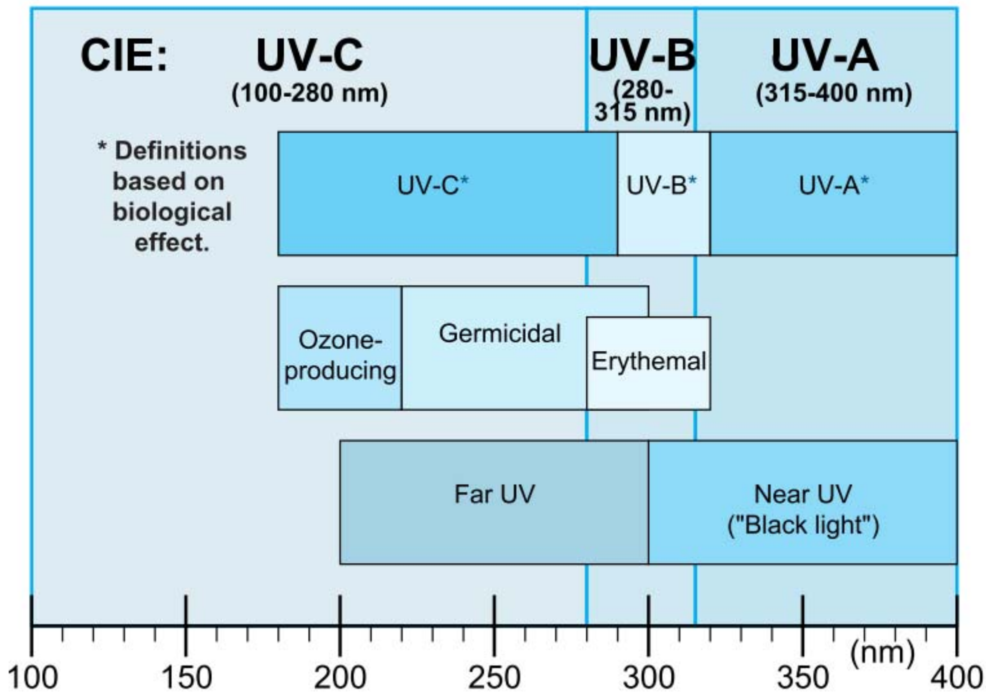


Figure 2.11 Common ultraviolet band designation ***(Ryer, 1997)***

There are many studies that consider the effect off UV-C irradiation on the dried product. However, to consider only the light passing through the Earth atmosphere and its effect on solar radiation, we will focus mainly on UV-A and UV-B from 280 up to 400 nm, see Figure 2.11.

2.5.3 Effect of UV Light on Product Quality

From the previous chapter, we have concluded that the co-called UV-C light is not present at the Earth ground level. However, there is also research that consider artificial UV-C light as a possibly positive wavelength on food quality and preservation. The effect of preservation might be interesting in longer UV light waves. Literature about UV-B and its effect on quality does not seem to be covered much. According to food quality indicators, browning is one of the important aspect closely connected to the increase in temperature. (Ryer, 1997) The UV and browning of product exposed to UV-B wavelength is considered important for further investigation.

Firstly, browning changes of a food product is important in food handling and processing of products exposed to heat. For the food industry, browning index is important in case of quality grading and sorting to meet market requirements. Market requirements are necessary to meet in case the processed product is aimed to be preferable by certain consumers or overcome such market barriers. From the perspective of small-scale farm primary producers, basic marketing is essential to be competitive on the market (FAO, 2013). Increase in browning index resulting from the sun drying process is described as non-enzymatic browning similarly as processes of baking or frying and others affecting product quality.

The so-called Maillard reaction takes place in complex chemical reaction of sugars, amino acids, proteins and nitrogen compounds that are heated together. The reaction occurs during the process of heating in foods. Since 'we also eat with our eyes', the significance of Maillard browning in food exposed to heat is projected in acceptance or unacceptance by consumer. There is also a known disadvantage in nutritive values. The Maillard reaction produces antioxidant components as well. (Martins et al., 2000)

In general, there are certain characteristics of drying apples related to colour. For the sake of better understanding of the CIE LAB model according to CIE standards of colour results (2004), the parameters L*a*b* and their change by browning process are explained. The drying, respectively browning process is supposed to increase the values of a* and b* and decrease the values of L* and Hue (Pathare et al.,2013).

3. Aim of the Thesis

The objective of this work was to investigate effects of different glazing on the quality of the final dehydrated product with use of direct (integral) passive solar drier.

4. Materials and Methods

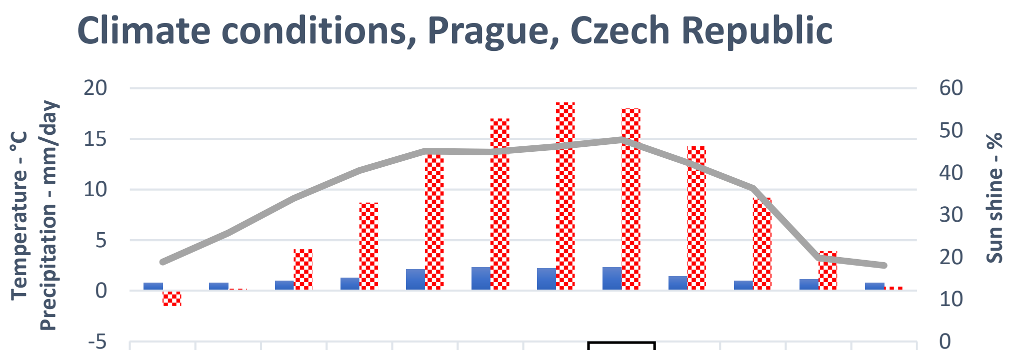
The methodology was based on design and construction of four experimental solar driers each with different material used for glazing layers including calculations and optimization of selected material for construction.

Several experiments for testing the quality of product (slices of apple) during drying under four different glazing layers (glass, polycarbonate, plastic glass, PP foil) were set up. During the experiments, parameters such as temperature, relative humidity, moisture content and final colour of apples were measured. Methods used were inspired by Perez-Gago et al. (2006).

4.1 Experiment Location

The drying was conducted in the Czech Republic, at the Czech University of Life Sciences Prague at the exact location of 50° 07' 48.1" N and 14° 22' 32.5" E at 280 m above sea level. Climate conditions were described as continental influenced climate with warm dry summers and moderately cold winters. Average year data were measured as 9 °C and 500 mm of precipitation. (CULS, 2017)

Figure 4.1 shows the temperature, precipitation per day and sunshine fraction in percentage. The data were based on location of the measurements conducted, its latitude, longitude and elevation and were based on Aguastat FAO (2017) Climate information tool. The experiment was conducted during the month of August. The data are showing that the highest sunshine fraction of the year (47.8 %) and mean temperatures (18 °C) are in August.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Prc. mm/d	0,8	0,8	1	1,3	2,1	2,3	2,2	2,3	1,4	1	1,1	0,8
Tmp. mean °C	-1,5	0,2	4,1	8,7	13,7	17	18,6	18	14,3	9,2	3,9	0,4
Sun shine %	18,8	25,7	33,9	40,5	45,1	44,9	46,2	47,8	42,4	36,3	19,8	18

Figure 4.1 Climate conditions, Czech Republic
(Based on: FAO, 2017)

The weather conditions of drying were measured by a meteorological station nearby to the experiment. Information about temperature and humidity were measured by Temperature and Relative Humidity Prober - Model HMP45C (Campbell Scientific Inc., USA). The data were gathered from the database of the meteorological station. These data were matched with the measures obtained from the drying experiment.

4.2 Design and Construction of Experimental Solar Driers

The experimental solar driers in form of boxes were designed as classical direct non-forced solar driers. Uncomplicated design construction meets the possibility to apply such drier for broader use, accessible with reasonable initial investment, for example. Hence, the drier was designed on an experimental scale being aware of possible obstacles to rescaling considering the materials used. Following steps were taken to design and build the drier:

a) The computer model of the box was designed, see Figure 4.4: Design of experimental solar drier, ISO view: (a) – wooden OSB deskand Figure 4.4
b) Following construction materials were used, Figure 4.4 shows the use materials according the following letters:
    a. Wooden box – OSB desk 18.0 mm thick
    b. Iron layer, absorber plate – 0.5 mm thick
    c. Acrylic matt colour – black (0199), water soluble
    d. Screws and profiles – screws for wood and iron, L profile to keep the transparent layer
    e. Transparent layers (glazing) – 31.6 cm × 54.0 cm
        i. Polycarbonate – 4.0 mm thick
        ii. Glass – 3.0 mm thick
        iii. PP foil – 0.04 mm thick
        iv. Plexi – 2.0 mm thick
    f. Net for drying material – 26.4 cm × 46.4 cm
    g. Anti-insect net – 40.0 cm × 10.0 cm (see Figure 4.5 - B)

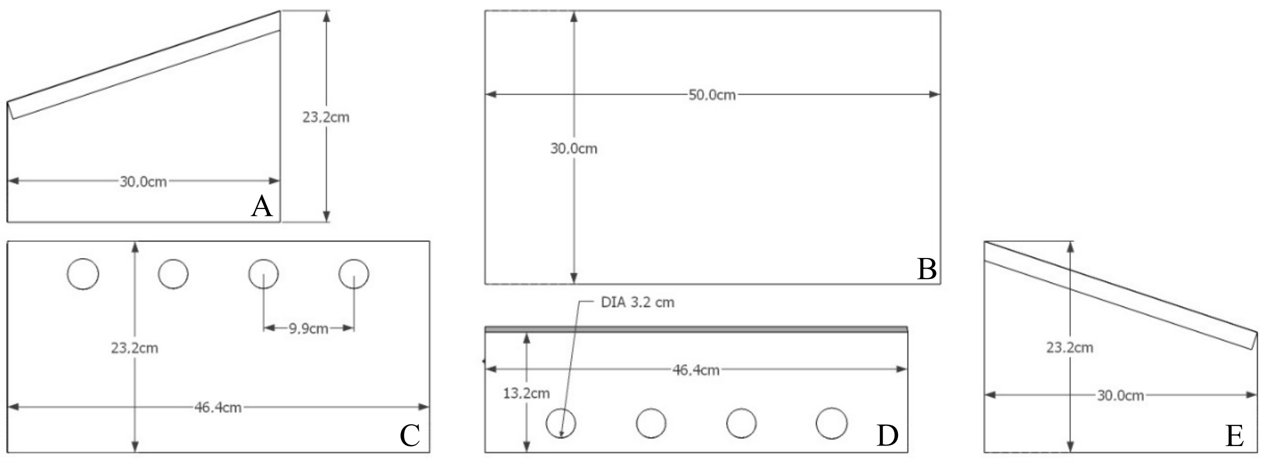


Figure 4.2 Layout of five OSB desk parts (1.8 cm thick) for shell of the experimental drier; A – right wall with attached "L" profile, B – bottom part, C – back wall with drilled holes, D – front wall with drilled holes, E – left wall with attached "L" profile

In total, four identical boxes were constructed. Firstly, we have started by cutting the (a) OSB desk (also known as "fake-board") into five different pieces shown in Figure 4.3 -

A. The cutting was done by hand-held circular saw with adjustable angel of cutting. All the cuts were done perpendicularly besides the piece C and D, see Figure 4.2. The front and back wall tops were cut by the angel of 18.4 °, as it was calculated by arctan (10 cm / 30 cm), see Equation 4.2.

$$\propto = \arctan \frac{a}{b}$$ **Equation 4.1**

For more details of the construction, see Figure 8.1 and 8.2 in the Appendices. Figure 8.3 was prepared to make your own paper model of the drier for better visualisation of the drier itself and for educational purposes.

$$\propto = \arctan \frac{a}{b}$$ **Equation 4.2**

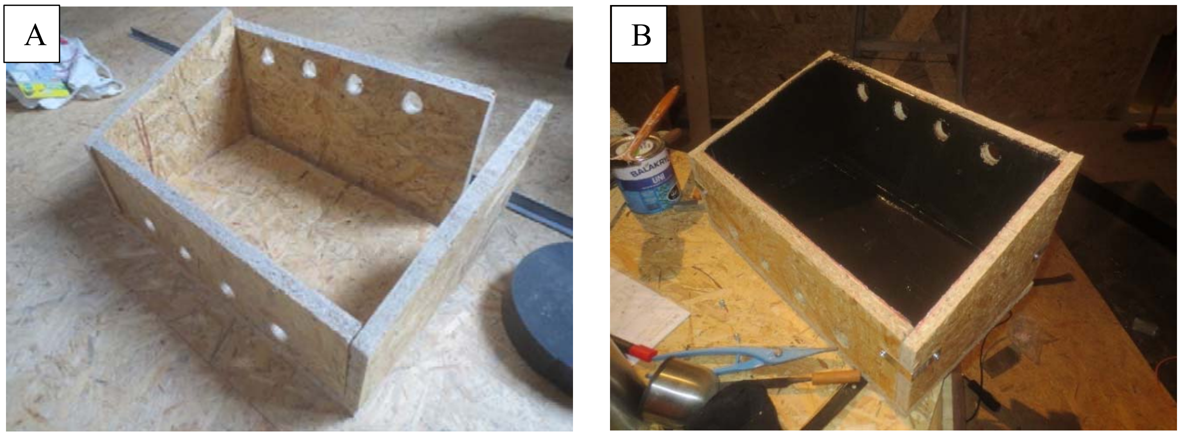


Figure 4.3 Construction of experimental drier: A – shell of the drier, B – drier with iron inner layer painted black

After the shell (a) OSB desks were cut and the holes in piece C and D were drilled (four on each part) with a diameter of 3.2 cm, all five parts were attached together by screws supported by iron "L" profiles.

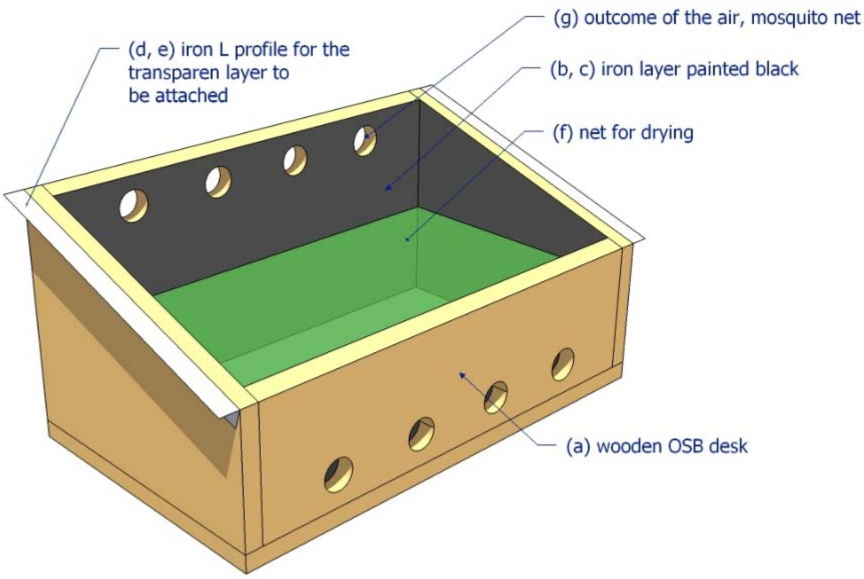


Figure 4.4: Design of experimental solar drier, ISO view: (a) – wooden OSB desk; (b, c) – iron layer painted back; (d, e) – iron L profile for the transparent layer to be attached; (f) – net for drying

4.2.1 Glazing Materials

Glazing material selection was done according the UV light transparency as well as according to material typically used for driers (Amer et al., 2010). The glazing materials were not picked with attention to the thermal resistance of material.

The UV transparency of glazing materials was measured during the pilot measurements and is presented by percentage of the level of UV irradiation passing through. Following parameters of glazing materials are presented, see Table 4.1

Table 4.1 Technical data; UV transparency (measured), Thickness (measured), Lambda (based in ČSN EN ISO 6946), U-value (calculated)

Glazing material	UV Transparency [%]	Thickness [mm]	Lambda [W/mK]	Thermal Resistance [m²K/W]
Polycarbonate	0.0	4.0	.20	.200
Glass	74.5	3.0	.76	.004
PP Foil	89.5	0.4	.22	.002
Plexi	75.2	2.0	.19	.011

In Table 4.1, the measured data of thickness and UV transparency were displayed. For determination of thermal resistance, the Lambda value must be known. These data and calculation of thermal resistance is based on ČSN EN ISO 6946 was used for the calculation, see Equation 4.2.

$$\boldsymbol{R = \frac{d}{\lambda}}$$

Equation 4.3

Thermal resistance of the material is only for orientation purpose. During the pilot study, the inside temperature was also affected by adhesion or the material resulting in higher heat loses in sections connecting with the glazing material.

The range of UV light measured was between 290 and 390 nm. Multiple measurements were carried with accuracy of 4 %. Data measured were used as baseline for further measurements.

Thermal transmittance (known as U-value), measured in watts per meter squared with change of 1 °K is the ability of certain structure to transmit heat over one Kelvin.

4.3 Drying Experiment

Measuring was done at the Faculty of Tropical AgriSciences in August 2015 and August 2016, four days of measures were done. Apples of 'Jonagold' variety were chosen as a popular apple possible to use for further processing due to its relatively large size of 220 to 260 g of weight during the harvesting. (Girard and Lau, 1995)

Fresh apples were collected for the experiment with similar appearance (size, colour and shape) to be measured. After the fresh apples were collected, the slices were prepared using an electrical slice cutter. All the slices were cut to form 3 mm thick slices (with precision of 0.2 mm). After the cutting, all the slices were measured by Vernier caliper measurement instrument.

Measurements of colour change were based on CIE LAB measure techniques. Temperature colour difference and browning index were analysed. Data on UV transparency were measured in each box to provide look at the differences of the colour, as the colour of food product is an important quality indicator (Pathare et al., 2013).

Following steps of measurement were obtained (4.3.1) before drying, (4.3.2) during drying and (4.3.3) subsequent methods within one measurement unit.

Before drying

Experimental driers were placed facing the South direction. See Figure 4.5 - A.

1. Slices of apples, were cut by ZELMER 393.5 (Zelmer, Poland) with a thickness of 3.0 mm thick. For each box three slices were prepared, twelve in total.

2. Parameters of temperature, by data logger Comet System S3121 (Comet System, s.r.o., CR) and colour, by Konica-Minolta CM-600d (Konica Minolta Business Solution, CR), were measured before the drying.

3. Four boxes were filled with apple slices, each with three pieces and covered by different transparent layers (Polycarbonate, Glass, PP foil and Plexi), see Figure 4.5 - B.

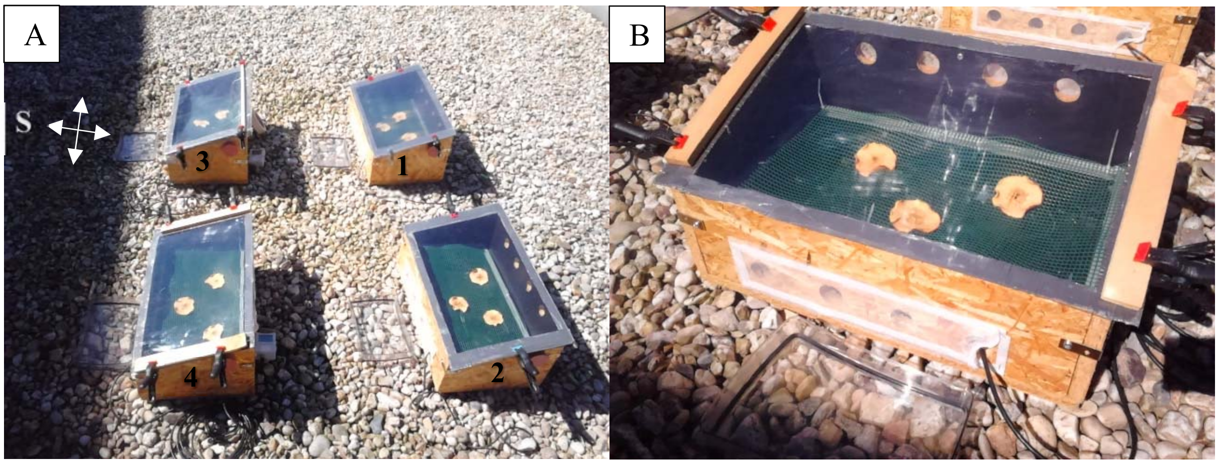


Figure 4.5 Drying experiment, A - orientation of the driers (1 - Polycarbonate, 2 - Glass, 3 - PP foil and 4 - Plexi), B – close up with Data Logger cable attached

During drying

Following parameters of measurements were obtained. Total drying time was six hours, total of seven measurements times were recorded (one before, five during the drying process and one after).

1. **Temperature** and **relative humidity** inside each drier during the whole experiment by data logger Comet System S3121 with external temperature and humidity prober. The data logger was calibrated according ČSN EN ISO/IEC 17025. Measuring data were automatically saved every 10 minutes of drying. The temperature was measured with precision of 0.4 °C and the relative humidity with precision of 2.5 %.

2. **Colour** of each slice of apple was measured three times during every hour of experiment. In total, nine measurement experiments were recorded by Konica-Minolta CM-600d. Following settings for measurement were set:

    a. standard illumination D65 (daily light with colour temperature 6504 K)

    b. Colour space of CIE LAB used.

    c. Observation angle of 10 ° chosen according CIE LAB standard 1964 (CIE, 2004)

d. SCI (Specular Component Included) colour observation – colour was measured within the light reflected

3. **Weight** of the apple slices was measured once in an hour by KERN 572-30 with accuracy of 0.1 mg.

a) **UV light** was measured inside the drier and outside in the same time during the drying experiment to describe UV light transparency of each glazing material used during the drying. This was measured by UV Light Meter YK-35 UV with second range accuracy of 0.01 mW/cm^2 with UV sensor spectrum from 290 to 390 nm wavelength. UV light was measured inside and outside of the driers; each comparison was done immediately after each other to get the true value of UV absorbance by glazing material.

4. **Final dehydration process** was done after the last drying in the driers in an oven to get the initial moisture content of the samples. Oven MEMERT 100-800 was used for that purposes.

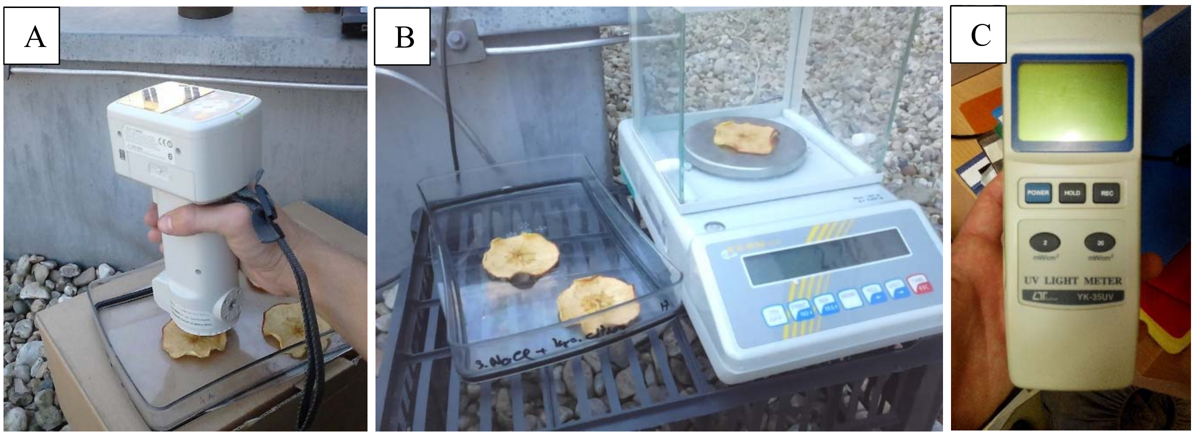


Figure 4.6 Equipment for measurements; A - Konica-Minolta CM-600d, B - KERN 572-30, C – UV Light Meter YK-35 UV

After drying, Calculations

Several calculations were conducted and different parameters were measured after the drying process, as used by Pathare et al. (2013), for example;

Colour data in CIE LAB colour projection were obtained by hourly measurements in form of L*a*b* coordinates. Every hour, each apple slice was measured at three spots and Equation 4.4 and Equation 4.5 were used for calculation of Hue and chroma attributes, respectively. The spots measured were picked up randomly in distance of second third (meaning form outer distance of ‘a’ to ‘2a’) from inner and outer edges of apple slice. For better understanding see Figure 4.7.

1. Hue is representing the wavelength or frequency of the radiation. In practice Hue is an attribute that is determined by a* and b* calculated as an angle, see $H_{ab} = \arctan\frac{a^*}{b^*}$ Equation 4.4.

$$H_{ab} = \arctan\frac{a^*}{b^*}$$

Equation 4.4 Hue attribute, degrees

2. Saturation (also described as Chroma) is representing the level of white light present. Saturation is then mixed with Hue to allow “washed out” colours to be described, see Equation 4.4.

$$C_{ab} = \sqrt{a^2+b^2}$$

Equation 4.5 Chroma attribute, -

3. Brightness (also described as Lightness, Luminance or Value) stands for the intensity of the colour or number of protons reaching the eye.

For determination of initial moisture content, the samples were placed after each drying day into oven for 24 hours at 105 °C and then the weight was measured. The material moisture content was calculated from following data, see Equation 4.5.

$$w(\%) = \frac{mw-md}{mw}\times 100$$

Equation 4.6

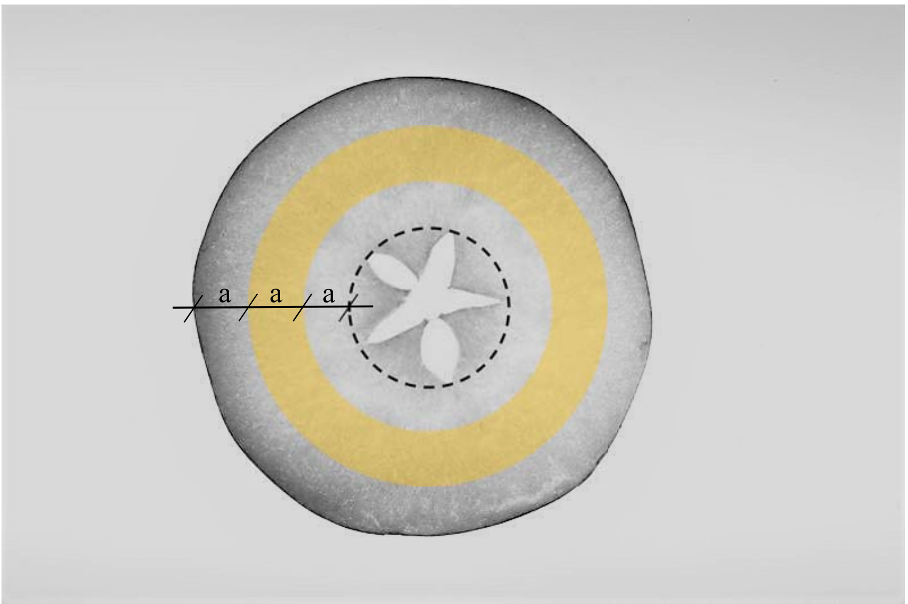


Figure 4.7 Slice of an apple, model example for colour measurements; distance between inner and outer edges is divided into three rings. The middle ring is valid for measurements.

4.4 Statistical Analysis

All the results were carried out with use of IBM SPPS© version 24, 2017 (International Business Machines Corporation, ČR) computer statistical application and Microsoft Excel© 2016. For comparing means of inside temperature, browning index and chroma between the boxes, one-way analysis of variance (ANOVA) was used. Subsequently, in a case of significant result of ANOVA, Tukey honest significant difference (HSD) test was applied as post hoc test. In addition to that, correlation between relevant variables (temperature, browning index) was calculated, with use of Pearson's correlation coefficient as the most suitable coefficient for two metric variables.

From the post-hoc tests the Tukey HSD (honest significant difference) was used to see all the pairwise comparison between groups, it uses the range and standard deviation to for these sub-sets (number of sub-sets is based on variation and standard deviation).

5. Results and Discussion

Following results were obtained from the gathered data. These results are based on representative data analysis.

Data measured during the experiment in drying boxes are shown in respect of the four separate dryings of each with different glazing material. Results carried out are represented either as data measurements during two separate measuring days or mean values of the data gathered.

Table 5.1 Ambient temperature, humidity and radiation

	Day 1			Day 2		
	Temperature [°C]	Humidity [%]	Radiation [kJ/m2/10min]	Temperature [°C]	Humidity [%]	Radiation [kJ/m2/10min]
Maximum	30.4	52.8	452.8	28.3	56.7	450.6
Minimum	22.3	23.8	283.7	21.7	33.5	281
Mean	27.1	36.6	399.3	25.6	42.9	394.8
Standard deviation	2.73	9.34	53.35	1.86	7.30	53.89

Table 5.1 shows the measured values during the drying process. Temperature, humidity and radiation during day one and two. The temperatures of both days are showing similar values, overlapping by their confidence intervals of the mean values. The mean values during the drying experiments was observed as 26.4 °C, with the minimum of 21.7 °C and the maximum of 30.4 °C. Figure 2.1 shows the values of day 2 projected in graph. Right scale is representing the radiation; left scale shows the temperature and humidity during of the drying time period.

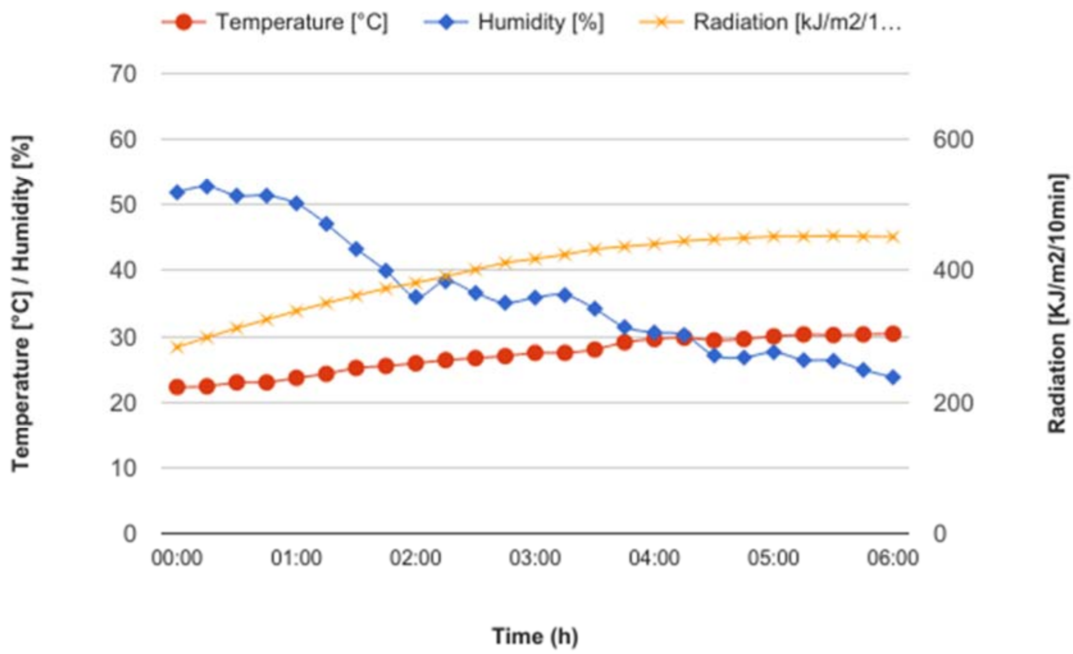


Figure 5.1 Temperature, Humidity and Radiation during drying based on meteorological data

5.1 *Colour Changes in Time*

Table 5.2 shows the selection of initial and final colour measurements in CIE Lab and the Hue angle, showing the initial and final degree of Hue. The table is showing the colour changes in the total drying time of six hours. The Change in Hue angle decreases from yellow (at 90°) or nearly yellow towards red (at 0°) in case of all the glazing materials, both days.

Table 5.2 Colour values measured, change from initial to final colour

		Initial colour			Final Colour			
		L*	a*	b*	L*	a*	b*	Hue [degrees]
Day 1	Polycarbonate	73.77	2.18	27.67	72.16	8.06	39.05	86, 79
	Glass	73.60	2.45	28.72	69.05	11.16	38.98	85, 74
	PP Foil	76.80	0.72	23.10	71.60	8.65	34.54	88, 76
	Plexi	75.56	1.40	25.27	71.25	9.93	36.12	87, 75
Day 2	Polycarbonate	76.29	0.39	23.17	70.04	8.82	36.12	89, 76
	Glass	72.17	1.68	26.58	61.69	12.26	35.97	86, 71
	PP Foil	74.85	0.14	22.34	70.26	8.96	34.27	90, 75
	Plexi	72.76	1.75	28.18	67.51	12.02	38.60	86, 72

Colour progress during the experiment shows various linear trend of drying parameters of CIE LAB space. These measured data are representing drying process trend in all the driers. Following graph shows the change in given values, see Figure 5.2.

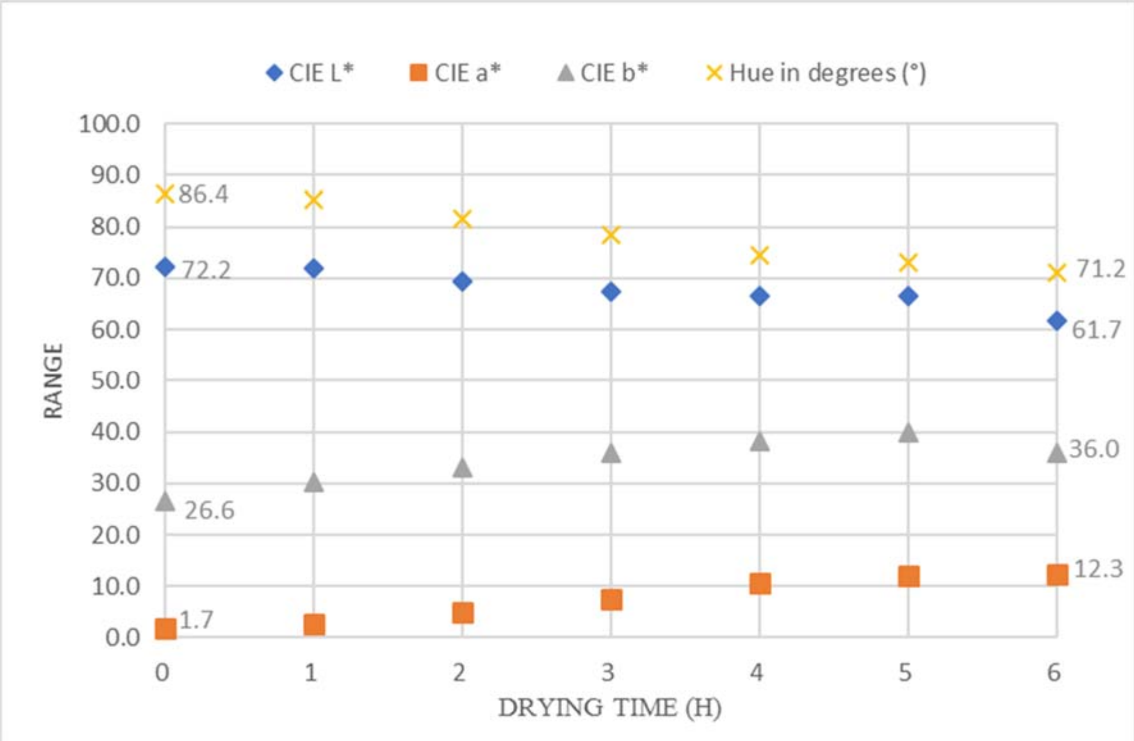


Figure 5.2 Change in CIE LAB parameters during drying; L* – Lightness, colour coordinates a* and b* are for reddish/greenish and yellowish/blueish respectively, Hue in Degrees

Figure 5.2 is representing the change of colour drying of apple slices and browning respectively. All the measured data are as follows. The decreases of lightness (L*) from 72.2 to 61.7 as well as Hue decreases on the colour space (turn clockwise, see **Chyba! Nenalezen zdroj odkazů.**) from 87.4° to 71.2°. The CIE a* and b* parameters shifted from 26.6 to 36.0 and 1.7 to 12.3 and therefore increased. In all the shown cases, the trend is linear with R2 values shown below.

$y = -1.61x + 72.82$ $R^2 = 0.91$ **Equation 5.1** L* - lightness

$y = 2.01x + 1.31$ $R^2 = 0.96$ **Equation 5.2** a* - reddish/greenish

$y = 1.87x + 28.65$ $R^2 = 0.76$ **Equation 5.3** b* - yellowish/blueish

$y = -2.73x + 86.82$ $R^2 = 0.98$ **Equation 5.4** Hue – angel of colour

Equations 5.1 and 5.4 have a decreasing trend, negative signed is present by the x variable, these are representing the mentioned L – lightness and Hue. On the other hand, the Equations 5.2 and 5.3 have increasing trend in time that applies for parameters of a* and b* of the colour coordinates. Therefore, our measurements prove the general model of drying of apple slices - the positive a* and b* tends to more reddish and yellowish colours in general.

These results correspond to the results of Pathare et al. (2013) as it is introduced above. During the drying process, the decreases of lightness (L*) and Hue decreases on the colour space occurred and the a* and b* parameters increased.

5.2 *Influence of Temperature on Browning Index*

The correlation between Temperature and Browning index was measured separately for each glazing material used. Bivariate Pearson Correlation test of the strength of a linear relationship shows association between temperature inside the box and the Browning index respectively and Colour difference, see Table 5.3.

Table 5.3: Bivariate Pearson Correlation done separately for Polycarbonate, Glass, PP Foil and Plexi of Temperature and Browning index. Analysis based on hourly measurements of 9 records per an hour over 7 hours. (N=63).

Temperature (I)		Polycarbonate	Glass	PP Foil	Plexi
Browning Index (J)	Pearson Correlation (I, J)	.90*	.88*	.84*	.96*
	(Significance)	.000	.000	.000	.000

*. Correlation is significant at the 0.05 level (2-tailed).

Correlation was tested under the significance level of 5 %. An analysis of Bivariate Pearson Correlation showed that the effect of Temperature on Browning Index is significant, p = .000 and strong (Pearson's ρ between 0.84 and 0.96) in all the cases in .

Table 5.3. These results correspond to the studies of Ryer (1997) and Krokida et al. (1998), which prove that the browning of the drying product is closely related to its exposed temperature.

5.3 Influence of Glazing on Drying Process

Process of drying was measured in different boxes to see the response of colour appearance over different glazing materials used for drying.

Firstly, the temperature and humidity are analysed. Figure 5.3 shows how the temperature changes separately for glazing materials (polycarbonate, glass, PP foil and plexi) during the six drying hours. During the second hour, the highest difference of temperatures was measured from the mean values of 31.0 °C to 44.3 °C. The humidity inside the driers shows the decreasing tendency, lower than ambient humidity.

With lower humidity, the higher the temperature is observed. This fundamental drying tendency corresponds to the drying process explained, for example by Earle (1983) or Tobergte et al. (2013) and many other researchers.

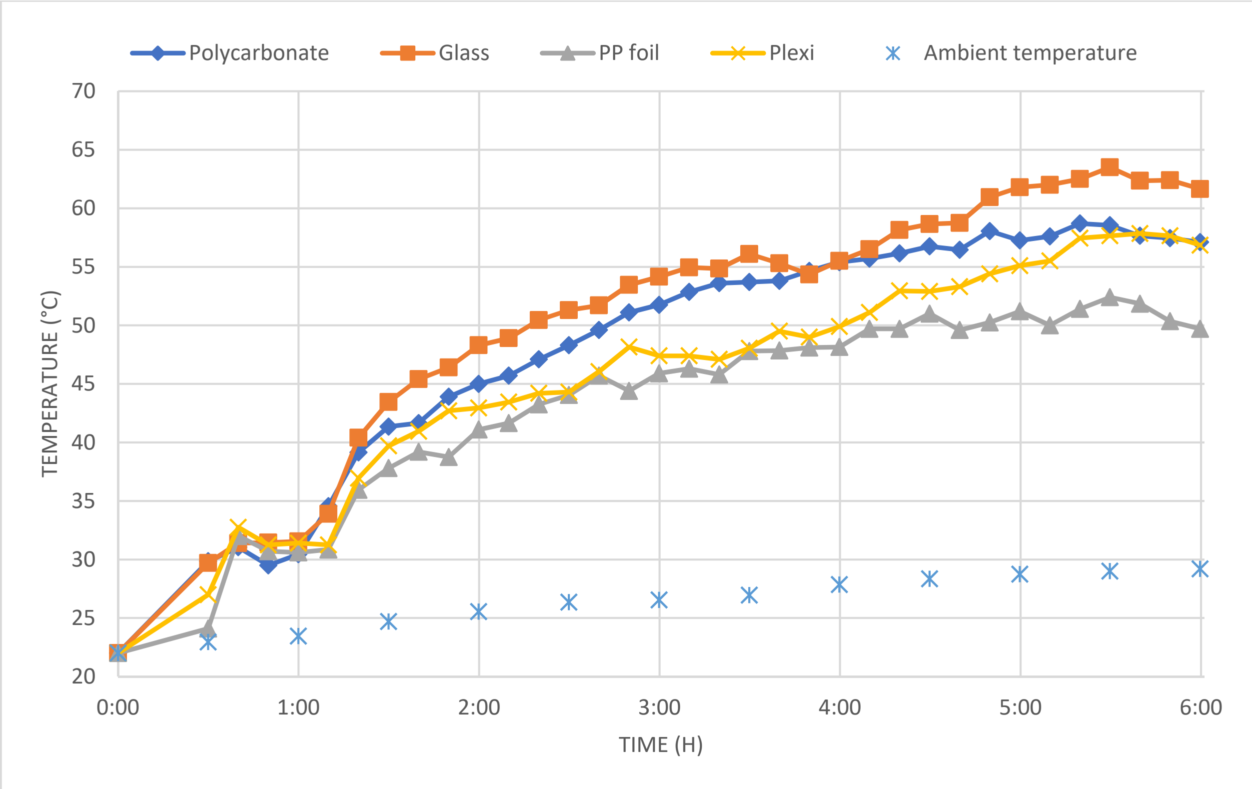


Figure 5.3 Temperature changes during drying process for different glazing

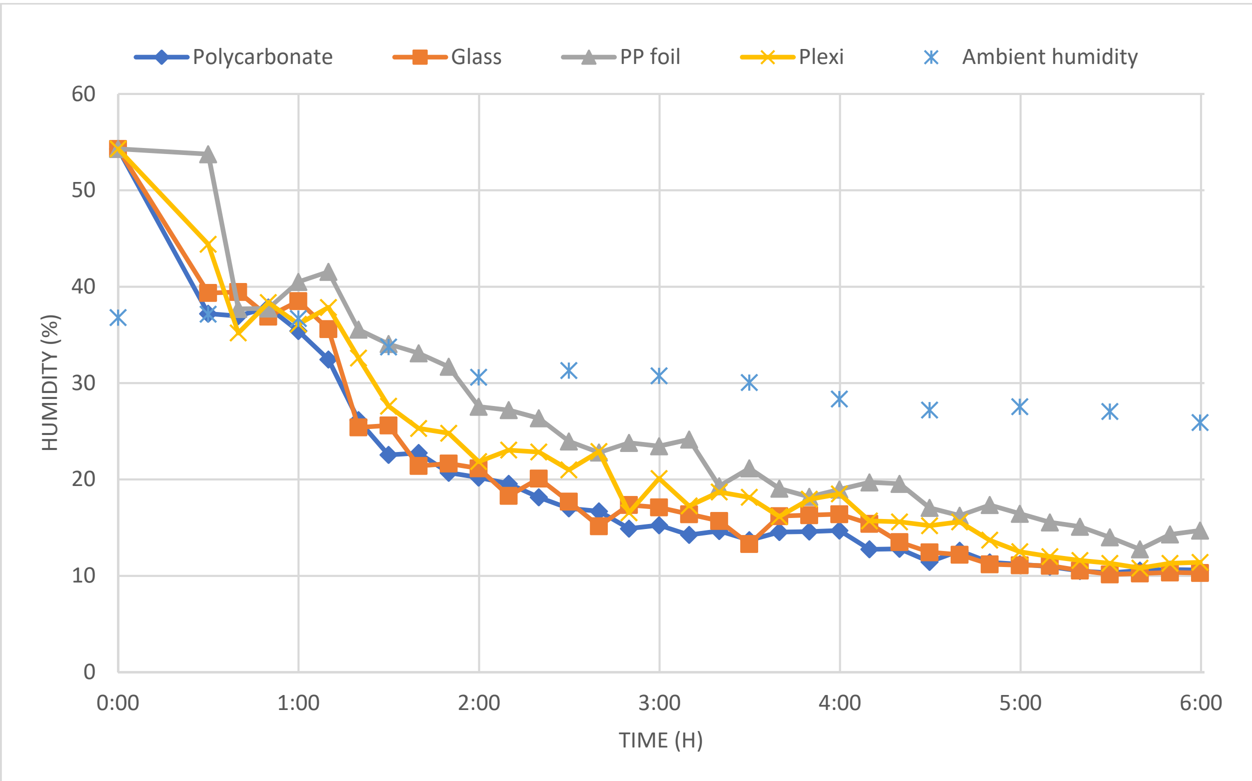


Figure 5.4 Humidity change during drying process for different glazing

Form the Table 5.4 Temperature Temperature and Humidity inside driers, the lowest temperatures are observed by PP foil with mean temperatures of 41.8 °C, the highest by glass glazing of 52.1 °C. Descriptive statistics of temperature measured shows that the drying of product did not take place equally over the driers due to different glazing material used. The evidence of lowest temperature and highest humidity of mean values (41.8 °C, 24,5 %) and extremes (50.7 °C, 12.8 %) by PP Foil will be considered in following text.

Table 5.4 Temperature and Humidity inside driers

Glazing material	Mean* temperature s	Standard Error (*)	Maximum temperatures	Mean^{X} humidity	Standard Error (^{X})	Minimum humidity
Polycarbonate	51.1	1.96	62.3	18.1	1.46	10.3
Glass	52.1	2.10	65.5	18.9	1.55	10.2
PP foil	41.8	1.41	50.7	24.5	1.68	12.8
Plexi	45.6	1.73	59.2	21.0	1:54	10.8

Secondly, the temperature inside the drying boxes is compared to see the relation with Browning Index measured from previous section. An analysis of variance (ANOVA) showed that there is significant difference in inside temperature between the drying boxes, F = (3, 268) = 8.29, p = .000. It can be concluded that there is an effect of type of glazing on inside Temperature. Tukey HSD (honest significant difference) post-hoc test was carried out for multiple comparisons (see Table 5.5). The Significance shows that there is no significant difference within the sub-sets (I, II, III) as these groups are split by so-called honest significance difference, to see all the pairwise comparison.

Table 5.5 Influence of drier glazing on Temperature

Temperature (°C)	N	I	II	III
PP foil	68	44.03		
Plexi	68	46.59	46.59	
Polycarbonate	68		49.16	49.16
Glass	68			51.53
Significance		.375	.372	.443

(Means for groups in homogeneous subsets are displayed.)

ANOVA post-hoc Tukey HSD test

Data between different driers are showing the mean values of inside temperature. From Table 5.5, the lowest temperature during the drying process was recorded in case of PP foil and the highest for glass cover drier. Tukey test shows the differences measured within the subsets (I, II, III) that are not significantly different under tolerance level of 5 %. Following significant differences are observed, also seen from Table 5.5.

- Significant difference in inside temperature was found between the drier with PP foil (44.03) and the drier with Polycarbonate cover (49.16).

- Significant difference in inside temperature was found between the drier with PP foil (44.03) and the drier with glass cover (51.53).

- Significant difference in inside temperature was found between the drier with Plexi (46.59) and the drier with glass cover (51.53).

An analysis of variance was conducted to compare colour of samples in different driers. There was a significant effect of type of drier on Browning index, F = (3, 68) = 81.71, p = .000, see Table 5.6.

Table 5.6 Influence of drier glazing on Browning Index

Browning Index	N	I	II	III	IV
PP Foil	18	55.48			
Polycarbonate	18		58.75		
Plexi	18			62.45	
Glass	18				66.24
Significance		1.000	1.000	1.000	1.000

ANOVA post-hoc Tukey HSD test

As well as in the case of inside temperature, the lowest and highest Browning Index means were measured in driers with PP foil drier and Glass drier, respectively.

- Post hoc comparisons using the Turkey HSD test indicated that the mean score of the Browning Index between all four driers is significantly different.

Finally, to see the chromatic colour change, the chroma was tested separately over the driers. The results are showing significance in PP foil covered drier in case of PP foil as it is classified by Tukey test in separate subgroup. An analysis of variance showed that the effect of glazing type on Chroma was significant, $F = (3,68) = 35.92$, $p = .000$.

Table 5.7 Influence of drier glazing on Chroma

Chroma	N	I	II
PP Foil	18	35.52	
Polycarbonate	18		38.53
Plexi	18		38.94
Glass	18		39.28
Significance		1.000	.269

ANOVA post-hoc Tukey HSD test

Table 5.6. presents the Tukey HSD results of final Chroma light parameters.

- The only significant differences were carried out between PP Foil drier and all three driers. The other three driers were not significantly different from each other.

From these results of the analysis of variance, the colour indicators as Browning Index and Chroma at the end of the measurements are proving the effect of temperature on colour change but not of the UV light. In all the tests the lowest temperature and lowest colour changes were observed by the glazing (PP foil) that has the highest transparency of UV-B light. These results suggest that the UV-B light does not have significant effect on colour change therefore does not affect quality of dried product, in means of colour quality indicator.

Following the statistical analysis, we may proceed to discuss the results of drying experiment in case of temperature and colour indicators with available literature.

Du et al. (2014) did broad testing of UV-B light effects on various post-harvest products, that were exposed to direct radiation of diverse time amounts. The results were different over diverse measured products; some product colours were significantly affected by the UV. However, UV-B irradiation did not have effect on post-harvest apples (Red delicious and Golden delicious).

Another study, based on artificial UV-C light effects was described by Gómez et al. (2010). Slices of apples were exposed to irradiation for different 'rest' times. Browning was significant only in case of slices that were cut and rested for few days before irradiation took place. But more importantly, the slices exposed to irradiation were less affected to microorganism growth.

The colorimeters for today's use measure CIE LAB coordinates only over a small spot of the item. This could result in not very representative item colour measurements. "In order to carry out a detailed characterization of the colour of a food item, and thus to more precisely evaluate its quality, it is necessary to know the colour value of each point of its surface" (Pathare et al., 2013). This is important to consider especially in case of heterogeneous items such as food products. (León et al., 2005; Pathare et al., 2013). However, there was no comparison done between the mentioned techniques such as RGB digital images with multiple measurements with colorimeter. For the further studies, it would be valuable to compare these colour measuring instruments for food product analyses.

6. Conclusions

Drying of post-harvest products is a very complex process of diverse chemical, physical and nutritional factors. In this work, we have focused only on a small fraction of all the quality indicators. The chemical changes of browning, as one of the important indicators of quality, are directly connected to the overall drying process. In the theoretical part, the drying process was examined from different perspectives as the methodology was based on these fundaments and on previous experiments. The drying results were showing the complexity of such process. The data were sorted either by the driers with different boxes or by the measured parameters and the results were analysed.

In the overall drying process, the trend in colour change seen in CIE Lab parameters was found, compared and approved by the available literature. The correlation between Temperature and Browning Index development was found significant among all the experimental driers. Afterwards, these data were analysed separately for each experimental drier and interesting results were found. The apple slices exposed the most to UV irradiation (PP Foil, 89 % UV) had the lowest browning index measured and the Chroma change was significantly lower than in other three driers with lower UV transparency. On the other hand, the temperature inside PP foil was the lowest. This brought the conclusion that the temperature correlates with colour change, but the UV light and colour do not correlate.

The conclusion shows that the UV light does not affect the quality of dried product, specifically of slices of apples. During the experimental drying in case of PP Foil, temperature did not exceed 55 °C due to the high thermal transmittance of the foil. The moderate temperatures resulted in low change in colour. In this case, lower temperature was beneficial, but in practice drying process must be considered individually. Factors such as temperature, humidity, size of drier, type of drying product, sunshine or latitude play a role.

All the colour data gathered were carried out by multiple measurements. However, another trend is to measure colour in quantitative approach by scanning the whole surface of the product. The question for further studies would be to compare qualitative multiple colour measurements with quantitative digital scanning techniques.

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8. Appendices

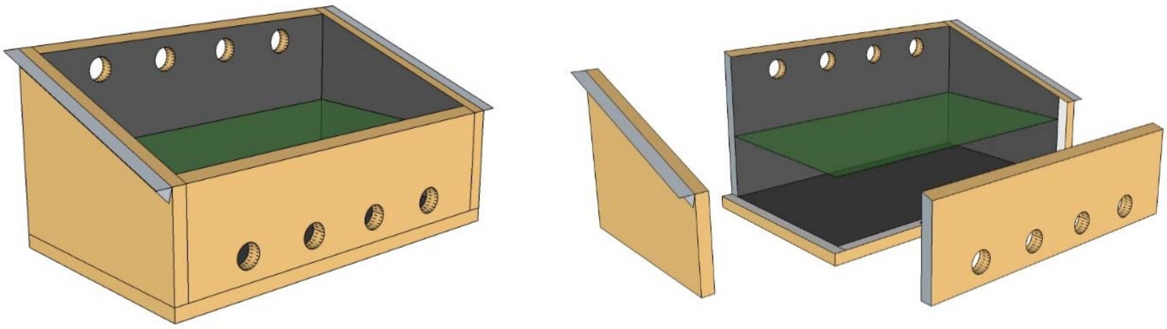

Figure 8.1 ISO projection, model of solar drier

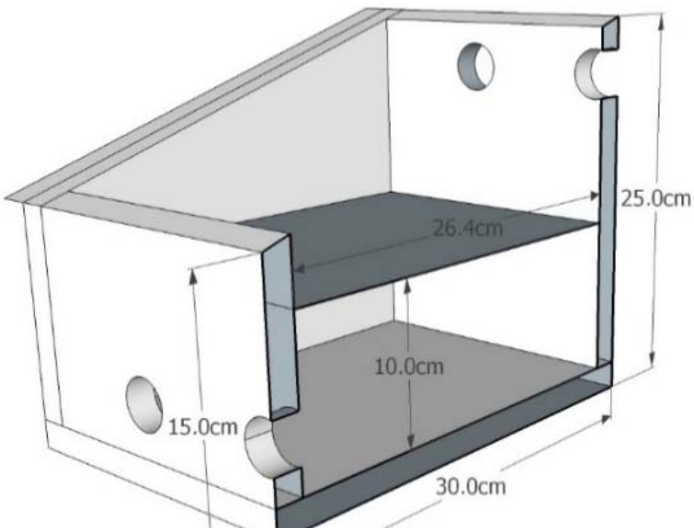

Figure 8.2 ISO projection, cross-section of experimental drier

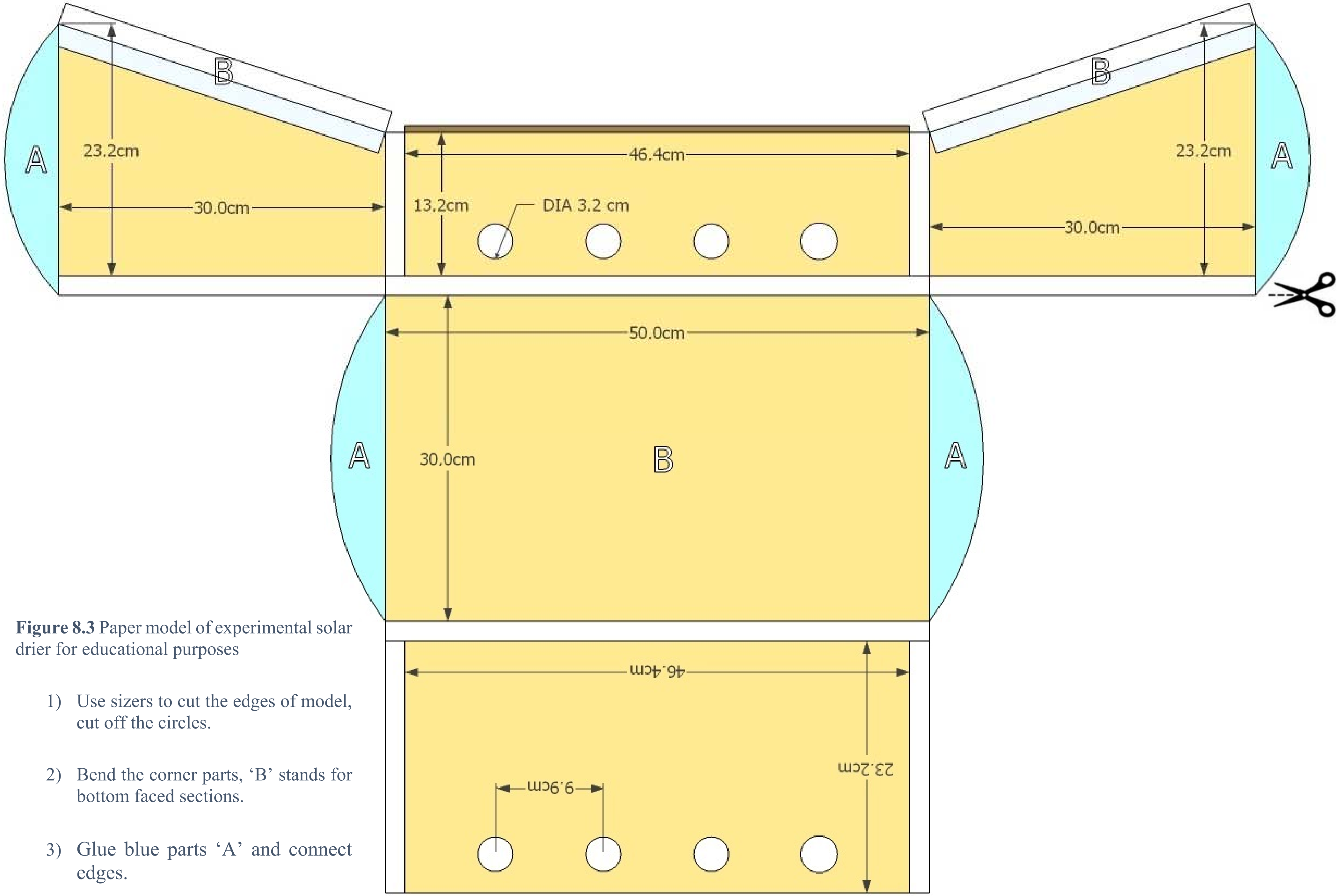

Figure 8.3 Paper model of experimental solar drier for educational purposes

1) Use sizers to cut the edges of model, cut off the circles.

2) Bend the corner parts, ‘B’ stands for bottom faced sections.

3) Glue blue parts ‘A’ and connect edges.