PERFORMANCE OF NOVEL PORTABLE SOLAR DRYING TECHNOLOGIES FOR SMALL AND MID-SIZE GROWERS OF SPECIALTY CROPS UNDER INDIANA WEATHER CONDITIONS

by

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To my grandmother Magdalena, who was ahead of her time and who in her search of freedom opened the doors for me, to be the woman I want to be, without limits.

To my parents, who taught me with love the value of discipline, education and persistence.

To my brother and his great courage to be unique and make me unique.

To Antonio, for taking out the best of me with his unconditional love.

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ABSTRACT

Solar drying of specialty crops like fruits and vegetables is widely used for product quality preservation, shelf-life extension, and adding value towards marketing purposes. Drying involves heat and moisture transfer from the product, thus it reduces costs of transportation and storage due to the decrease in volume and increase in nutrient density of the dried product. Therefore, it is one the of the most important unit operations for minimally processed foods among small and mid-size farmers, processors and even large food processors. Moreover, drying is an energy-intensive operation that represents between 10% to 15% of the total energy consumption by food industries. While open-air sun drying of crops is the most commonly used method in the world especially by small and mid-size growers, there is a lack of commercial solar drying technologies available for use by these growers. Additionally, a lot of the research conducted on various types of experimental solar dryers are mostly based on experimental drying practices, without mathematical considerations of the drying kinetics, and minimal evaluation of final product quality in comparison with the common open-air sun drying method, which is affected by contamination from external factors such as dust and other foreign matter. Quality and drying kinetics affect the efficiency/performance of the dryers, and not considering them can increase production cost, and reduce the profit of the operation. Thus, the use of models for predict drying behavior, and effects of the drying methods on product quality are needed as engineering aspects for the evaluation of drying technologies and their improvement.

The overall goal of this thesis was to study the performance of two related portable multipurpose solar dryers, Dehytray^{TM} and Dehymeleon^{TM}, in comparison to open-air sun drying by drying tomatoes, apples and mint under West Lafayette, Indiana weather conditions. Thin layer drying tests were conducted on tomato slices, apples slices and mint leaves, with three temperatures [24°C (75°F), 35°C (95°F) and 54 °C (130°F)], and an airflow velocity of 1 m/s to determine the drying kinetics of these products during diurnal drying cycles typical for solar and/or open-air sun drying. Subsequently, field drying tests were conducted for tomatoes slices, apples slices and mint leaves with the two solar drying technologies (Dehymeleon^{TM} and Dehytray^{TM}) and open-air sun drying using uncovered Dehytrays as the control. The average temperatures achieved for these technologies were 45°C (113°F), 60°C (140 °F) and 27°C (80.6 °F) for the Dehymeleon^{TM}, Dehytray^{TM} and open-air sun drying, respectively. Moisture diffusivity were in

the order of 10^{-4} to 10^{-9} (m^2/s) for the different methods, depending directly on the product, temperatures and air flow inside the drying chamber.

Quality attributes (color, vitamin C and microbial growth) were measured before and after the field drying tests. Color difference (ΔE) for Dehymeleon™ solar dryer showed the least variation compared with the fresh products. However, for the Dehytray™ ΔE increased due to the impact of its higher temperature and direct sunlight exposure that led to Maillard reactions and caramelization in the case of tomatoes and apples slices. Additionally, vitamin C (Ascorbic acid) content for tomatoes and apples slices was affected for the high ranges of temperatures reached inside the Dehytray™. Denaturing of vitamin C was less observed for Dehymeleon™, maintaining values of 166 mg/100 g dm for tomatoes, and 104.2mg/100g for apples slices. There was no significant difference ($\alpha = 0.05$) in the microbial growth for the Dehytray™ and open-air drying compared to the fresh product, however, there was significant difference for the Dehymeleon™ when drying tomatoes and apples slices, without up one log reduction on the original microbial population. In the case of mint, Dehymeleon™ had a 2.3 log reduction, which is similar to L-lactic acid sanitizer achieved by another study in the literature, compared with 0.4 log obtained by the Dehytray™ and 0.47 log obtained by open-air sun drying. The differences in microbial growth were observed because the temperatures inside the drying chamber of the Dehymeleon™ was low and product moisture content was above the safe equilibrium moisture content (EMC) for both tomatoes and apples during the early critical hours at the onset of the drying process, which was favorable to mold growth. The lack of a fan to intermittently or constantly flush out humid air released from the crop dried in the Dehytray™ negatively affected its performance. The insufficient airflow in the drying chamber of the Dehymeleon™ and its inability to achieve the high temperatures observed in the Dehytray™ negatively affected its performance. Both solar dryers, Dehymeleon™ and Dehytray™ achieved high hygienic condition during drying due to their enclosed chambers than protected the crop from contaminant in the environments. Their portability and design for large-scale manufacturing and deployment are a positive development that would be helpful to small and mid-size growers, as well as households (home gardens). Areas for further research were highlighted.

Keywords. Solar drying, sun drying, food quality, diffusion, drying kinetics, fruits and vegetables, thin-layer drying

CHAPTER 1. INTRODUCTION

This thesis presents a study about the performance of two novel portable solar drying technologies, Dehytray ™ and Dehymeleon™, which were developed at Purdue University by Professor Ileleji Group, and currently being commercialized by JUA Technologies International LLC, based in West Lafayette, Indiana. Field drying tests conducted in West Lafayette, Indiana were conducted for three selected crops: tomatoes, apples and mint using both portable solar drying technologies in comparison with open-air sun drying as the control. Thin-layer drying experiments were conducted in the lab using a thin-layer drying apparatus to understand the thin-layer characteristics using both empirical and theoretical modeling. The performance of the solar drying technologies was evaluated by drying duration, color change/vitamin C retention, microbial loads during and after drying using appropriate statistical tools.

This chapter highlights the problem of lack of commercial portable dehydrators for small and mid-size growers and provides justification for the need to evaluate new technologies that allow growers/citizens to preserve food, reduce post-harvest losses and retain the nutritional value in dehydrated (dried) food products, while adding value to the products to help income generation by small and mid-size farmers in both developed and developing countries. In section 1.1, research justification was addressed with an overview of the financial cost of global post-harvest losses, nutrient-rich agriculture and value addition to small and mid-size growers. The lack of ready to use off-the-shelf commercially available solar crop dryers, in spite of the large body of work that has already be conducted globally on solar crop drying is discussed in the context of the two novel portable drying technologies, Dehytray™ and Dehymeleon™ tested in this thesis. The research hypothesis, main goal and objectives of this thesis are presented in Section 1.2. Finally, section 1.3 describes the reminder of the thesis chapters.

1.1 Research Motivation

Solar drying is one of the most common techniques used for food dehydration, and consequently for food preservation known throughout civilization. Reducing moisture content in crops and foods drops water activity to a level that will not support microbial growth. Thus, drying enables the foods and crops to be stored dry without the further addition of energy in storage such as is the case with refrigeration, while keeping the quality of the product in terms of nutrients like vitamins and antioxidants. In this context, value is added to the crop product due to the extension of shelf life and thus has the advantage of preserving natural nutrients that can complement dietary requirements. Therefore, growers would be able to increase their income based on the added value and the off-season sales of the dehydrated products. To accomplish these, over the years many advancements have been done to improve the efficiency and drying capacity of thermal dryers with various design.

Open-air sun drying is by far the most common method of drying used in developing and developed countries for drying specialty crops (Marouzé et al., 2014). However, current techniques of open-air sun drying have a low heat gain from solar radiation and thus low water removal capacity compared with solar drying. Therefore, sun drying processes in open-air can extend for several days under unfavorable weather conditions. Thus, crops are exposed to dust, insects, vermin and livestock for extended drying periods and become quite contaminated with foreign matter (debris, feces, animal hair, etc.), which would cause the final dried product to degrade in quality. In some cases, there is repeated drying and rewetting of the crop from rain during the drying duration, which causes elevated moistures to be maintained for a long period of time such that mold begins to grow before achieving a safe storage moisture.

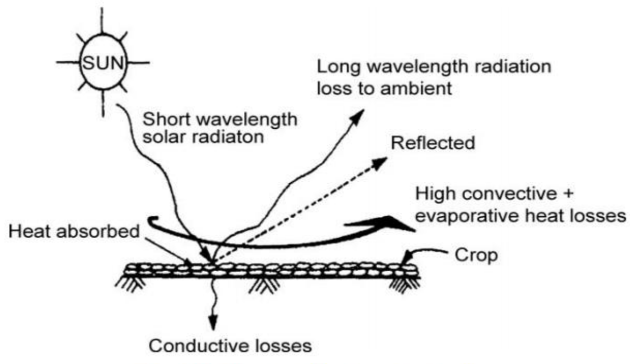

Figure 1.1. Working principle of open sun drying. (Sharma et al., 2009)

The consequences of delayed drying and the lack of a standardized process also impact product quality and nutritional values directly. Another inherent disadvantage from open-air drying is contamination due to the direct exposure to the environment, including external factors such as birds, insects and pollution. These phytosanitary contaminations on dried products are not desirable in national and international markets. Unlike open-air sun drying, a solar dryer constitutes a specialized enclosed structure, where the drying process is controlled, the product is protected from rewetting by rain and the produce is protected from contamination by the elements (Ekechukwu and Norton, 1999). Since the products are protected and the drying time is reduced significantly, the quality of dried product obtained by solar dehydration is better than open-air sun drying (Suresh Kumar, 2010).

Although sun drying techniques have been used and studied for a long time, the need for improvement, research and creation of standardized methods is still lacking. Therefore, this thesis investigated the performance of two related solar drying technologies designed to achieve high quality dried product (better nutrition and phytosanitary qualities) of dehydrated specialty crops.

One of the solar drying technologies, Dehytray™ was commercially launched in the market in December 2018, while the other technology, a larger unit, the Dehymeleon™ is still under development toward commercialization. While the Dehytray^{TM} is currently being tested in several countries - USA (Indiana, Georgia and California), Nigeria, Kenya, Senegal, South Africa, Ghana, Tajikistan and Peru, this thesis focuses only on field trials conducted in Indiana. Field trials on the Dehymeleon^{TM} was conducted using prototype version III.

1.2 Objectives

1.2.1 General Research Goals

The overall goal of this thesis was to study the performance of two related multipurpose solar dryers, Dehytray^{TM} and Dehymeleon^{TM}, under West Lafayette, Indiana weather conditions. Both solar dryers were developed at Purdue University under a USAID grant to the Feed-the-Future Lab for Post-Harvest Handling and Food Processing (FPL) led by Purdue University. Two of four objectives of FPL were to improve drying and storage of cereals by smallholder farmers in the humid tropics and to drive the value chain through processing and improved nutrition (USAID FPL, 2014), with focus in Senegal and Kenya. JUA Technologies International, LLC. a three-year old start-up is commercializing the Dehytray^{TM} and Dehymeleon^{TM} and working with Purdue University and Fort-Valley State University, Georgia under a USDA-NIFA Grant#: 12236690 supporting this research effort, to focus on the techno-economics of dehydrating specialty crops grown on small and mid-sized farms in Indiana and Georgia. Additionally, research collaboration was also developed with Dr. Rebecca Milczarek with the Healthy Processed Foods Research Unit, USDA Agricultural Research Service (ARS) Lab in Albany, California. This collaboration enabled me to spend one month in the summer of 2018 conducting field experiments on the drying of tomatoes and nectarines using the Dehytray^{TM} in comparison to open-air sun drying under California weather conditions. Note that drying and dehydrating mean the same thing, the process of moisture reduction, and would be used interchangeably in this thesis. The overall goal of this part of the project was to determine the technical requirements and end dried product quality for on-farm drying of three selected specialty crops (tomato, apple and mint) using the Dehytray^{TM} and Dehymeleon^{TM}, with relevance to small growers in Indiana.

1.2.2 **Specific Objectives**

The specific objectives of this thesis were:

1. Determine the drying characteristics of three selected specialty crops (tomato, apple and mint) using thin-layer drying experiments to simulate diurnal drying cycles typical of solar and/or open-air sun drying.
2. Evaluate the technical requirements and drying performance as measured by the drying rate of two solar crop drying technologies (Dehytray^{TM} and Dehymeleon^{TM}) for specialty crops (tomato, apple and mint) under Indiana weather conditions.
3. Evaluate the end-product quality of dried specialty crops dehydrated using the technologies in Objective 2 based on color, nutrition, microbial and phytosanitary parameters.

1.3 Thesis Outline

The reminder of this thesis is divided into six Chapters. A review of the literature on solar drying technologies and the effect of drying on food quality for vegetables and fruits is presented in Chapter 2. Chapters 3, 4 and 5 explain in detail the field trials of solar and open-air sun drying studies conducted for tomato, apple and mint, respectively. Conclusions and future work are discussed in Chapter 6.

1.4 References

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CHAPTER 2. **LITERATURE REVIEW**

2.1 Food dehydration

Food dehydration simultaneously combines heat and mass transfer processes for reducing moisture content - heat transfer from the heating source to the product and mass transfer from the product to the surrounding air by water release (Srikiatden and Roberts, 2007). Thus, drying removes liquid from the product by evaporation, decreasing its moisture content to safe levels. As long as the dried product has been dried to low safe storage moisture levels and kept in airtight containers such as Ziploc bags or PICS hermetic bags (Williams et al., 2017) thereafter, the shelf-life and nutrient levels would be preserved for a reasonable amount of time, one year or more without refrigeration.

Dehydration has been one of the most used techniques for food conservation since ancient civilization. Compared with cool chain, drying has been used for a longer time as a food storage technique and is cheaper because no additional energy is needed for maintaining a certain low temperature of the storage environment. For example, it has been used by African cultures, pre-Columbian societies, and now modern food industry (Marouzé et al., 2014). Various drying (dehydration) techniques have been practiced over the centuries, and most of them are based on solar energy, primarily open-air sun drying and solar dryers. However, the current systems of solar dehydration cannot process the total demand of dried products, neither can they deliver the end dried product quality demanded by consumers. Due to this necessity, industrialized dryers have been designed to reduce drying time and improve end dried product quality, especially phytosanitary requirements. Unfortunately, industrial dryers can also result in increases in product cost, the need for multiple unit operations, and also quality deterioration such as nutrient denaturing from high temperatures. Therefore, there is the need to study and combine drying techniques in order to improve drying systems that can achieve high quality standards through better control of drying chamber temperatures.

Dryers can be classified into high temperature and low temperature dryers. The usage of one or the other, is strictly related to the desired quality conditions of the final product (Imre, 2014) . Commonly, high temperatures dryers are referred to as those that use electric or fossil fuel energy as the heating source. Alternatively, for low temperature dryers the energy origin can vary from electric or fossil fuel to solar energy, which is the most used (Ekechukwu and Norton, 1999). The technologies, Dehytray^{TM} and Dehymeleon^{TM}, tested in this thesis are both solar dryers and classified as low temperature dryers. Current and previous technologies on food dehydration will be reviewed in this segment, and the focus will be on solar drying techniques, due to their relevance to this study.

2.1.1 Classification of dryers by operational temperatures

Low temperature dryers

Low temperature drying systems are typically solar dryers such as the Dehytray^{TM}, and are designed to dry with operational temperatures ranging between 30^{o}C (86^{o} F) to 60^{o}C (140^{o} F) (Imre, 2014), which depend on the prevailing ambient temperature. This kind of dryers are designed to drive the drying process using natural air flow. However, other kinds of ventilation configurations exist in solar dryer designs, e.g., Dehymeleon^{TM}, which uses several fans to circulate heat and expel humid air, thereby accelerating the drying process using low temperatures. Even though heat gain is not constant throughout the drying process due to diurnal changes in ambient temperatures; the product will ultimately reach its equilibrium moisture content by the combination of air flow and heat gain. Some of the advantages of low temperature dryers are high nutritional and organoleptic qualities obtained in the end dried product. However, a disadvantage is the slow drying rate, which results in occurrence of microbial growth on the product during the drying process, as well as a reduction in throughput per batch from slow drying.

High temperature dryers

These systems come from the need of reducing drying times. Most of these dryers are used for industrial operations and off-farm processing. Operating temperatures oscillate between 70ºC (158ºF) to 100º C (212ºF). Due to the high temperatures used in the drying, products are exposed to the heated air for shorter periods of time. However, some of the quality is lost in the dried product, especially denaturing of nutrients and decoloring by the high temperatures (Molnár, 2014). For instance, studies on the heat sensibility of important nutrients like Vitamin C, antioxidant activity, and phenols have been conducted to show the impact of high temperature dryers on the nutritional quality of the product (Georgé et al., 2011). For example, Georgé et al., found the importance of temperatures during drying to maintain levels of vitamin C on two different kinds of tomatoes, dried by two different drying techniques such as freeze drying and oven drying. Microbial growth is considerable low in products dried with high-temperature dryers due to the high drying rate in these drying systems.

2.1.2 Classification of solar energy drying systems

Solar drying systems have been widely reviewed in the literature. The description of all the existing kinds of dryers is summarized based on a classification done by Ekechukwu and Norton (1999), and this served as a guide to review the new technologies tested in this thesis as shown on Figure 2.1. Solar drying can be classified into two major groups: open-air sun drying and solar-energy dryers. The latter group depends on the heating mode used and how solar energy is utilized during the drying process.

Open-air sun drying

Due to the necessity of finding ways to preserve food, open-air sun drying has been used as one of the oldest alternatives to reduce moisture content of agricultural products. As shown in Figure 2.1, open-air sun drying can be divided into two categories, i) drying in situ or field drying, such as when the crop is left on the plant to reach a certain harvest moisture content level before harvesting, ii) drying during the post-harvest process, where drying is conducted to a much lower final moisture content level for safe storage by spreading the produce in a thin layer, typically done on a paved floor, hard rock surface, tarpaulin or on the bare ground (dirt) (Enebe and Ezekoye, 2006). The latter method results in a poor product quality, primarily due to the poor hygienic conditions.

During open-air sun drying, solar radiation is absorbed by the product surface as shown in Figure 1.1 heat and moisture transfer take place by natural convection and diffusion, respectively. The whole process depends on the weather conditions, solar radiation, and natural air velocity (prevailing wind). This classifies it as an unsteady state process (Imre, 2014). The intense labor involved in product handling and poor heat absorption, mixed with cross-contamination problems due to exposure in the open air, limit the drying process for open-air sun drying. Despite some of the disadvantages of this low temperature method, open-air sun drying does better in preserving some nutrients. However, some browning and bleaching occurs due to the product being directly exposed to the sun (Omolola et al., 2017).

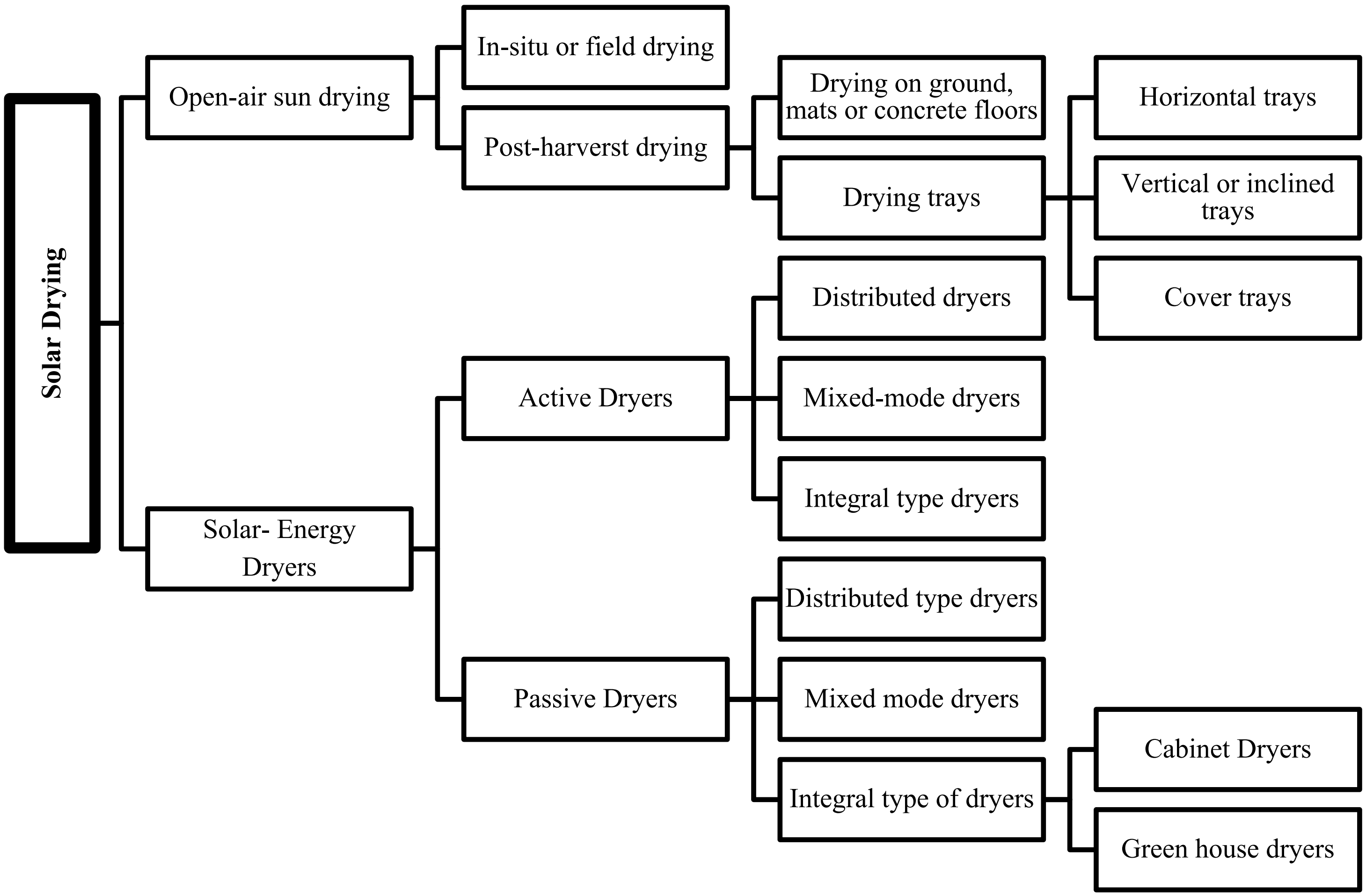


Figure 2.1. Classification of dryers and drying modes. Modified from Figure 1 (Ekechukwu and Norton, 1999).

While there are several disadvantages of open-air sun drying, it is used due to the abundance of solar irradiation, not only in tropical countries, but also in some regions of the United States such as in California (Figure 2.2). Applied studies in the Sub-Saharan region shows that around 70% of the drying was done with open-air sun drying techniques (Bhandari et al., 2005; Chen et al., 2009; Kandpal et al., 2006; Sreekumar et al., 2008)

a) b)

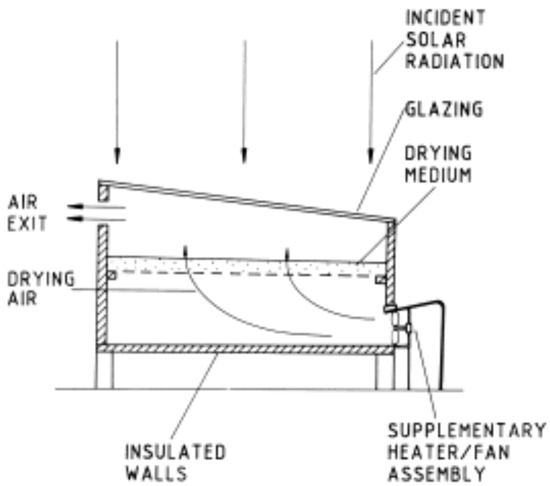
Figure 2.2. Drying tomatoes in California: a) open-air sun drying on wooden trays (close-up view) and b) field views of trays of tomatoes drying on a drying pad.

Solar Drying

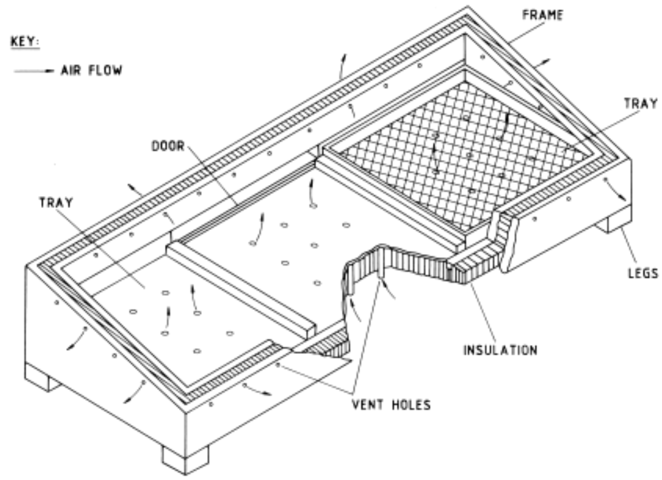
Contrary to open-air sun drying, solar drying involves the use of an enclosed space to concentrate solar irradiation and temperature, and in many cases increased airflow in order to increase crop drying rates and prevent contamination by foreign materials. Thus, it reduces dust, insects, rodents, and contamination from the environment. Furthermore, solar drying uses different ways to concentrate heat, thus utilizing the solar radiation more effectively. Different types of solar dryers have been developed over time, involving several different thermal capture and heat transfer methods, and special configurations shown in Table 2.1. These designs are still based on empirical knowledge rather than fundamental physics and engineering theory. The lack of scientific background makes standardization a difficult task. This is reflected on the final quality of the product, and the possible markets it can be sold in. Besides the thermal capture of heat, forced airflow is used to achieve higher drying rates. These solar-energy forced air convection dryers are also classified into direct, indirect or mixed types of active dryers, Figure 2.1. The Dehymeleon™ (Fig. 2.6) can be categorized under the indirect-active dryers' classification, while Dehytray™ (Fig. 2.7) is a direct-passive solar dryer.

Direct, indirect and mixed dryers

Direct solar dryers are characterized by the use of transparent covers to protect the crop from rain, dust and other sources of contamination (Imre, 2014), while indirect dryers use opaque chambers and solar collectors as a separate or inbuilt structure. Although, in both cases solar radiation is used as the principal source of heat, the direct heat gain differs due to the configuration of one or another. For example, while indirect dryers use the solar collector to increase the temperatures of the air inside the drying chamber, direct dryers rely on the absorption of solar radiation by the product. In this case the heat is confined inside the dryer creating a greenhouse effect (El-Sebaii and Shalaby, 2012), which increases the temperatures, with a low heat gain due to the reflection of part of the solar radiation to the atmosphere and to the surrounding soil. The heat and moisture transfer to the air is driven by convection (Brenndorfer et al., 1987). The heat gain in both types of dryers depends on the weather conditions and solar irradiation.



a)



b)

Figure 2.3. Direct dryers a) Active solar-energy cabinet dryer b) Direct natural-air circulation (passive) solar-energy dryer (Ekechukwu and Norton, 1999)

Direct solar dryers are commonly used for the dehydration of wet products in thin layers on one tray. In contrast, indirect dryers can dehydrate various trays stacked inside an opaque drying chamber. The final product quality in each type of dryer also varies. For example, color deterioration and browning occurs for direct dryers as the product is directly exposed to ultraviolet radiation (Omolola et al., 2017). While for indirect dryers color change, browning, and caramelization will occur due to the high temperatures reached inside the drying chamber (Omolola et al., 2014). Direct dryers can also be classified into cabinet, greenhouse Table 2.1, and tunnel solar dryers. Dehytray^{TM} is a direct solar dryer. Some examples of indirect dryers are chimney dryer, cabinet with black body and Dehymeleon^{TM}, solar drying tray.

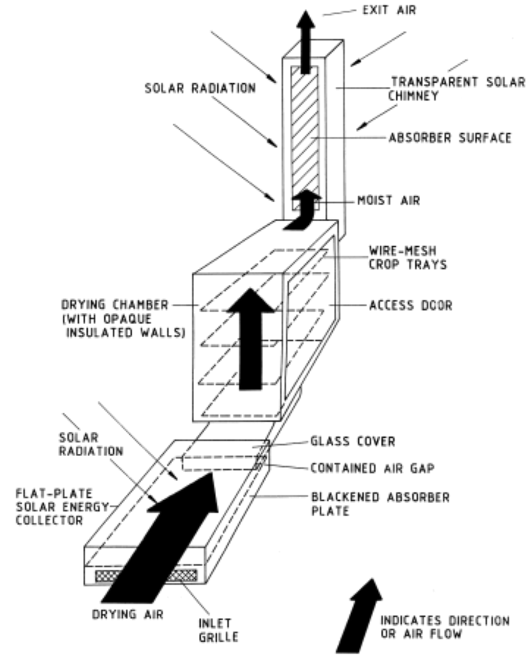


Figure 2.4. Indirect-passive chimney dryer (Ekechukwu and Norton, 1999).

Mixed dryers, as the name indicates, combines features from the two types of dryers described previously in this section. Thus, the combination of designs makes it a better alternative.

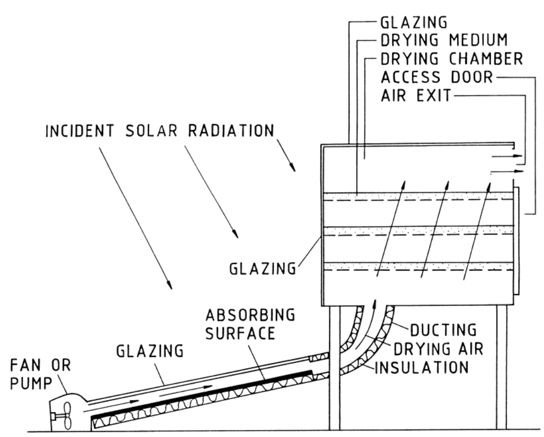


Fig. 31. Features of a typical mixed-mode active solar -energy dryer.

Figure 2.5. Mixed-mode active solar-energy dryer.

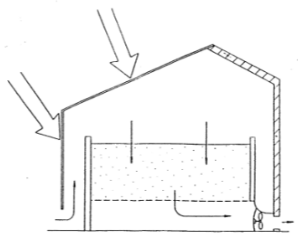
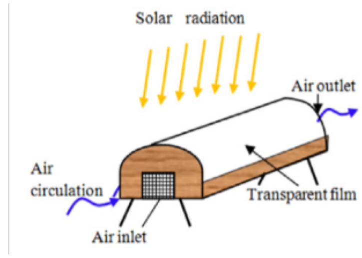
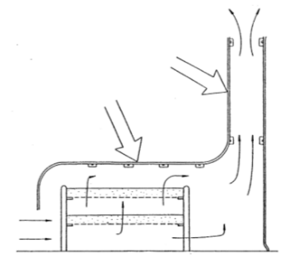
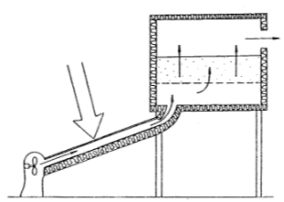
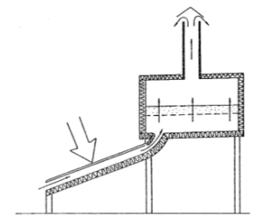
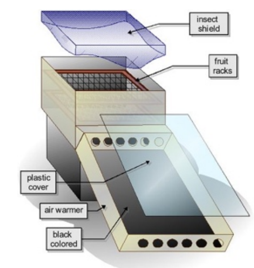
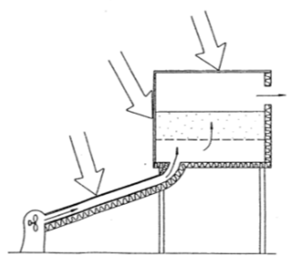
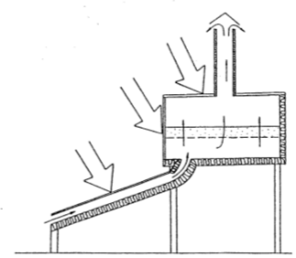
Active Dryers

Active dryers use other sources of energy such as electricity or fuel, to complement either the heating or the powering of the forced-air circulation systems. Photovoltaic energy is used to power the fans in most of the cases, by using a solar panel attached to the structure, as is the case of the Dehymeleon^{TM} or the case of Innotec tunnel dryer, one of the most common commercial dryers around the world. Table 2.1, on images g).

Passive dryers

The performance of passive solar dryers depends primarily on the prevailing solar-energy and the natural-circulation of air. They are called passive solar dryers, because they do not employ fans or other dynamic mechanisms to pass air through the crops. Instead, the air is moved by buoyancy forces or as a result of the natural wind pressure (Ekechukwu and Norton, 1999). Examples of passive solar dryers are shown in Table 2.1, on images b), d) and f).

Table 2.1. Drying technologies classification and review. Modified from (Imre, 2014)

Type	Active Dryers	Examples Active Dryers	Passive Dryers	Examples Passive Dryers
Direct type	 a)	Greenhouse dryers (Marouzé et al., 2014)  	 b)	Dehytray™ (Sold comercialy) 
Indirect type	 c)	 Innotec-Tunnel dryer (Sold comercialy)	 d)	Chimney Dryers 
Mixed mode	 e)	Dehymeleon™  g)	 f)	UC-Davis Chimney Dryer 

SOLAR RADIATION AIRFLOW

2.1.3 Dehymeleon™

The Dehymeleon™ is a solar drying technology that was developed at Purdue University in 2015 as part of a USAID FtF FPL project to develop small and low-cost dryers for maize (corn) with focus on reducing post-harvest losses and improving quality in maize in Senegal and Kenya. The philosophy behind its design is to have a dryer than could be used for different crop types ranging from granular materials like grains, oilseeds, coffee or processed cereals like couscous, to leafy vegetables, teas, herbs, spices and flowers, and high moisture fruits and vegetables such as mango, apple, tomato, chili pepper, etc. The technology is classified as an active-solar dryer. The Dehytray™ and Dehymeleon™ drying technologies are both exclusively licensed from Purdue University by JUA Technologies International and are being commercialized under the US Patent and Trade Office (USPTO) registered trademarks Dehytray™ and Dehymeleon™. Both technologies complement each other; the Dehymeleon™ is an upgrade of the Dehytray™. Also, the Dehytray™ tray is used alone (without the cover) as the holding device for the wet material when drying crops in the Dehymeleon™.

Version II of the Dehymeleon™ shown in Figure 2.6 and III (not shown) were used during the field drying tests undertaken in this thesis. A description of versions I and II can be found in Shrestha (2017). The drying chamber volume was reduced from version I to II in order to enable it to fit into the back of a pickup truck commonly available in both developing and developed countries. The Dehymeleon™, a multipurpose solar dryer, version II is 1.27 m in length, 1.02 m in width and 0.48 m in height, and has its thermal collector located on the top of the drying chamber at an incline angle of 21^{o} (Shrestha, 2017). The volume of the drying chamber is 0.64 m^3 and holds 9 drying trays of 0.85m length by 0.41m width by 0.12m height stacked four trays high in front and five trays high at the back. The drying chamber of the third version of the Dehymeleon™ dryer is slightly larger in volume and is able to hold 10 Dehytrays™ stacked 5 trays each side by side without their covers. While version II of the Dehymeleon™ solar dryer is fully described in Shrestha (2017), description of the changes and new configurations in version III cannot be discussed in this thesis due to intellectual property (IP) protection issues with JUA Technologies International.

Figure 2.6. Dehymeleon™ version II

2.1.4 Dehytray™

Dehytray™ is also a drying Technology developed at Purdue University as part of a USAID FtF FPL project to develop small and low-cost dryers for maize (corn) with focus on reducing post-harvest losses and improving quality in maize in Senegal and Kenya. It is exclusively licensed to JUA Technologies International for commercialization and became available for sale in the market since December 2018. At the moment, the Dehytray™ is being field tested under several US government funded grants and the private industry in Kenya, Senegal, Nigeria, Ghana, South Africa, Tajikistan, Peru and the USA (Indiana, Georgia and California). This Dehytray™ drying technology has two different components. The main tray, made with a black polypropylene copolymer that meets FDA standards for food contact applications, and a protective lid with transparent windows made from acrylic sheets that allow sun-light, as is shown in Figure 2.7. The black tray and cover frame are both made from polymers approved by the US FDA for food contact. A simple vent that can be opened and closed shut by sliding action of a transparent acrylic sheet controls humidity and temperature within the tray. On a sunny day, the temperature inside the tray is twice that of the ambient, and decreased by 5°C, when the vent is open. It is preferable that the vent be open when drying materials to facilitate better expulsion of humid air and prevent extremely high temperatures when using the Dehytray™. The Dehytray™ is a passive solar-dryer where the heat and moisture transfer from the product and out of the tray is driven by natural convection. The black tray absorbs heat, which is radiated inside the drying chamber, while the transparent window enables sun-light penetration and trapping of heat, essentially like a greenhouse. The small volume of air in the tray that is heated compared to the surface area, which radiates heat into the tray is what enables the doubling of the temperature in the tray over the ambient temperature.

Unlike other solar dryer designs in the literature or available commercially, the Dehytray™ is portable, provides a superior environment for dehydration and prevents contamination of the dried product by livestock, dust and the elements. While is a smaller unit, it works quite well for small grower agriculture and individual households and can also be used by mid-size farms. Its design is quite simple and intuitive. It is sold in broken down unassembled parts, which can be easily assembled in one-minute following three simple steps.

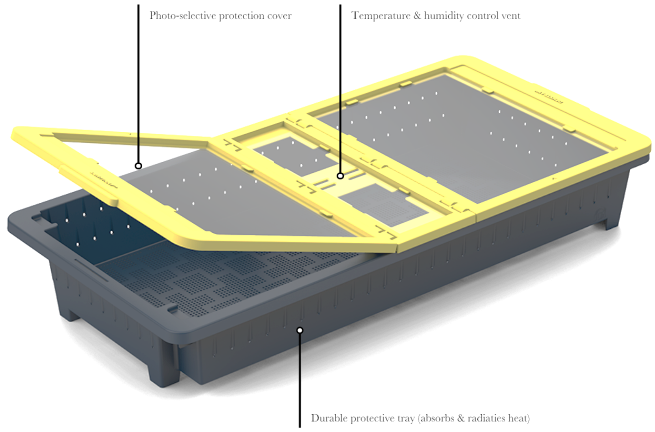


Figure 2.7. Dehytray^{TM}

2.1.5 Identification of gaps on solar drying systems

During the review of the current drying technologies, some gaps where identified. They are related mostly to poor standardization of drying processes, as well as the lack of commercialization of drying technologies and their massive production. Despite a considerable number of studies have been conducted to understand solar drying processes for various food products, there are very limited ready-made manufactured solar dryers that can be purchased off-the-shelf. The dependence of weather conditions makes the efficiency of the proposed dryers hard to operate in other locations different than where the dryers were original designed to operate in. Additionally, the diversity of designs and their fabrication on a unit basis by local artisans interfere with the standardization of manufactured units, transfer of the technology, and R&D toward their improvement. This thesis is unique in that it explores the performance of two commercial solar drying technologies designed to be mass produced, and their performance in drying three different crops under West Lafayette, Indiana, USA weather conditions.

2.2 Thin Layer drying (TLD) for drying kinetics

Optimization of drying processes are totally related to the behavior of the product while drying, that is the drying kinetics of the crops (grain, oilseeds, fruits and vegetables). Multiple factors can affect the drying behavior of the product, which are primarily air temperature, airflow rate, thickness of the product, and some other intrinsic characteristics (texture, moisture content, etc.) of the material to be dehydrated. Drying kinetics models allows the understanding of the effect of drying conditions on drying rates, and in deciding parameters of design, equipment optimization and product quality improvement (Giri and Prasad, 2007). Therefore, understanding the drying kinetics of a crop under a given condition represents an important step toward predicting the drying rate of a crop and evaluating the performance of a dryer. Thin layer drying modeling has been used to predict the drying performance of multiple food products by assuming the drying rate depends only on drying temperature, air flow rate, product size, and initial moisture contents (Yaldiz et al., 2001).

2.2.1 Drying rate models

Most of the models applied for TLD are semi-theoretical or empirical. Semi-theoretical models are solutions of Fick's second law of diffusion and variations of its simplified form, like Henderson and Pabis models, Midilli (2002) and their respective modifications. Other models are derived from Newton's law of cooling, and a simplified variation of Fick's second law. For example, Page model, is largely used for corn and other cereals (Earbay and Icier, 2010). A list of some models used for fruits and vegetables are shown in **Table 2.2**.

Table 2.2. Thin- layer models for drying fruits and vegetables.

Model name	Model equation	Food product	Reference
Newton model	*MR = exp(-kt)*	Red chili, strawberry	El-Beltagy and others (2007)
Page model	*MR = exp(-ktn)*	Kiwi, corn, banana, bitter melon	Akoy (2014); Tzempelikos and others (2014)
Henderson and Pabis model	*MR = a exp(-ktn)*	Apple slices	Meisami-asl and others (2010); Hashim and others (2014)
Midilli and others mode	*MR = a exp(-kt) + bt*	Apples slices, mint leaves, Chili, Mango slices and Pumpkin, pepper	Darvishi and Hazbavi (2012); Ayadi and others (2014)
Modified Midilli and others	*MR = a exp(-kt) + b*	Jackfruit	Gan and Poh (2014)
Approximation of diffusion	*MR = a exp(-kt) + (1 - a) exp(-kbt)*	Tomatoes, green pepper, Pumpkin slices	Yald´yz and Ertek´yn (2007)
Weibull model	*MR = ∝ -b exp(-k0tn)*	Persimmon slices	Tzempelikos and others (2015)

2.2.2 Diffusivity models by Fick's second law of diffusion

The mechanics of drying of agricultural products includes surface diffusion, and liquid/vapor diffusion (Onwude et al., 2016). However, the dominant mechanism is liquid diffusion, due to the mass transfer process, which is governed by the removal of moisture from the crop.

Drying curves are a good approximation in understanding the diffusivity phenomenon while drying. Fick's law of diffusion can be simplified by its variation, the Newton's law where the moisture ratio represents the mass transfer rate during the drying process. Further analysis and description of the calculation methods are established for each crop. Therefore, a combination of the thin layer model and calculation of the moisture ratios, can be used to understand drying rates for a proposed drying technology. Fruits and vegetables are characterized for a falling rate drying curve due to their water bonding. An example of a fruits and vegetable drying curve is shown in Figure 2.8.

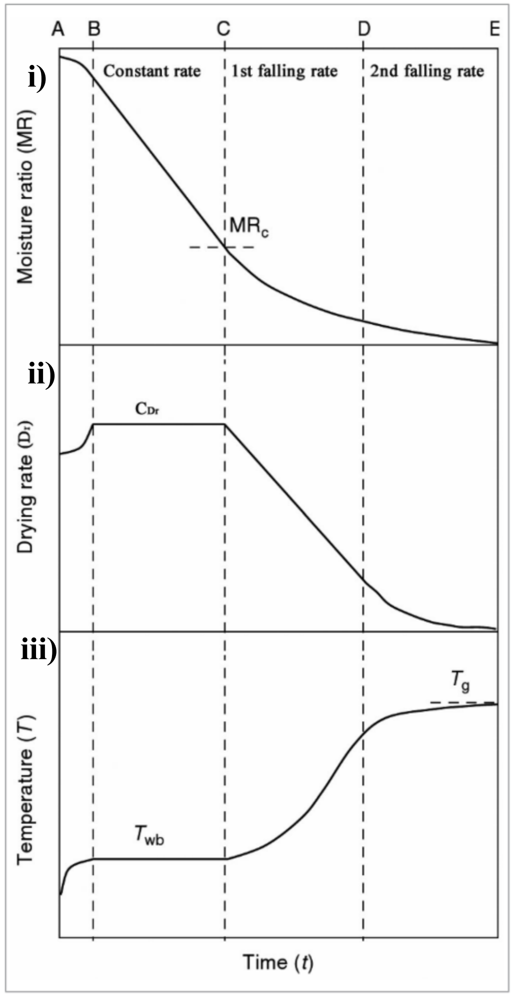


Figure 2.8. Typical drying curve for food products, i) Moisture ratio vs time, ii) Drying rate vs time and iii) Temperature vs time (Adapted from Carrin and Crapiste, 2008).

2.2.3 Gaps on thin layer drying modeling

Thin layer drying modeling is widely use in the prediction of drying performance for solar dryers, by assuming constant temperatures for a defined range of time. However, temperature profiles vary considerably during the solar drying process, drifting apart from the real solar drying scenario. This thesis proposes a drying cycle model based on data collected for the Dehymeleon™ during the summer 2017. The simulation of the cyclic pattern of diurnal temperatures in a thin-layer experiment will be further described in the methods section.

2.3 Quality indicators on dehydrated products

The quality of agricultural products has been defined by several authors in the literature. For example, Kramer (1965) defined quality as the characteristics that differentiate the product and have a significance on determining its degree of acceptability. Moreover, fruits and vegetables quality is determined by their organoleptic, physical and chemical characteristics (Omolola et al., 2017). According to Barret et al. (2010), four different attributes are the most important when talking about fruits and vegetable quality: i) color and appearance, 2) flavor (taste and aroma), iii) texture and iv) nutritional value (content of vitamins, antioxidant, etc.). However, the last classification can be subjective due to its dependence on user appreciation.

Dehydration is also used for enhancing the storage stability of products. Some quality parameters like water activity, moisture content, microbial growth and bacterial contamination are also important indicators related to shelf life. These parameters are also closely related to the drying technique used and the unit operations along the post-harvest chain. Sagar and Suresh (2010), reviewed the recent technologies used for food dehydration and their effect on product quality, and concluded that energy consumption and quality of dried products are critical parameters in the selection of a drying process. Although, open-air sun drying and solar drying present some quality problems due to their low operational temperatures (Sagar and Suresh Kumar, 2010), they also prevent the denaturation of some nutrients such as vitamins A and C, which is an advantage over high temperature dryers.

For the performance evaluation of the two novel drying techniques, Dehymeleon™ and Dehytray™, three quality indicators were used: i) nutritional value of vitamin C, ii) microbial contamination, and iii) color change.

2.3.1 Nutritional values: Vitamin C

Ascorbic acid commonly known as vitamin C is an organic acid, present in most of the fruits and vegetables, which are consumed daily. Humans are unable to synthesize vitamin C, and therefore they need external resources of this vitamin. While in crystal form, vitamin C can be stable at ambient conditions for an extended period. However, when dissolve in water, its stability depends from the storage conditions. Thus, vitamin c is easily degraded by factors such as temperature, pH, light, and oxygen (Santos and Silva, 2008). The mechanism of vitamin C degradation is shown in Figure 2.9, where temperature and photodegradation work as a catalyst of oxidation reaction. The aerobic degradation of ascorbic acid leads to the production of dehydroascorbic acid.

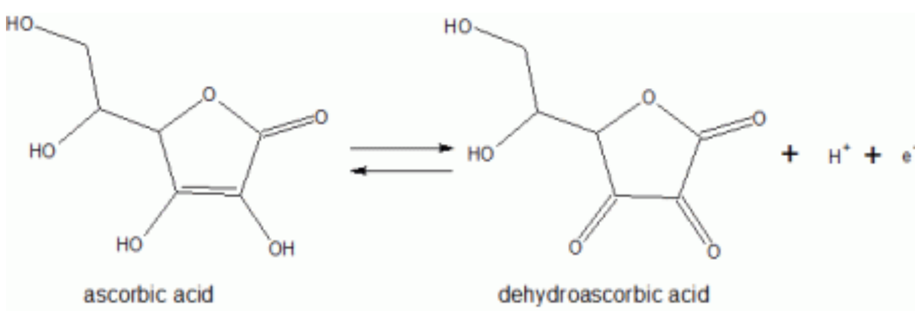


Figure 2.9. Mechanism of vitamin C degradation by air exposure, light and temperature modification (Goula and Adamopoulos, 2010a).

Multiple studies about the effect of drying technologies on vitamin C degradation have been conducted. Santos (2008), reviewed vitamin C degradation by various drying systems, including solar and open-air sun drying. Some studies have found ascorbic acid to be moisture and temperature dependent (Villota and Karel, 1980). Goula and Adamopoulos (2006) found that the reaction rate of vitamin C degradation diminishes at moisture contents below 65% (wet basis). However, when moisture content reached 65-70% (Goula and Adamopoulos, 2010b), the reaction seemed to increase, due to the concentration of ascorbic acid on the product (Khraisheh et al., 2004).

As mentioned before, ascorbic acid degradation also depends on temperatures during drying. Several drying methods including solar and open-air sun drying have been studied to understand the degradation of ascorbic acid. For low temperature dryers, the exposure of products to direct sun-light and hot spots, accelerates degradation processes of ascorbic acid. Studies carried by Maeda and Salunkhe (1981), show that degradation of vitamin C does not only depend on temperature, but also on the type of drying process, that is if the product is exposed to direct or indirect sun-light (Maeda and Salunkhe, 1981). With indirect exposure, less degradation of ascorbic acid occurs.

Vitamin C content in dried products are affected by the type of drying. Negi and Roy (2000), found that in leafy vegetables, open-air sun drying has a higher impact on ascorbic acid degradation due to the direct exposure to the sun-light than solar dryers, which use sun-light indirectly (Negi and Roy, 2000).

This thesis aims to study the difference of three different drying processes for tomatoes, apples and mint on vitamin C content. Furthermore, specific levels of vitamin C for the selected crops, both fresh and dehydrated product will be presented in the “Materials and Methods” section.

2.3.2 Food safety: microbial and bacteria contamination in solar drying

Food safety is an important quality parameter in the food industry. Safe levels of microbial contamination and bacteria are desired to accomplish human health and market standards. Reduction or prevention of microbial growth is needed in order to maintain quality. However, agricultural products, such as fruits and vegetables create a perfect environment for microorganism and bacteria growth due to their high moisture contents that range between 70% to 95%. To reduce this susceptibility, a rapid reduction of water activity to inhibit bacteria, yeast and mold growth should take place. Therefore, drying techniques are a good fit for reducing microbial growth. Thus, solar and open-air sun drying are among the oldest and the most common forms of food preservation. However, their dependence on weather do not allow them to reach high levels of final product quality. Optimization of these drying systems is needed to reduce the effect of their drawbacks (Bourdoux et al, 2016).

In the case of fruits and vegetables, the principal sources of cross contamination occur during production, harvesting, storage and transportation. Post-harvest contamination can occur as well with some processing operations, such as cutting or slicing, washing and drying. According with Bourdoux et al. (2016), studies involving the behavior of microorganisms on solid food matrices dehydrated by techniques like solar and open-air sun drying has been scarcely conducted. Therefore, a lack of information has been identified concerning the survivability of microorganisms during drying with low temperatures of complex solid matrices such as solid foodstuffs (Smelt and Brul, 2014).

For solar drying techniques, some studies indicate the reduction of mesophilic bacteria, yeast and molds during the dehydration of cowpea (Wachuku et al., 2003). Eze et al. (2011), found that open-air solar drying of ginger, did not reduce the presence of aerobic bacteria, but prevented it from spreading, while solar drying reduced the count to levels less than 1 CFU/g (colony forming count per gram).

Likewise, it was identified that mesophilic bacteria is common in solar drying techniques (Bourdoux et al., 2016a). For example, Karabulut et al. (2007), conducted a study for apricots using open-air sun drying, which lasted for more than 180 hours and resulted in an increment in microbial contamination. Therefore, aerobic bacteria, yeast and mold should be studied when conducting solar drying processes. Additionally, Burnham et al. (2001), identified the presence of *E. coli and coliforms* during dehydration of apples by convective drying with temperatures of 62.8 ºC for 6 hours. The definition of microbiota during the solar dehydration process and their impact on each crop will be described in each section.

2.3.3 Color

Color is a characteristic that comes from the natural pigmentation of fruits and vegetables. Agricultural products change their color during their ripening process, aligning color with concepts such as fresh or rotten, depending on the family and characteristics of the produce. Barret et al. (2010), suggested that primary color pigments associated with quality are fat soluble compounds such as chlorophylls (green) and carotenoids (yellow, orange, and red). Other water-soluble pigments are also related to ripening and freshness such as anthocyanins (red, blue), flavonoids (yellow), and betalains (red) (Barrett et al., 2010).

Even though color change is a natural process, it can also be caused by a combination of factors such as temperature, oxidation by enzymatic reactions, and long-term exposure to heat that can result in browning caused by Maillard reaction. Drying has shown an impact on color change, due to the range of temperature experienced by the crop during the process. Although, solar drying and open-air sun drying are low temperature dryers, exposure to other factors as direct sun-light and hotspots (heat concentration) will produce either enzymatic reaction, bleaching, or Maillard reaction. Whether or not all the color changes are associated with temperature, there are a range of factors contributing to color deterioration during the drying process. Clydesdale and Francis (1976) summarized the factors that deteriorate color for each common compound in foods. For example, green pigments such as chlorophylls are sensitive to heat and acid mediums, while flavonoids are sensitive to oxidation but not to heat (Clydesdale and Francis, 1976).

Enzymatic browning, Maillard reaction and caramelization

Enzymatic browning is a result of an oxidoreduction reaction, while Maillard reaction is associated with the process of amino acid reduction, and caramelization with the transformation of sugars or carbohydrates into a melamine compound (Martinez and Whitaker, 1995) . Oxidoreductions either enzymatic or chemical could occur during any step in the chain of an agricultural product, most commonly during processing such as slicing, drying or packaging. In contrast, Maillard reaction is more present during thermal processes, such as drying, baking and cooking (Billaud et al., 2005).

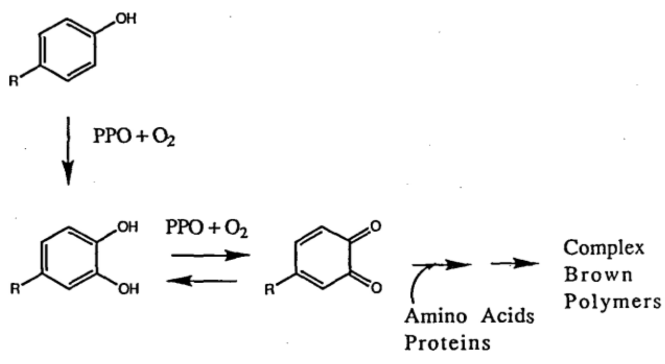


Figure 2.10. Enzymatic browning reaction for a phenolic compound (Otwell and Iyengar, 1992).

Enzymes involved in browning processes are polyphenol oxidase, which catalyze the oxidation of polyphenolic compounds, and phenylalanine ammonia lyase, which catalyzes the synthesis of precursors to phenolic substrates (citation). These reactions are generally recognized as deleterious to the organoleptic quality of the foodstuffs (Barrett et al., 2010). Thus, research is needed about active molecules or natural inhibitors in the prevention of such oxidative reactions. Prevention on caramelization and Maillard reaction is associated with the management of temperatures during the drying process; recommended temperatures to avoid browning range between 30 º C to 50 º C.

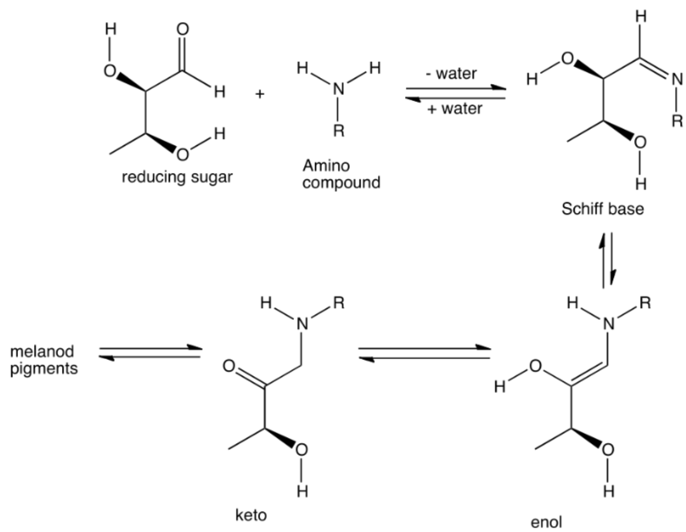


Figure 2.11. Example of Maillard reaction for an amino compound (Billaud et al., 2005).

Pretreatments usages and applications

Pretreatments could be chemical molecules or natural inhibitors such as citric acid, ascorbic acid, sulphites, sulfur deoxidize, and salt, among others. The objective of using pretreatments during the processing of foodstuff, especially some fruits and vegetables is related to the inhibition of undesired reactions like oxidation, that will cause damage not only to color but to nutrients like vitamin C, described in the previous section. Products being dehydrated by solar drying techniques are processed minimally, but still are exposed to environmental conditions, mechanical damage and other catalysts of oxidation reactions for long periods of time. The pretreatments mentioned, have the primary role of reducing the pigments precursors (quinones) to colorless, or less reactive diphenols, as shown in Figure 2.12 (Laurila et al., 1998). Selection of the pretreatment method will be associated with availability, convenience and ease of application. In the case of this study, sulphites were not an alternative due to adverse health effects reported in the literature (Laurila et al., 1998). Instead, organic acids such as ascorbic acid and citric acid, and especially in their natural forms like diluted lemon juice were studied as an alternative. Ascorbic acid is one of the most reviewed alternatives to replace sulphites due to evidence as an inhibitor of enzymatic browning.

However, ascorbic acid added in the process could interfere with the vitamin C measurements carried before and after dehydration. Finally, citric acid was selected as the alternative for inhibition of enzymatic browning. Citric acid as a dipping treatment has been used in potatoes by Mattila et al. (1995) and in tomatoes slices by Porretta (1991), where they presented inhibiting results. Enhancing of color was found in both studies.

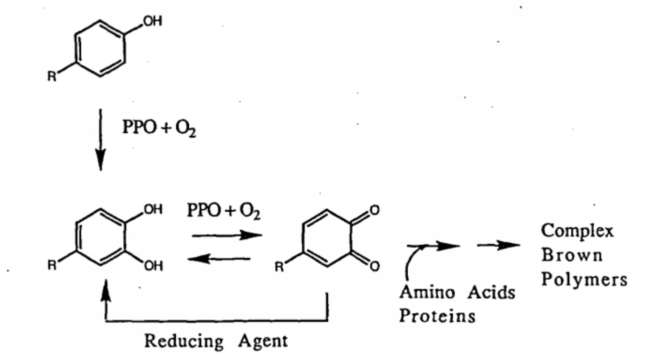


Figure 2.12. Role of reducing agents such as sulphites or organic acids pretreatments (Laurila et al., 1998).

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CHAPTER 3. DRYING STUDIES ON TOMATOES

3.1 Abstract

The aim of this study was to determine the effect of temperature on the drying kinetics and quality attributes of tomatoes (var. Roma) slices, using two different drying technologies (Dehymeleon^{TM} and Dehytray^{TM}) compared with open-air sun drying. Experiments were conducted at Purdue University, West Lafayette, Indiana. Thin layer drying tests were conducted on tomato slices of thickness approximately 5 mm, at three temperatures [24°C (75°F), 35°C (95°F) and 54 °C (130°F)], and air flow velocity of 1 m/s to identify the drying kinetics of the product for diurnal drying cycles typical for solar and/or open-air sun drying under summer weather conditions in West Lafayette, Indiana. Subsequently, field drying tests were conducted for tomatoes slices of thickness approximately 5 mm with two solar drying technologies (Dehymeleon^{TM} and Dehytray^{TM}) and open-air sun drying using uncovered Dehytrays as the control. The average temperatures achieved for these technologies were 45°C (113°F), 60°C (140 °F) and 27°C (80.6 °F) for the Dehymeleon^{TM}, Dehytray^{TM} and open-air sun drying, respectively. Quality attributes (color, vitamin C and microbial growth) were measured before and after the field drying tests. Color difference (ΔE) for Dehymeleon^{TM} solar-dryer showed the least variation compared with the fresh produce. However, for the Dehytray^{TM} ΔE increased due to the impact of its higher temperature [60°C (140°F)] that led to Maillard reactions and caramelization. Additionally, vitamin C (ascorbic acid) content was affected for the high ranges of temperatures reached inside the Dehytray™. Denaturing of vitamin C was less observed for Dehymeleon^{TM}, maintaining values of 166 mg/100 g dm, twice the final values for the Dehytray^{TM} and open-air sun drying, which were < 80 mg/100 g dm. There was no significant difference ($\alpha = 0.05$) in the microbial growth for the Dehytray^{TM} and open-air sun drying compared to the fresh produce, however, there was significant difference

for the Dehymeleon™. This was observed because the moisture content of the Dehymeleon™ was above the safe equilibrium moisture content (EMC) of the product (EMC for tomatoes = 11%) for a long time at the onset of drying due to the low temperatures achieved in the drying chamber, and thus a slow rate of drying.

3.2 Introduction

The demand for high nutritional food products has increased over the past years, and therefore, their storability and quality are important due to the increase in world population and the need of dietary supplements. Tomato is one of the most popular table vegetables, however, it is highly perishable, with one week of shelf life when fresh and sensitive to chilling damage when refrigerated (Das Purkayastha et al., 2013). Because of these characteristics, drying has been studied as an alternative to reduce losses and extend shelf life. Other kinds of processing have been also studied in the case of tomatoes, for example, canning, purees, and tomatoes' pasta (St George et al., 2004), but these are expensive processes for small and mid-size growers.

Though dried tomatoes are processed by high temperature dryers (Argyropoulos et al., 2008), they are also commonly dehydrated by solar technologies such as open-air sun drying, one of the most used drying methods around the world. Other kinds of enclosed solar dryers, mostly experimental solar dryers under development have been used for drying (Kostoglou et al., 2010).Drying of tomatoes has been considered as an important alternative for reducing the dependence of seasonal crops and extension of the marketing period of the produce during the year.

Das Purkayastha (2013) studied the drying characteristics of tomato slices using hot air convective drying for blanched tomatoes and found a relationship between process temperatures and reduction of quality. For example, temperatures higher than 60°C (140 °F) reduced vitamin C content and increased color variation (ΔE) on the samples, affecting the final quality (Das

Purkayastha et al., 2013). Additionally, the drying behavior of the tomatoes like most of the vegetables and fruits, shows that drying curves were determined by a falling rate period. This means that most of the water removal during the drying occurs during the beginning of the process, thus, the high initial moisture contents (85-96% MC) of tomatoes make drying a critical process (Nwakuba et al., 2016). Failure to remove the free water during the first hours of drying will translate into undesired microbial growth and consequently, spoilage of the product (Nwakuba et al., 2016). Therefore, a safe equilibrium moisture content (EMC) has to be reached at the end of the drying process to allow safe storage. Kiranoudis el al. (1993) determined the values for safe equilibrium moisture content for tomatoes, using experimental data for three different temperatures (30ºC, 45ºC and 60º C), reporting values between (10%-15% EMC) (Kiranoudis et al., 1993). Sacilk et al (2005) conducted thin layer drying experiments for tomatoes slices with a solar drying tunnel, getting similar values for the final moisture content, having EMC range between (10%-11.5%).

As mentioned before, open-air sun drying has been used for several years to dehydrate tomatoes slices. However, quality is commonly affected due to the long drying times, which lead to adverse conditions such as microbial growth and enzymatic reactions that would negatively transform the final product (Rajkumar et al., 2007). Although, several studies about drying techniques for tomatoes have been done, information about commercial solar dryers (i.e. Dehymeleon™ or Dehytray™) is not available. Information on drying performance of these technologies will help to understand the limits and benefits on production of quality dehydrated products using these technologies. Therefore, this chapter studies the performance of the technologies Dehymeleon™ and Dehytray™, and their effects on quality parameters defined in the literature review.

3.3 Materials and methods

3.3.1 Produce material

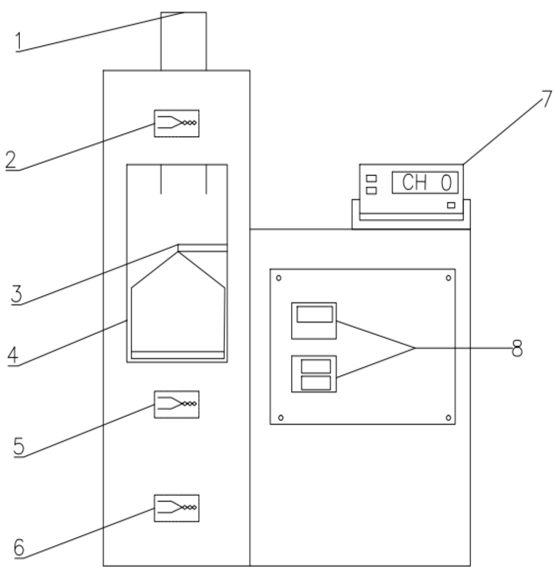
Tomatoes

Fresh tomatoes (*Solanum lycopersicum,* var. Heirloom) were acquired from Piazza Produce (Indianapolis, Indiana) during the summer of 2018. Fresh samples were classified in order to standardize the maturity and grade. Tomatoes samples were cut into halves, and sliced with a meat slicer (Elite, Platinum, Maxi Matic Inc, China) to achieve a thickness of 5 ± 0.2 mm. After cutting, tomatoes halves and slices were pretreated by dipping them in a water solution of 5% citric acid for 10 minutes in order to inhibit enzymatic browning. The initial moisture content of fresh sample slices was determined before pretreatments by using the air-oven method at 100 ^{o}C for 24 h (AOAC 2000). The average moisture content was found to be 94.1% (w.b.). Tomatoes for tests carried at Purdue University were processed and dried at same day of receiving, and after four days of being harvested.

3.3.2 Drying of tomato slices and tomato halves

Thin layer drying tests

Thin layer drying experiments were conducted at Purdue University in the Spring of 2018 using a thin layer drying apparatus shown in Figure 3.1. Drying was conducted to mimic the cyclical changes in ambient temperatures using three temperatures ranges of 24°C (75°F), 35°C (95°F) and 54 °C (130°F). The temperature was changed every three hours starting from the lowest temperature 24^{o}C through to the highest temperature 54^{o}C and back to the cycle from 24^{o}C until tomato slices reached a constant dry weight indicated by infinitesimal weight change. Tomato slices of 5 ± 0.2 mm thickness were placed on a mesh tray in thin layers (one layer thick). The tray was placed in the thin-layer drying apparatus chamber with a perpendicular air flow velocity of 1 m/s flowing from the top through the slices to the bottom of the chamber. The air used for drying was heated by an electric heater (Chromalox Inc., USA) and blown using a 1/3 hp centrifugal fan (Dayton, Iowa, USA) via an air duct (1) from the top into the drying chamber as shown in Figure 3.1. Temperatures and weight change of the tomato slices upon loss of moisture were collected every five minutes using a Fluke data logger (model Hydra 2620A, Fluke, Everett, WA, USA) connected to thermocouples and a load cell. Thermocouples placed in location (2) and (5, 6) as shown in Figure 3.1, measured the temperature of the hot air entering the drying chamber at the inlet and the temperature of the humid air exiting the drying chamber at the outlet, respectively. The drying surface area occupied by the tomato slices was of 0.093 m^2.



Definition of thin-layer drying system components:

1) *A centrifugal fan* (model Dayton 2C820, 1/3 hp, 3450 rpm, 0.5” static pressure), which blows air through the drying chamber.
2) *Thermocouple* that measure the temperature of the air before the material sample (crop).
3) A *load cell* connected to the other end of the scale balance, and a fluke data logger automatically records weight data as drying proceeds.
4) *Drying Chamber* with screen mounted scale for automatic weighing of sample.
5) *Thermocouple* that measure the dry bulb temperature of the air passing the sample.
6) *Thermocouple* that measure the wet bulb temperature of the air after the material sample.
7) *Fluke data logger*, (model Hydra 2620A).
8) *Displays* for pressure and temperature from the first thermocouple controlled by a Chromalox controller

Figure 3.1. Thin-layer drying apparatus at Purdue University used for the experiments.

Drying tests conducted on the field

Drying tests using the Dehytray™ (uncovered and covered) and Dehymeleon™ were conducted at the ADM Agricultural Innovation Center, West Lafayette, Indiana. The uncovered Dehytray™ was used to mimic open-air sun drying. During the summer of 2018, three replications were conducted for all three drying technologies tested using tomato slices. Specific procedures are described in the following section and the sequence of the procedures conducted for the trial is depicted in Figure 3.4.

Dehymeleon™

Uncovered Dehytray™ was filled with a thin layer of tomatoes slices, with each tray holding approximately 2 kg of fruit. Three trays with tomato slices were placed inside the drying chamber of the Dehymeleon™ solar dryer, and the weight was measured for each one twice per day (in the morning prior to taking the solar dryer outside and in the evening after moving the solar dryer indoors) using a digital scale platform. Drying was tracked by loss in weight and tomato slices were inspected daily for signs of mold growth. The Dehymeleon™ consists of three sets of fans, which are operated at different speeds during the drying process. The top fans (3), which pull air through three copper coils (one fan per coil) were run at 100% of full load, while the bottom six fans and three front fans, which pull air out of the chamber were run at 20% of full load. Extech (model RHT10, Extech instruments, Nashua, NH, USA) relative humidity and temperature sensors were distributed inside the chamber and programmed to collect data every 30 min for every trial run.

Dehytray™

Three units of Dehytray™ were filled with a thin layer of tomato slices, with each tray holding approximately 2 kg., Three replications were conducted using tomato halves. Extech (model RHT10, Extech instruments, Nashua, NH, USA) temperature and relative humidity sensors were placed inside one tray of three replication per sample type (slices and halves) and the data loggers were programmed to collect data every 30 min during daytime while under the sun and overnight when placed in the barn till the end of the tests. Weight was measured for each tray twice per day (in the morning prior to taking the solar dryer outside and in the evening after moving the solar dryer indoors) using a digital scale platform. Like for the Dehymeleon™ studies, drying was tracked by loss in weight and tomato slices were inspected daily for signs of mold growth.

Figure 3.2. Dehytray^{TM} arrangement when placed under the sun during drying studies.

Open-air sun drying

The performance of the Dehytray^{TM} and Dehymeleon^{TM} technologies were compared against the commonly used open-air sun drying method. Approximately 2kg of sliced tomatoes were placed on the Dehytray^{TM} without the cover as shown in Figure 3.3 and placed under the sun daily until drying was accomplished. The trays were weighed using a digital scale platform twice per day as described before. The drying process was monitored until slices reached a constant weight. Ambient temperatures were tracked using a HOBO data sensor/logger (model MX 2300 RH&T, ONSET, Bourne, MA, USA).

Figure 3.3. Open-air drying trials with tomato slices using uncovered Dehytray™ trays.

3.3.3 Dying kinetics for thin layer drying and field tests

Moisture Ratio

During the drying process, moisture content decrease was controlled by the diffusion mechanism described by Fick's second law. The most used thin layer drying equation is similar to the Newton's law for cooling process, which assumes that the bulk moisture (*M*) depends on drying time (t), the integration of the differential, ($\Delta M/\Delta$t) and was calculated by the following expression:

$$Moisture\ Ratio\ (MR) = \frac{M_t - M_e}{M_i - M_e} = e^{-kt} \tag{1}$$

where (M_i) and (M_e) are the initial and equilibrium moisture contents, % (d.b), and (M_t) is the moisture content at any time t, % (d.b). The drying rate constant k is a function of drying air temperature, which was determined by linearizing the thin-layer drying equation:

$$\ln(MR) = \ln\left(\frac{M_t - M_e}{M_i - M_e}\right) = -kt \tag{2}$$

where (k) is the drying rate constant, min^{-1}, and (t) is the drying time, min. Data was plotted for the cycles of dried tomato slices, the drying rate (k) was obtained from the slope of the straight line of each falling rate identified. A polynomial regression was applied to the (*MR vs t)* curve, to identify falling rate periods in the case of thin layer tests. For field tests, an exponential regression to the form of Equation (1) was conducted with the software (Origin-Pro 2018b, Origin Lab Corporation, Northampton, MA, USA).

Diffusivity Calculations

Moisture diffusion (*D*) was calculated using Fick's second law, assuming tomato slices as a thin slab (Rajkumar et al., 2007) and due to the fact that most of the drying occurs in the falling rate period. For long periods of drying, a simplification of the slab equation is applied:

$$(MR) = \frac{M_t - M_e}{M_i - M_e} = \frac{8}{\pi^2} e^{\left(\frac{-D\pi^2}{4L^2}\right)} = A\, e^{\left(\frac{-D\pi^2}{4L^2}\right)} \tag{3}$$

Where, *(D)* is the diffusivity (m^2 /s), and (*L)* is the thickness of the sample (m). The effective moisture diffusivity values were determined by plotting experimental drying data in terms of *ln (MR)* versus drying time (t). A plot of *ln (MR)vs (t)* gives a straight line with a slope equal to (*S*). Knowing the tomato slice thickness and the slope from the above plot, the moisture diffusivity was calculated for different drying processes.

$$S = \left(\frac{-D\pi^2}{4L^2}\right) \tag{4}$$

Where *S* is the slope when plotting ln(*MR)* versus the drying time (t).

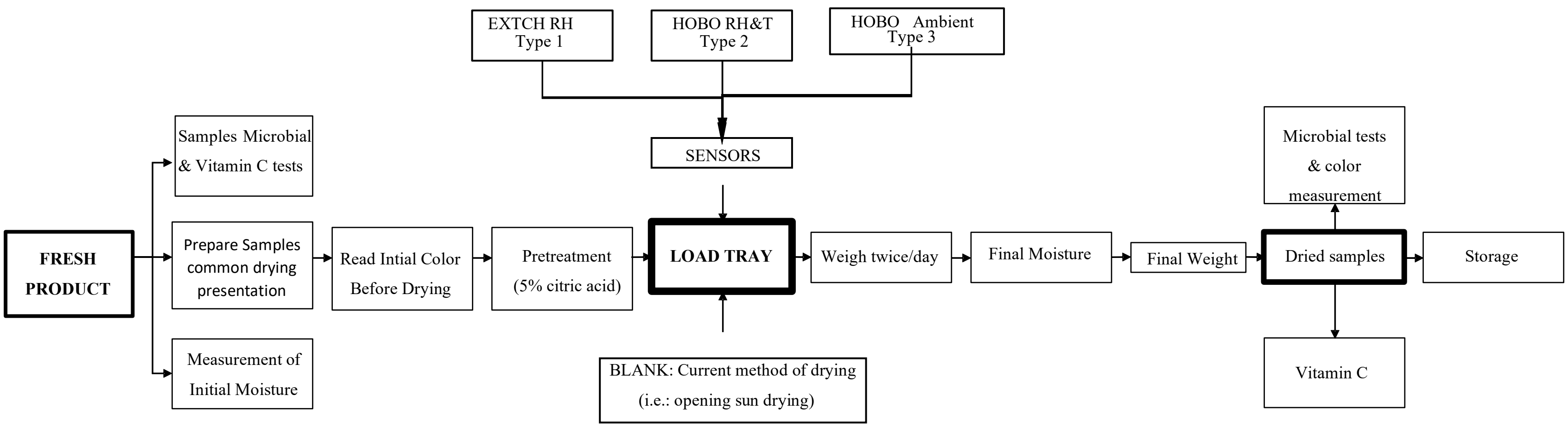


Figure 3.4. Sequence of processes used for the solar drying studies conducted at Purdue, West Lafayette, Indiana.

3.3.4 Quality indicators

Vitamin C quantification

Vitamin C concentration on fresh and dried tomatoes samples was determined by redox titration using iodine solution, to generate an oxide-reduction to convert ascorbic acid into dehydroascorbic acid, while the iodine was reduced to iodine ions (Eqn. 5).

$$\text{Ascorbic acid} + I2 \rightarrow 2\ I- + \text{Dehydroascorbic acid} \tag{5}$$

Samples of 100g where blended with a (Ninja blender) into 50ml of Nano purified water and strained through a paper filter. Six replicas were conducted per each drying technology. Solutions used: 1) Iodine solution with a concentration of [0.005 mol/L], 2) starch indicator [1%], 3) Sulfuric acid [3 mol], 4) Ascorbic acid [0.250g/100ml] for standard determination. Iodine solution was added with a burette to the dissolved sample with (0.5g) of the starch indicator. Reaction of free iodine with the starch indicator during titration indicate the concentration of ascorbic acid by calculating the volume used during the titration of the samples for tomatoes and the titration for the ascorbic acid standard (Canterbury, 2016).

$$Volume\ of\ Iodine\ solution\ (V_I) = \frac{Total\ volume}{number\ of\ trials} \tag{6}$$

Then, ascorbic acid was determined by eqn. 7:

$$(Total\ vitamin\ C) = \frac{V_I\ (samples\ titration)}{V_I\ (standard\ vitamin\ C)} * 0.250\ g\ (ascorbic\ acid) \tag{7}$$

Color change

Color on fresh and dried tomato slices was measured using a colorimeter, model CR-400 (Konica Minolta, Japan). Nine color measurements per batch of drying were conducted for both fresh and dried samples. The color values were $L*$, $a*$ and $b*$ color space. Color difference ΔE was determined by the following equation:

$$\Delta E = \sqrt{\left(L_0^* - L^*\right)^2 + \left(a_0^* - a^*\right)^2 + \left(b_0^* - b^*\right)^2} \quad (8)$$

Where: ΔE is the color difference and L_0^*, a_0^* and b_0^* are the color values for the fresh samples, green-red and blue-yellow chromaticity, respectively. Larger values of ΔE represent a larger color difference between dried samples from fresh samples. Minolta calibration plate of CR200 was used with 2 observer values.

Microbial Growth

Total Aerobic Count

Sampling and plating methods were based on the Bacteriological Analytical Manual (BAM) by FDA for Aerobic Plate Count (Donnelly et al., 1976). Four 25g of selected crops samples were taken from each of the fresh and dried product. Each sample was blended in 225 mL of Nano purified water, pH 7.0 (water) for 2 min using a Ninja blender. Three serial dilutions were performed using Nano purified water as the diluent and the samples were spread-plated on Total aerobic counting Petrifilm per the manufacturer's direction (3M Microbiology Products 1999). The plates were incubated for 48 h at 30°C and the average CFU/ml of total aerobic bacteria was calculated.

Yeast and mold quantification

All methods used were based on the BAM by the U.S. FDA for enumeration of yeasts and molds in food (Tournas et al. 2001). Four 25g of selected crop samples from each of the fresh and dried fruit or vegetable were added to sterile blender bottles with 225 mL of Nano purified water.

The samples were blended for 2 min to obtain a homogeneous mixture using a Ninja blender. The samples were then serially diluted in Nano purified water and spread-plated on counting Petrifilm per the manufacturer's direction (3M Microbiology Products 1999). The Petrifilm were incubated at 25°C for 5 days and the number of yeasts and molds enumerated and expressed as CFU/ml.

Quantification of total coliforms

Enumeration of total coliforms from the selected crops samples were conducted by using 3M Petrifilm^{TM} Coliform Count (CC; 3M Microbiology Product, St. Paul, MN). Five 25 g of samples were taken from each of the fresh and dried product of the selected crops. Each sample was blended in 225 mL of Nano purified water for 2 min using a Ninja blender. Samples were serially diluted in Nano purified water and planted on CC Petrifilm per the manufacturer's direction (3M Microbiology Products 1999). The CC Petrifilm was incubated at 35°C for 24 h, and the average CFU/ml of total coliforms was calculated.

3.4 Data Analysis

All observations were reported as means of the corresponding replications. One-way analysis of variance (ANOVA) was conducted using a means difference Turkey test with ($\alpha = 0.05$), using OriginPro 2018b package (Origin-Pro 2018b, Origin Lab Corporation, Northampton, MA, USA) to determine whether the quality indicators were significantly different for the various sun drying methods used.

3.5 Results and discussion

Thin layer drying experiments and a set of field experiments were performed in order to understand the drying behavior of tomato slices and tomato halves under diurnal solar drying cycles. This section presents the results for the separate tests and analyzes the drying characteristics of tomato slices using an empirical thin layer model and its relationship with the field results. The drying kinetics for the different test implemented were calculated besides the drying times for the different methods used, to understand the effect of temperature on drying behavior. Consequences of the difference in temperatures for the drying methods were investigated using quality assessment of vitamin C, color change, and microbial growth in the fresh and dried tomato slices.

3.5.1 Drying curves

Drying of tomato slices and tomato halves was conducted to consider the drying behavior for different drying methods named previously in this chapter. Different drying curves were plotted to understand the variation in moisture during the process. This section shows drying curves for TLDE, and field experiments using open-air sun dried, Dehymeleon™ and Dehytray™ methods. Curves of moisture ratio versus time, weight loss versus time, moisture content versus time, and drying rate are plotted for each drying method. Drying curves also show the relationship of moisture loss versus temperature and the reduction of relative humidity during the drying processes.

The examination of the following curves also helps to predict the mechanism of moisture loss for tomato slices and halves during drying. Analyzing the curves, it was found that tomato drying is characterized by a falling rate process, where the mass transfer is governed by the liquid diffusion or capillary flow as a property of the product that changes under the specific conditions of temperature in each experiment.

3.5.2 Thin layer drying experiments

Drying behavior was studied with lab experiments using a thin-layer drying apparatus to simulate the diurnal drying cycles through three temperature regimes [24°C (75°F), 35°C (95°F) and 54 °C (130°F)], which was changed every three hours until samples reached a constant weight. Product was dried on a surface area of 0.093 m^2 and an initial weight of 393.35 ± 25g (0.393 kg). Moisture ratio curve is shown in Figure 3.5 .

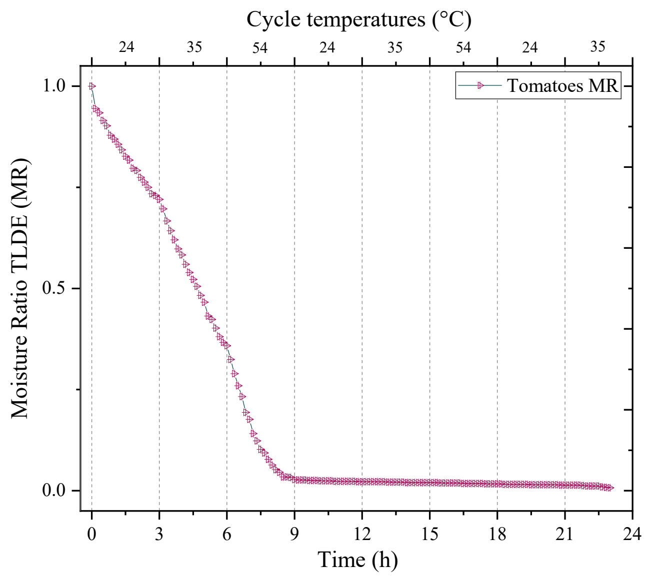


Figure 3.5. Moisture ratio versus time for TLDE test for tomato slices.

Evaluation of the TLD tests using TLD models

Newton, Page, Modified Midilli, and Henderson and Pabis TLD models were used as moisture ratio models to predict the moisture content of tomato during drying as a function of drying time. Values for the regressions are shown in **Table 3.1**. The four models showed a high coefficient of determination (R^2) for the diurnal drying cycle simulated in this study. From the models, the Page had the highest R^2 and lowest SSE, thus, it was selected to represent the thin layer drying behavior for tomato slices used in this study. The Page model has been found to be the most suitable model for tomato drying in other studies by Das Purkayastha et al. (2013), Belghith et al. (2016), and Belghith et al. (2016), Rajkumar et al. (2007) and Sacilik et al. (2005).

Table 3.1. Mathematical models applied to thin layer drying curves.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k=0.2022 ± 0.017	0.932	0.866	0.079
Page	$MR = e^{-kt^n}$	k = 0.046 n= 1.833 ± 0.09	0.987	0.164	0.034
Modified Midilli	$MR = ae^{-kt} + b$	a = 1.171 ± 0.047 b = -0.039 ± 0.022 k = 0.205 ± 0.019	0.952	0.067	0.613
Henderson and Pabis	$MR = ae^{-kt}$	a = 1.15 ± 0.052 k = 0.228 ± 0.015	0.946	0.679	0.070

Drying rate and diffusivity

Thin layer experiments conducted to simulate a solar drying cycle does not present a constant drying rate, instead, the drying process is governed by a falling rate where the drying ratio decreases continuously with the reduction in moisture content and the increment in drying time. The process was characterized by four falling rates, due to the periodical changes in temperature. The falling rate changes every three hours as is shown in

Figure 3.5, but tend to be constant as samples approach constant weight. Specific values for each falling rate are shown in **Table 3.2**. Drying behavior of tomato under the drying conditions can be explained by the moisture diffusivity of the product, which increases with temperature, and thus, for the third falling rate, moisture diffusivity reaches its maximum value. This phenomenon occurs because the bond of water molecules with the food matrix is lost and the energy to remove water decrease at higher temperatures. During this time and in most part of the drying test, the diffusion of liquid water is the primary mass transfer mechanism. The drying rates are related to temperature, and most closely to water content. When the drying temperatures increase, drying rates increases as well. As moisture is reduced to the air equilibrium moisture content (EMC), the drying rate gradually decreases toward an infinitesimally value of EMC. This phase is the most difficult phase of moisture loss because moisture release is from more closely bound water.

Table 3.2. Drying kinetics for tomato slices TLDE.

Main falling rates	Total drying time (h)	Average temperature (^{0}C)	Initial MC%	Final MC%	Drying Rate (kg H_2O/h*m^2)	Moisture Diffusivity D_{eff} (m^2/s)
1st Falling rate	1-3	24	94.10	91.40	0.1180	11.964x 10^{-7}
2nd Falling rate	3-6	35	91.40	78.81	0.1529	15.492x 10^{-7}
3rd Falling rate	6-9	54	78.81	29.27	0.9254	93.762x 10^{-7}
4th Falling rate	9-22	37.7	29.27	11.14	0.0505	51.167 x 10^{-7}

The implementation of thin layer tests helps to understand what target temperatures are required to optimize the drying rate during the drying of tomato. As is shown on **Table 3.2**, most of the reduction of the tomatoes water content occurs in the first nine hours, and this results agree with the study by Das Purkayastha et al. (2013).

Sample preparation method also affects the rate of drying. For example, it is necessary to cut tomato into thin slices, which reduces the path to moisture loss, increases the drying surface area, and provides a good exposure of the inner core for the release of water to the environment. The thin-layer tests, which mimic the diurnal changes in temperatures provided a good comparison between drying using constant heat versus changes in heat over the drying period. Constant heat was only 3 hours faster than cyclic heating during drying of tomato slices for a constant temperature of 50°C.

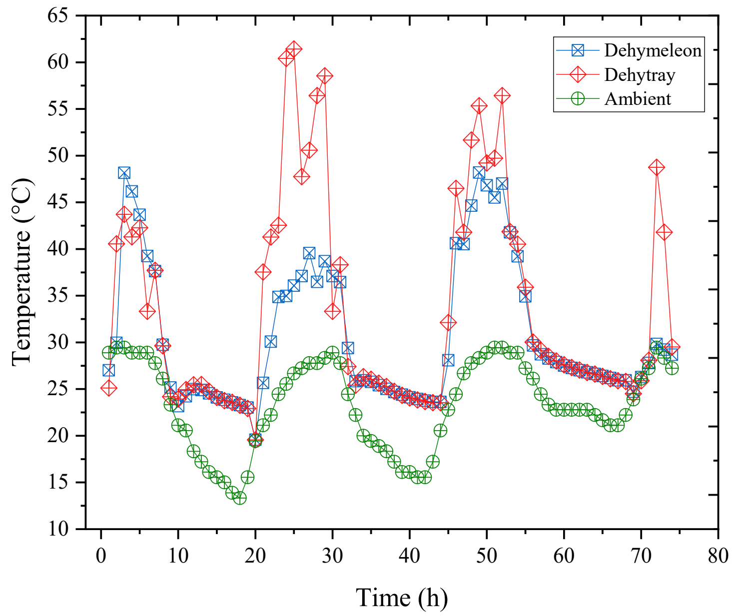
3.5.3 Field experiments for open-air sun drying, Dehytray™, and Dehymeleon™

During the four days of tomato slices drying experiments (July 17 and July 20 of 2018), temperature and relative humidity data was collected and is shown in Figure 3.6. The air and product temperatures started increasing significantly during noon times and decreased in the evening hours, whereas the relative humidity reached the lowest value during direct exposure to sunlight during sunshine hours. Diurnal exposure to sunlight was between the first 10 hours, second day between 20 to 35 h, third day 48 to 58 h and fourth day from 70 to 75h. It was observed that the temperatures inside the Dehytray™ and Dehymeleon™ were higher than ambient air temperature. The difference between the ambient temperature of open-air sun drying and the Dehytray™ and Dehymeleon™ was 27 ºC and 16.6 ºC on average, respectively.

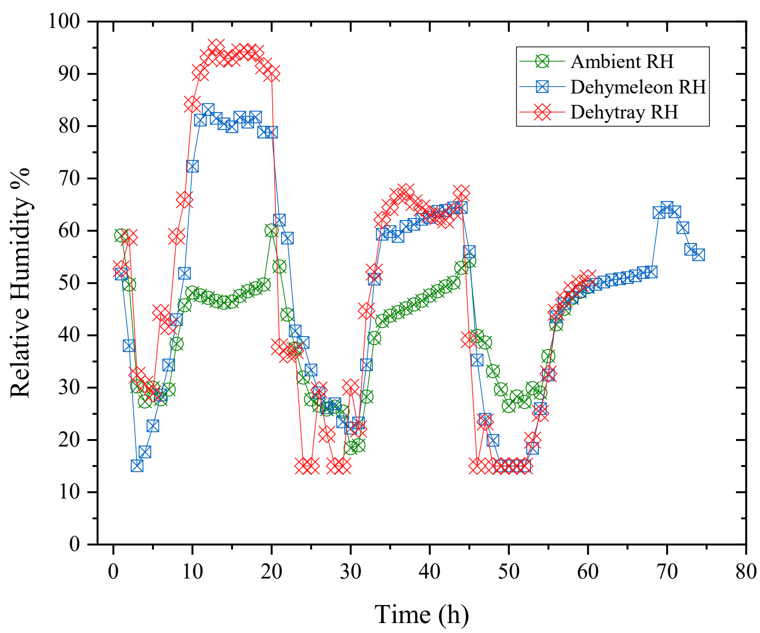
Higher temperatures are due to the enclosure and the heat concentration on the top solar collector in the case of Dehymeleon™. Consequently, relative humidity decreased due to the high temperatures inside the enclosed drying chamber but increased during the night due to the trapped moisture of the product under the cool chamber temperature. In some cases, increments of relative humidity may lead to rehydration of the product overnight and condensation of water inside the drying chambers of both the Dehytray™ and Dehymeleon™. Note that no condensation was observed during drying of tomato using the Dehytray™ and Dehymeleon™. As was expected, it was very evident that temperatures were highly influenced by the weather (ambient air temperature, relative humidity, and air flow) during the drying test. Weather conditions for each day were slightly different, following a constant pattern for ambient temperature.

Open-air sun drying tomato slices

Open-air sun drying is the most common drying technique used by growers; therefore, it was used as the performance comparison method for the Dehytray™ and Dehymeleon™ drying experiments. Change in moisture content, moisture ratio, drying rate, and moisture diffusivity were measured and calculated for this drying process and are shown in Figure 3.7. Initial moisture content of the tomato slices was 94.1% (w.b) and reached a final moisture content of 16.1% (w.b) after 30 hours of sunlight exposure and 60 hours of the whole process, which included the nighttime hours in an enclosed barn. Open-air sun drying presented a better performance during the first 12 hours of the test, reducing the water content of the sample by 45.76%, while the Dehymeleon^{TM} reduced moisture by 22.81%, and Dehytray^{TM} by 32.08% (percentage points of moisture).



a)



b)

Figure 3.6. Profile temperatures a) and relative humidity b) for Open-air (Ambient), Dehytray™ and Dehymeleon™ during the drying of tomato slices.

Values for moisture content changes are shown in **Table 3.3**. Faster drying rates for the open-air sun drying could be explained by the direct exposure of tomato slices to sunlight and better air flow in the open, compared to the enclosed nonaerated Dehytray™ and poorly aerated Dehymeleon™ solar dryers. Water released from the product is also liberated to the environment and rehydration caused by the same water removed is unlikely to occur if stored in an air-tight sealed package. The final product had a water activity of 0.49, making the product storage stable for increased shelf life, reducing the risk of microbial growth and deterioration from other undesired spoilage organism. Reduction of water activity during the first hours of the drying process, played an important role on the final quality of the product, reducing the possibility of enzymatic activity. However, sun drying is also linked to the loss of important nutrients due to faster drying rate under high temperatures, which denature nutrients such as vitamin C.

Table 3.3. Weight change, moisture content, moisture ratio for tomato slices dried by open-air sun drying using the Dehytray™ without the cover on.

Time (h)	**Weight (kg)**	**Moisture content % (w.b)**	**Moisture ratio (MR)**
0	1.96 ± 0.06	94.10	1.000
12	1.07 ± 0.06	48.34	0.058
24	1.01 ± 0.10	44.95	0.051
36	0.60 ± 0.10	24.61	0.020
48	0.57 ± 0.06	22.91	0.018
60	0.43 ± 0.06	16.13	0.012

t.d test done

The reduction of moisture content during the first hours of open-air sun drying has a similar trend that the drying behavior presented by tomato slices during the thin layer drying test. The drying curves, moisture ratio curve and temperature/RH for open-air sun drying are shown in Figure 3.7.

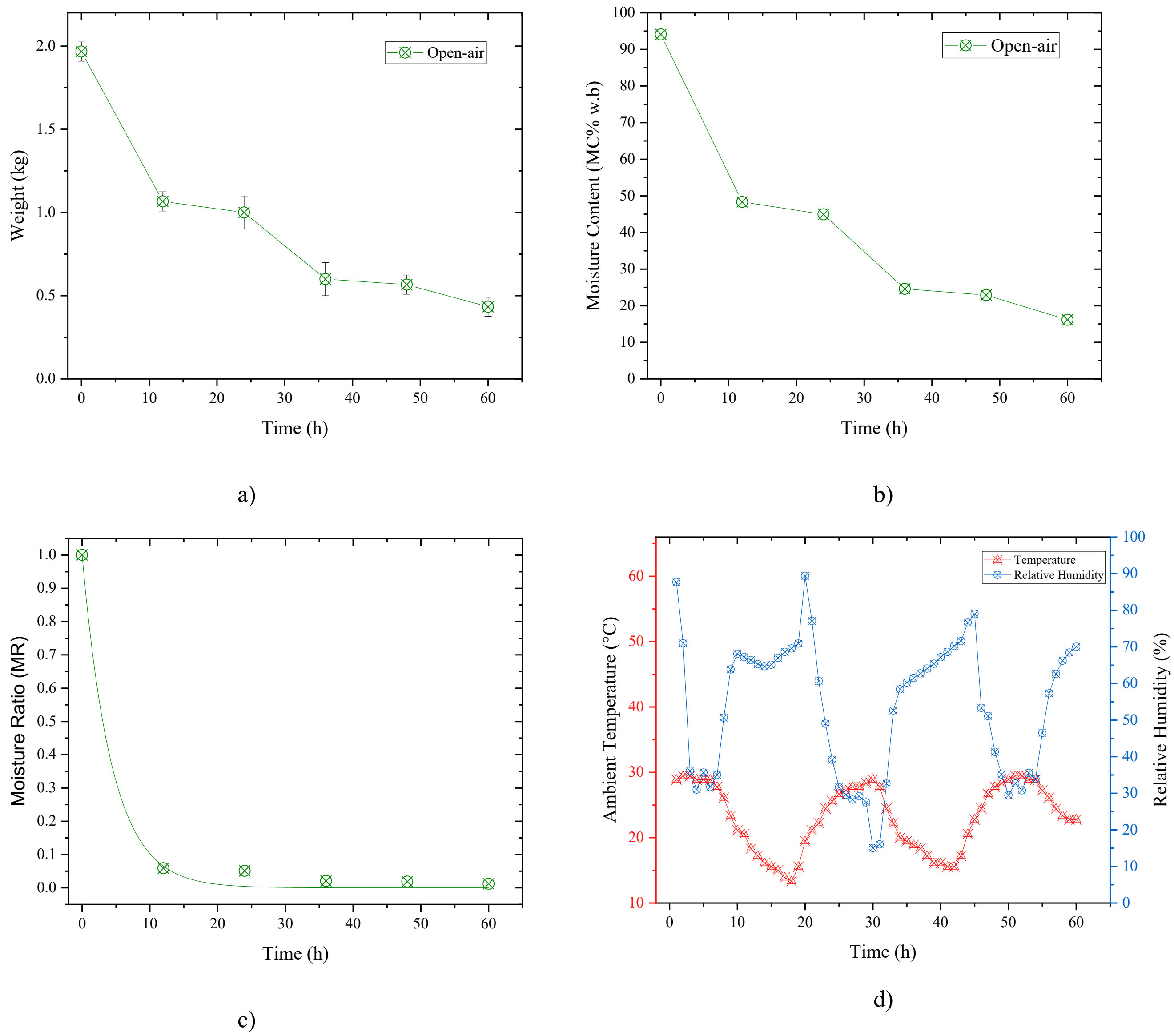


Figure 3.7. Open-air drying curves, temperatures and relative humidity values during the drying of tomato slices a) Weight loss, b) Moisture content change, c) Moisture ratio variation versus time and d) Ambient temperature and relative humidity.

Evaluation of the model for moisture ratio

Trend of moisture loss for open-air sun drying shows a similar trend as TLDE. This is reflected in the models by Newton, Page, Modified Midilli, and Henderson-Pabis, which were used as moisture ratio models to predict the moisture content as a function of drying time fitted with a high coefficient of determination (R^2). Values for the regressions are shown in **Table 3.4** and the Page model had the highest R^2 and lowest SSE, representing the best fit.

Table 3.4. Mathematical models applied to the open-air drying curve.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton (19XX)	$MR = e^{-kt}$	k=0.228 ± 0.082	0.996	3.15 x 10^{-3}	2.5 x 10^{-2}
Page model (19XX)	$MR = e^{-kt^n}$	k = 1.481 ± 0.767 n= 0.251 ± 0.154	0.999	2.6 x 10^{-4}	8.0 x 10^{-3}
Modified Midilli (19XX)	$MR = ae^{-kt} + b$	a = 0.975 ± 0.059 b= 0.025 ± 0.027 k= 0.275 ± 0.141	0.998	1.6 x 10^{-2}	8.5 x 10^{-4}
Henderson and Pabis (19XX)	$MR = ae^{-kt}$	a = 0.999 ± 0.078 k= 0.227 ± 0.099	0.995	3.0 x 10^{-3}	2.8 x 10^{-2}

Dehymeleon™ - tomato slices

Drying of tomato slices with the Dehymeleon™ was done for approximately six kilograms of tomato slices divided in three trays for sample replication. Trays were put inside the dryer in specific positions and changed during subsequent trials, so that they all experienced a different location inside the dryer to diminish bias. Trays were weighed two times per day (at the beginning and end of the day) and inspected to check for changes in quality by visual inspection. Quantitative quality assessment of vitamin C and microbial growth of yeast, mold and aerobic bacteria was conducted for fresh and dried samples. Every day after exposure under the sun, the Dehymeleon™ was taken inside the ADM Agricultural Innovation Center workshop building for storage overnight. It was found that tomato slices reabsorbed moisture during the night period, which may have been caused by the increase in relative humidity and decrease in temperature typical at night. The increment on relative humidity increases the risk of microbial growth and product deterioration, indeed low reduction of moisture during the first 12 hours of drying, also contributed to quality deterioration, that is further studied in section 3.5.4 of this chapter. However, the Dehymeleon™ prevented the sample from being contaminated from external factors such as dust and debris. As an enclosed method, temperatures inside the dryer rose 16.6 ºC over the ambient temperature and reduced the relative humidity for the heated air by half for the first and third day. The first drying trial was not uniform for all the trays due to the position of the trays in the drying chamber., characterized by three different levels inside the drying chamber of the Dehymeleon™. Tomato slices in the tray at the bottom dried slower than slices in the tray at the top, primarily due to cooler temperature and lower airflow at the bottom tray compared to the top tray. Reduction of moisture content during the first hours of drying contrast with the drying behavior of tomato slices during the thin layer drying experiments. The drying curves, moisture ratio curve and temperature/RH for tomato slices drying in the Dehymeleon™ are shown in Figure 3.8.

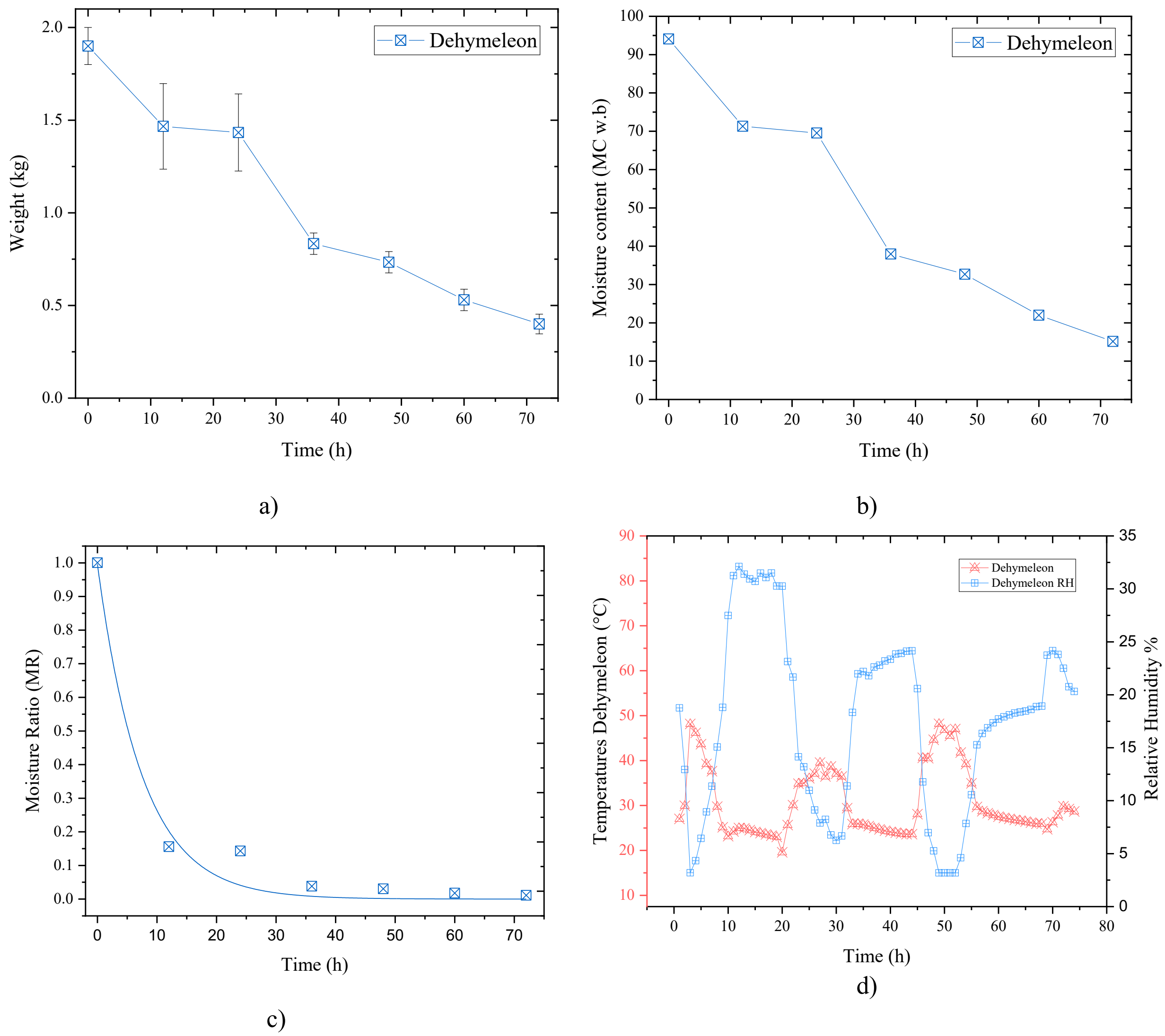


Figure 3.8. Dehymeleon™ drying curves, temperatures and relative humidity values during the drying of tomato slices a) Weight loss, b) Moisture content change, c) Moisture ratio variation versus time and d) Ambient temperature and relative humidity.

Table 3.5. Weight change, moisture content, moisture ratio for tomato slices dried using the Dehymeleon™.

Time (h)	Weight (kg)	Moisture content % (w.b)	Moisture ratio (MR)
0	1.90 ± 0.10	94.10	1.000
12	1.47 ± 0.23	71.29	0.156
24	1.43 ± 0.21	69.54	0.143
36	0.83 ± 0.06	37.96	0.038
48	0.73 ± 0.06	32.70	0.030
60	0.53 ± 0.06	21.99	0.018
72	0.40 ± 0.05	15.15	0.011

Evaluation of the model for moisture ratio

The drying behavior of tomato slices by Dehymeleon™ was modeled using moisture ratio models by: Newton, Page, Modified Midilli, and Henderson-Pabis, to predict the moisture content as a function of drying time fitted with a high coefficient of determination (R^2). Values for the regressions are shown in **Table 3.6** and the Page model had the highest R^2 and lowest SSE, representing the best fit.

Table 3.6. Mathematical models applied to the Dehymeleon™ drying curve.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k=0.133 ± 0.046	0.9808	0.015	0.049
Page model	$MR = e^{-kt^n}$	k = 0.579 ± 0.468 n= 0.445 ± 0.260	0.9954	0.004	0.026
Modified Midilli	$MR = ae^{-kt} + b$	a = 0.959 ± 0.144 b= 0.038 ± 0.063 k= 0.159± 0.085	0.9827	0.008	0.471
Henderson and Pabis	$MR = ae^{-kt}$	a = *0.995* ± 0.139 k= 0.132± 0.054	0.977	0.015	0.054

Dehytray™- tomato slices and halves

Two different group of drying experiments were conducted using the Dehytray™ drying method. One was done for approximately six kilograms of tomato slices, divided in three

Dehytrays with their respective covers, while the second group of tomato halves was around six kilograms divided in three Dehytrays. In this section, the two studies are described.

Tomato slices

Tomato slices having an initial moisture content of 94.1% were placed in three different Dehytrays with the transparent cover in place and were dried till they reached 12.1% final moisture content. The trays were inspected and weighed and data on weights were collected twice per day, specifically in the morning before starting the trials and when the trays were placed at dusk inside ADM Agricultural Innovation Center at Purdue University overnight. Dehytray™ removed 32.08% points of moisture during the first 12 hours, 10% more than the Dehymeleon™ which removed just 22.81% points of moisture, but 13.68% less than open-air sun drying. This difference with open-air sun drying could be explained by the less airflow present inside the Dehytray™, which caused a lower drying rate at the beginning of the trials. Although, Dehytray™ did not have direct exposure to air, it represents an advantage, because it protects the product from external contamination factors. As a result of the transparent cover, direct exposure to sun and higher drying temperatures in the covered tray also gives the Dehytray™ a better performance in controlling microbial growth, but not in color retention as is evaluated in section 3.5.4 in this chapter. Weight data for tomato slices dried using the Dehytray™ is shown in **Table 3.7**.

Table 3.7. Weight change, moisture content, moisture ratio and drying rate constant for tomato slices dried using the Dehytray™.

Time (h)	**Weight (kg)**	**Moisture content % (w.b)**	**Moisture ratio (MR)**
0	1.77 ± 0.06	94.10	1.000
12	1.20 ± 0.00	62.02	0.102
24	1.10 ± 0.10	56.36	0.081
36	0.43 ± 0.06	18.63	0.014
48	0.40 ± 0.00	16.74	0.013
60	0.33 ± 0.06	12.97	0.009

Temperatures profiles and relative humidity inside the Dehytray™ is show in Figure 3.9 d), the delta of temperature compared with the ambient is 27ºC on average, almost doubling the ambient temperature and ten degrees higher than the Dehymeleon™. This characteristic gain in temperature, allowed the Dehytray™ to reduce the relative humidity during the diurnal exposure to sun and reduced the drying time by 12 hours compare with the Dehymeleon™. However, the drying time used by the Dehytray™ was almost the same as that for open-air sun drying, with a variation on the final moisture content and ERH, due to the specific conditions of each method. For the Dehymeleon™, the relative humidity inside the drying chamber increased overnight due to the reduction of temperatures to almost ambient. However, as the reduction in moisture content was higher during the first 12 hours, samples had a lower risk of developing any enzymatic reaction and microbial growth, as in section 3.5.4.2.

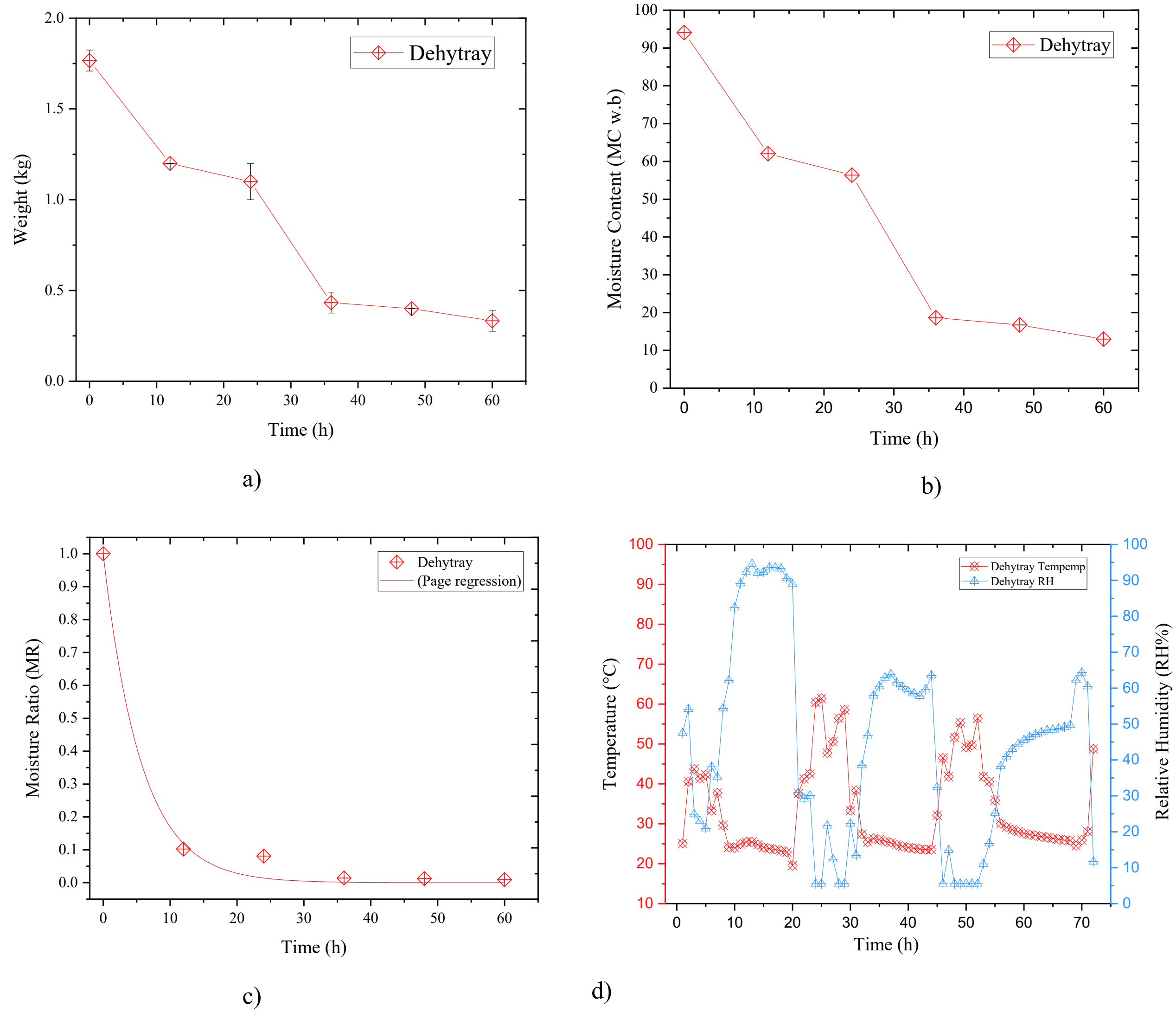


Figure 3.9. Dehytray™ drying curves, temperatures and relative humidity values during the drying of tomato slices a) Weight loss, b) Moisture content change, c) Moisture ratio variation versus time and d) Ambient temperature and relative humidity.

Evaluation of the model for moisture ratio

As had been studied for the different drying methods used in this test, modeling of the moisture ratio to predict the moisture content as a function of drying time was done using the following models: Newton, Page, Modified Midilli, and Henderson-Pabis, which fitted with a high coefficient of determination (R^2). Values for the regressions are shown in **Table 3.8**. As for the drying behavior shown during the TLDE, Page model had the highest R^2 and lowest SSE.

Table 3.8. Mathematical models applied to Dehytray™ drying curve for tomato slices

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	*k*=0.177 ± 0.056	0.993	0.005	0.032
Page model	$MR = e^{-kt^n}$	k = 0.787 ± 0.660 n= 0.416 ± 0.288	0.998	0.001	0.017
Modified Midilli	$MR = ae^{-kt} + b$	a = 0.974 ± 0.112 b= *0.025* ± 0.052 *k*= 0.203 ± 0.110	0.993	0.002	0.031
Henderson and Pabis	$MR = ae^{-kt}$	a = 0.999 ± 0.100 *k*= 0.177 ± 0.068	0.993	0.005	0.035

Tomato halves

Tomato halves were dried from an initial moisture content of 94.1% to 33.3% moisture content at the end of the test. The change in moisture and weight over time is shown in **Table 3.9**. This set of experiments were done in order to replicate the common drying practice of tomato halves. Although the temperatures inside the Dehytray™ presented the same profile as shown in Figure 3.9 d). The epidermis or skin of tomato cut into halves, behaves as a membrane and slows the drying process, while in tomato slices moisture is released from both sides having a higher surface area. Drying tomato cut in halves only allows moisture to be effectively released from one side (the cut exposed side), which increases the drying time. The reduced drying rate allowed some microorganism, yeast and mold enough time to propagate and spoil the product before it was sufficiently dried to its end-point equilibrium moisture content. Figure 3.10 shows the extent of deterioration of the tomato halves, where each picture shows a different drying stage during the test. The drying tests on tomato halves had to be stopped because of the early onset of spoilage, and quality assessment was unable to be performed on the product due to the extent of deterioration.

Table 3.9. Weight change, moisture content, moisture ratio and drying rate constant for tomato halves dried using the Dehytray™.

Time (h)	**Weight (kg)**	**Moisture content % (w.b)**	**Moisture ratio (MR)**
0	1.70 ± 0.10	94.10	1.000
12	1.53 ± 0.06	84.30	0.337
24	1.40 ± 0.10	76.45	0.204
36	1.10 ± 0.10	58.81	0.090
48	0.97 ± 0.06	50.96	0.065
60	0.70 ± 0.06	35.28	0.034
72	0.67 ± 0.06	33.32	0.031

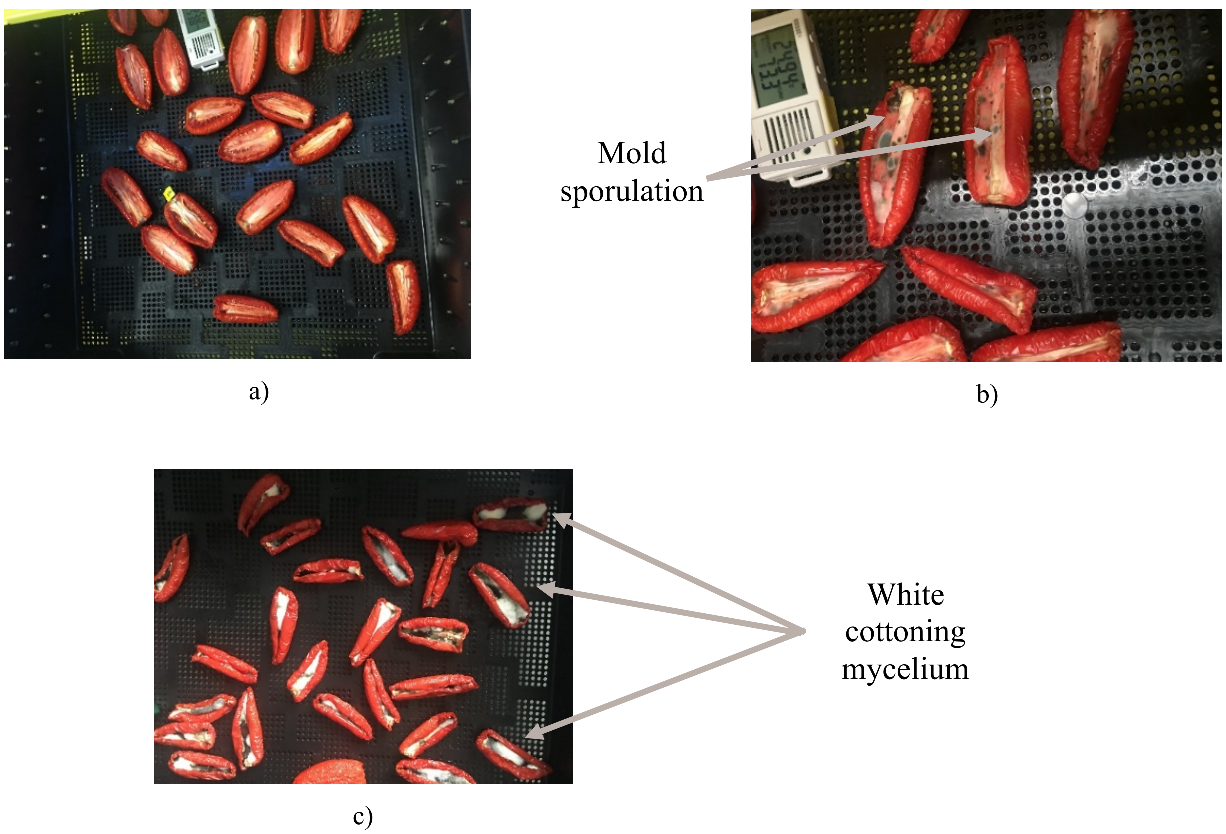
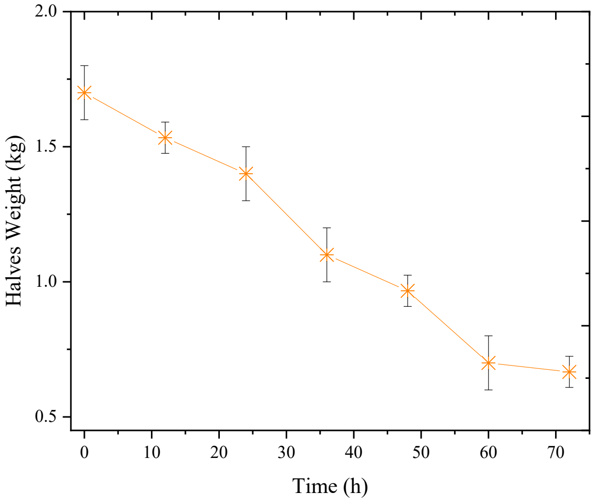
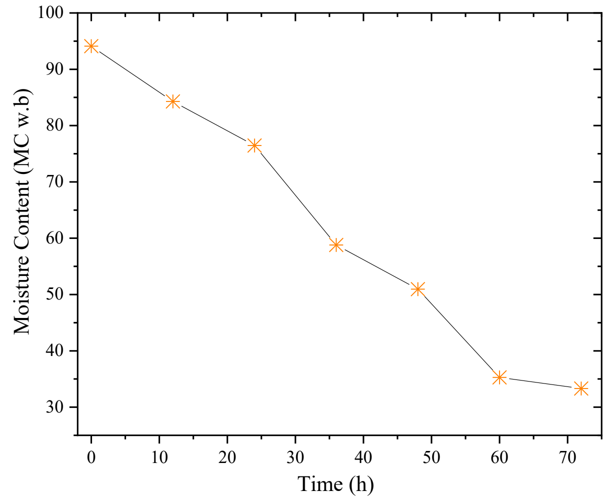


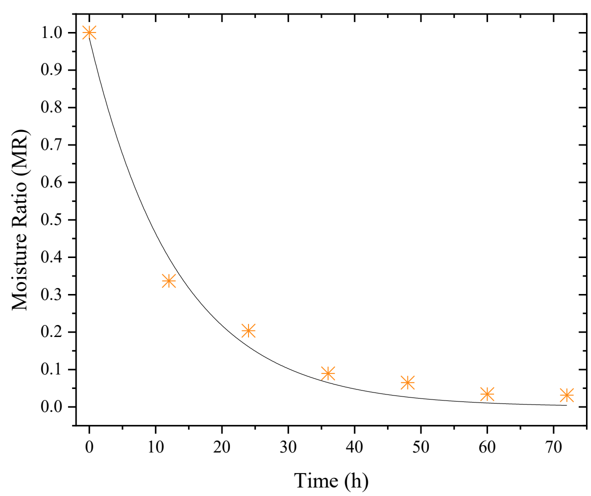
Figure 3.10. Tomato halves three days' check, a) 24 hours, b) 48 hours, c) 72 hours of the drying test.



a)



b)



c)

Figure 3.11. Dehytray^{TM} drying curves, temperatures and relative humidity values during the drying of tomato halves a) Weight loss, b) Moisture content change, c) Moisture ratio variation versus time.

Evaluation of the model for moisture ratio

Correlation with the open-air sun drying explained the first hours of the TLD. As for TLD, Newton, Page, Modified Midilli, and Henderson and Pabis models were used as moisture ratio models to predict the moisture content as a function of drying time fitted with a high coefficient of determination (R^2). Values for the regressions are shown in **Table 3.4**. As for the drying behavior shown during the TLD, the Page model had the highest R^2 and lowest SSE.

Table 3.10. Mathematical models applied to Dehytray™ drying curve for tomato halves.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	*k*=0.0765 ± 0.0145	0.987	0.009445	0.03968
Page model	$MR = e^{-kt^n}$	*k* = 0.197 ± 0.0631 *n*= 0.6797 ± 0.1011	0.9985	0.0008815	0.01328
Modified Midilli	$MR = ae^{-kt} + b$	*a* = 0.9487 ± 0.097 *b*= 0.04549 ± 0.051 *k*= 0.08926 ± 0.024	0.992	0.003942	0.03139
Henderson and Pabis	$MR = ae^{-kt}$	*a* = 0.9851 ± 0.1089 *k*= 0.0754 ± 0.01767	0.9848	0.00922	0.04295

Drying of tomato halves is an important practice in the industry due to the simplicity of product preparation for drying. However, in areas with unpredictable cool temperatures and high precipitation (RH of over 60%) in the summer such as Indiana, drying of halves represents a risk when 5 to 7 sunshine days with no precipitation cannot be guaranteed. In other words, drying of tomato halves is suitable for locations where weather conditions are mostly dry, with no precipitation during the drying season such as in California, and in sahelian tropical countries. For the more humid climates, drying tomato slices are a better option.

Drying rate and diffusivity

Drying rate of tomato slices with three different methods was studied. Additionally, one method for tomato slices was used as a real case approximation. The method used for comparison was open-air sun drying. The drying rate constant k was determined for the tomato slices dried and for the three different methods by plotting the drying data ln(MR) vs. drying time. A summary of the regressions conducted is presented in Appendix 1. The results are presented in **Table 3.11**. From the table, it was observed that the drying rate constant k value is consistent with the results obtained and analyzed previously in this chapter, where open-air sun drying and Dehytray™ show higher drying rates. As expected, the drying rate was lower for halves dried in the Dehytray™ and Dehymeleon™.

Based on Fick's moisture diffusion model, the moisture diffusivity of tomato slices was obtained, and the values are presented in **Table 3.11**. The moisture diffusivity of tomato slices dried using the Dehytray™ (7.89×10^{-7} m^2/s) was higher than the value for open-air sun dried slices (7.46×10^{-7} m^2/s) and Dehymeleon™ (6.32×10^{-7} m^2/s). This is consistent with the trend of moisture removal by each method, even when open-air sun drying removed most of the water during the first day, the trend in diffusivity helps understanding the mass transfer rate to the ambient, and contrast with the result per method. The Dehymeleon™ had low mass transfer to the environment than open-air and Dehytray™. Dehymeleon™ could not be used to successfully dry tomato halves and would need to be improved to enable the drying chamber to achieve a high uniform temperature coupled with good airflow.

Summary of drying hours per technology

Final drying time was established when a constant weight of dried product was reached in each method. The final moisture contents varied due to the difference in microclimates that generated different equilibrium moisture contents, but still on the ranges proposed by (Kiranoudis et al., 1993). However, the actual drying time, that is the time the tomato was exposed in the sun was calculated as compared to the diurnal cycles completed by each method. This gave a better idea of the effective time that the crop was being dried and helps to understand how many hours of sunshine at the specific temperatures was needed to accomplish the desired moisture content.

Table 3.11. Drying time for the different methods, initial and final moisture content, and drying rate with moisture diffusivity.

Drying method	Total drying time (h)	Sun-exposed Time (h)	Initial MC%	Final MC%	Drying Rate kg $H_2O/h*m^2$	Moisture diffusivity D_{eff} (m^2/s)
Open-air (slices)	60	30	94.10	16.13	0.063 ± 0.016	7.46 x 10^{-7}
Dehymeleon™ (slices)	72	36	94.10	15.15	0.057 ± 0.007	6.32 x 10^{-7}
Dehytray™ (slices)	60	30	94.10	12.97	0.075 ± 0.013	7.89 x 10^{-7}
Dehytray™ (halves)	>72[1]	N.A[2]	94.10	33.32	0.047 ± 0.004	4.15 x 10^{-7}

3.5.4 Quality indicators for tomatoes slices

Quality assessment of tomato slices was conducted for three main indicators: Vitamin C content, microbial growth and color change. Numerous studies have been carried out on vitamin C and color change for dried tomato slices. However, studies for microbial growth when drying with solar techniques is limited. The following sections present the results for the quality indicators and compare the values for fresh and dried samples for each drying method used on tomato slices.

Vitamin C content

Vitamin C is a thermolabile compound in most food products (Hussein et al., 2016). Its easy denaturation by heat make it a nutrient of interest when studying thermal processes such as drying, and how different temperatures affect its concentration. Consequently, in this study, the initial and final contents of vitamin C for tomato slices dried with three different methods were measured and evaluated, and are shown in **Table 3.12** and Figure 3.12. It was observed that the reduction in vitamin C content was related to high temperatures and direct exposure of tomato to sunlight. On

[1] Drying time was not calculated due to the need of stopping the test
[2] N.A, it does not apply because the test had to be interrupted before reaching equilibrium moisture content.

the contrary, Hussein et al. (2016) and Rajkumar et al. (2007) reported that temperature worked as a catalyzer for the oxidoreduction reaction that reduces vitamin C or ascorbic acid into dehydroascorbic acid. The Dehytray^{TM} that recorded the highest temperature during the tests, reduced the vitamin C content in dried tomato to 79 ± 7 (mg/100g d.m), from an initial vitamin C content of 260 ± 13 (mg/100g d.m) in the fresh tomato, which was significantly different ($\alpha \leq 0.05$) than the vitamin C content in dried tomato. The case of Dehytray^{TM} was also similar to open-air sun drying due to direct sunlight exposure. A similar result for drying methods directly exposed to sunlight were presented by Giovanelli et al. (2002) , which confirms the impact of temperatures and light on the degradation of vitamin C. The vitamin C of tomato slices dried using the open-air sun drying method were significantly different from fresh tomato and tomato slices dried using the Dehymeleon^{TM} but not significantly different from tomato slices dried using the Dehytray^{TM}. A similar value of the vitamin C content of tomato slices dried using open-air sun drying was 76 ± 8 (mg/100g d.m), which was also similar to that obtained by Giovanelli et al. (2002). The vitamin C content of tomato slices dried using the Dehymeleon^{TM} were comparable to the values from the study conducted by St George et al. (2004) for lyophilized tomato dried under temperatures similar to the average temperature inside the solar dryer, Dehymeleon^{TM}, which had a higher vitamin C content than the other drying methods used in this study. The total time of processing tomato or its direct exposure to high temperatures and direct sunlight is also an important factor that affects the denaturing of vitamin C. Although the total time for drying tomato slices using the Dehymeleon^{TM} was longer compared with the Dehytray^{TM} and open-air sun drying, the shade provided by the drying chamber of the Dehymeleon^{TM} protected the product from vitamin C degradation.

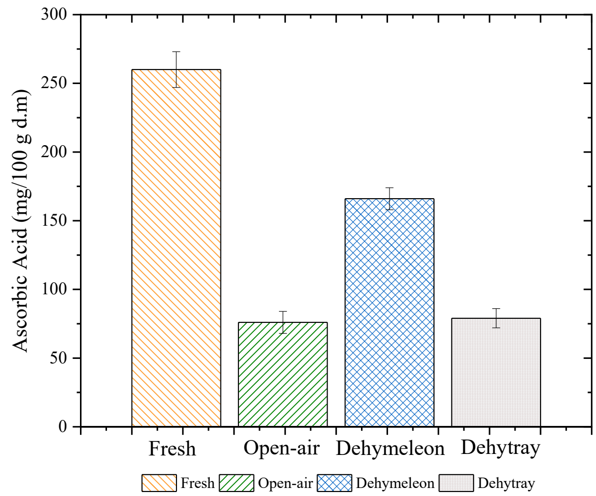


Figure 3.12.Comparison of vitamin C content of dried tomato slices for the three drying methods investigated against the value of fresh tomato.

Table 3.12. Vitamin C content for fresh tomatoes, and tomato slices dried by open-air sun drying, Dehymeleon™ and Dehytray™ solar dryers

	Fresh	**Open-air sun drying**	**Dehymeleon™**	**Dehytray™**
Vitamin C (mg/100g d.m)	260 ± 13 [a]	76 ± 8 [b]	166 ± 8 [a]	79 ± 7 [b]

In concluding, the reduction of vitamin C for the two methods with direct exposure to sunlight was around 70% from the fresh value, while reduction of vitamin C for Dehymeleon™ solar dryer was just 36%. This results are in agreement with the study by Goula and Adamopoulos (2010), Hussein et al. (2016), and St George et al. (2004). For significant reductions in vitamin C, as was the case of the Dehytray™ solar dryer other authors reported a reduction of 88% for temperatures between (70ºC-80ºC)(Lavelli et al., 1999). A similar pattern in vitamin C reduction was also found by Kadam et al. (2012).

Microbial growth

Microorganism are naturally present in fresh fruits and vegetables, due to their exposure to natural contaminants. Microbiota found on these kinds of food are commonly related to those present in the environment (Rosa et al., 2010). Therefore, vegetables such as tomato can be cross contaminated from the planting of the crop, and the following processes such as irrigation, harvesting, postharvest, and retailing. Factors that affect propagation or easy access to vegetable tissue are cuts during processing, and bruises incurred during transportation to name a few of them (Bourdoux et al., 2016b). Although, microbial biota is intrinsic of live products such as vegetables, its increment due to factors previously mentioned can result in quality degradation, serious spoilage, loss in economic value of the product, losses in production, recalls, and public health problems such as foodborne diseases due to mycotoxins, which are resistant to some thermal processes (Drusch and Aumann, 2005). Consequently, minimally processed fresh fruits are a good media for microbial growth, and particularly in the case of low temperature drying, were temperatures are not enough for reduction of microorganism and in some cases its inactivation (Nguyen-The and Carlin, 1994). In the case of tomato slices, more than one factor is present to increase microbial growth. This section presents measurements of fresh and dried tomato slices by three different drying methods by comparing colony forming units (CFU) of aerobic bacteria, yeast and mold, and coliforms before and after drying. The CFU measurement of microorganism is a general count and does not differentiate the counts of specific pathogens (i.e. *Salmonella*) or varieties of yeast and molds or *E. coli*.

Aerobic Count

Total aerobic plate count for tomato slices, fresh and dried is shown in Table 3.13. There was an average of $1.17x10^3$, $1.83x10^3$, and $6.67x10^2$ CFU/ml for the aerobic bacteria present on the fresh tomato, and dried tomato slices using the open-air drying and Dehytray™ methods, respectively. There was no significant difference in aerobic bacteria count between the fresh, tomato and dried tomato slices using open-air sun drying and the Dehytray™., neither was the CFU reduced during drying. Direct exposure to sunlight and peak temperatures around 70ºC for Dehytray™ are associated with bacteria inactivation, although, studies by Nguyen-The and Carlin (1994) suggest the kind of bacteria might have changed during the process. This means, as an example, *Listeria monocytogenes*, which is common in fresh tomatoes will die when they are cut into slices due to the changes in the pH media as was studied by Beuchat and Brackett (1991).

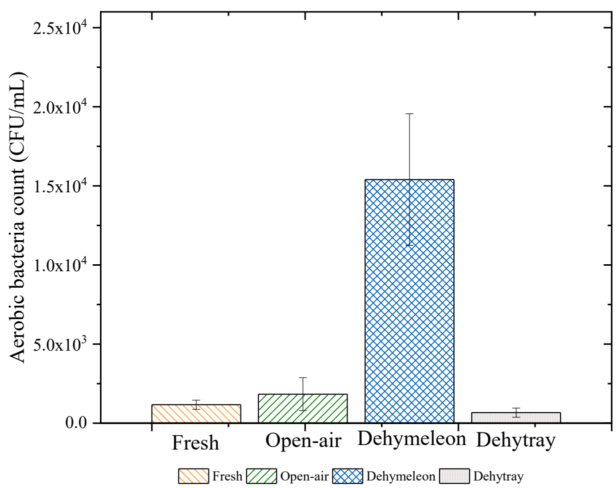


Figure 3.13. Comparison of aerobic bacteria count (CFU/mL) on fresh tomato and slices dried using open-air sun drying, Dehytray™ and Dehymeleon™.

In contrast to open-air sun drying and the Dehytray™, the CFU on dried tomato slices dried using the Dehymeleon™ increased significantly compared with the fresh product. The increase in bacteria activity for this samples can be explained as a consequence of the high-water activity of tomato slices during the initial stages of drying, where temperature was ideal for the growth of *mesophilic* bacteria and other possible *psychotropic* microorganisms. The specific bacteria pathogens were not identified in this study. The literature suggests that the presence of some *Pseudomonas*, representing about 80% of the contamination in minimally processed vegetables such as dried tomato slices (Nguyen-The and Carlin, 1994). Other studies have reported the presence of *Lactic acid* bacteria in populations ranging between 10^1 to 10^6 CFU for fresh and minimally processed foods (Rosa et al., 2010). Studies carried out on raisins established acceptable values for total aerobic plate count to less than 2.0 x 10^4 CFU (Mccoy et al., 2015). Therefore, open-air and Dehytray™ would be in the range for commercialization, while, Dehymeleon™ samples would not be acceptable.

Table 3.13. Aerobic bacteria counts (CFU/mL) and (CFU/g) for fresh tomatoes, slices dried by open-air, Dehymeleon™ and Dehytray™ .

Aerobic count	Fresh	Open-air sun drying	Dehymeleon™	Dehytray™
(CFU/mL)	$1.17 \times 10^3 \pm 2.9 \times 10^2$ [a]	$1.83 \times 10^3 \pm 1.04 \times 10^3$ [a]	$1.54 \times 10^4 \pm 4.16 \times 10^3$ [b]	$6.67 \times 10^2 \pm 2.8 \times 10^2$ [a]
(CFU/g)	$1.17 \times 10^4 \pm 2.9 \times 10^3$ [a]	$1.83 \times 10^4 \pm 1.04 \times 10^4$ [a]	$1.54 \times 10^5 \pm 4.16 \times 10^4$ [b]	$6.67 \times 10^3 \pm 2.8 \times 10^3$ [a]

Coliforms

Coliforms are just a hygienic traditional test used to indicate the quality of the product (Mccoy et al., 2015). Continuing with the analysis of aerobic bacteria count, specifically for coliform colonies, the values obtained were 1.66×10^2 CFU/ml for fresh, 0.96×10^2 CFU/ml, 0.43×10^2CFU/ml, and 0.83×10^2 CFU/ml, for open-air sun drying, Dehymeleon™ and Dehytray™, respectively **Table 3.14**.These values were not significantly different, and might be because their standard errors were quite high and overlapped each other Figure 3.14. This problem might have been caused by cross contamination of the sample.

Table 3.14. Coliforms counts (CFU/mL) for fresh tomatoes, and slices dried using open-air sun drying, Dehymeleon™ and Dehytray™

Coliforms	**Fresh**	**Open-air sun drying**	**Dehymeleon™**	**Dehytray™**
(CFU/mL)	$1.66 \times 10^2 \pm 1.50 \times 10^{2\ a}$	$0.96 \times 10^2 \pm 0.56 \times 10^{2\ a}$	$0.43 \times 10^2 \pm 0.15 \times 10^{2\ a}$	$0.83 \times 10^2 \pm 0.15 \times 10^{2\ a}$
(CFU/g)	$1.66 \times 10^3 \pm 1.50 \times 10^{3a}$	$0.96 \times 10^3 \pm 0.56 \times 10^{3\ a}$	$0.43 \times 10^3 \pm 0.15 \times 10^{3\ a}$	$0.83 \times 10^3 \pm 0.15 \times 10^{3\ a}$

A study on Afghan raisins found a relationship between temperature increase and reduction in coliform CFU (Mccoy et al., 2015). Coliforms were identified by Bourdoux et al. (2016) as one of the most common bacteria on dried products related to solar drying systems.

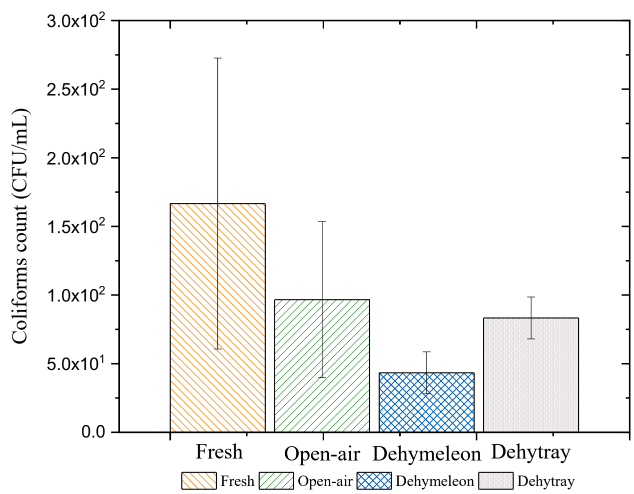


Figure 3.14. A comparison of coliforms counts (CFU/mL) for fresh tomatoes, and slices dried using open-air sun drying, Dehymeleon™ and Dehytray™

Yeast and Mold

Yeast and mold detection test were conducted for the three different drying methods investigated. No mold colony was detected, and only yeast colony detected is shown in **Table 3.15** and Figure 3.15. Various studies on yeast and mold detection on fresh and minimally processed food have been conducted to determine the mycotoxins that can contaminate tomato; aflatoxin being the most common one (Drusch and Aumann, 2005). After reading out the plates mold colonies were not detected, therefore, presence of molds that could lead to aflatoxin is discard.

Table 3.15. Yeast colonies count (CFU/mL) for fresh tomatoes, slices dried by open-air sun-drying, Dehymeleon™ and Dehytray™ .

Yeast	**Fresh**	**Open-air sun drying**	**Dehymeleon™**	**Dehytray™**
(CFU/mL)	$0.16x10^2 \pm 0.57\ x10^{1\ a}$	$3.00x10^3 \pm 1.00\ x10^{3\ a}$	$7.3x10^3 \pm 2.06\ x10^{3\ b}$	$1.66x10^2 \pm 0.57\ x10^{2\ a}$
(CFU/g)	$0.16x10^3 \pm 0.57\ x10^{2\ a}$	$3.00x10^4 \pm 1.00\ x10^{4\ a}$	$7.3x10^4 \pm 2.06\ x10^{4\ b}$	$1.66x10^3 \pm 0.57\ x10^{3\ a}$

In this study, yeast were the most prevalent organisms found in samples of fresh tomato and dried processed tomato slices. The CFU of yeast for the fresh tomato was the lowest and was not significantly different than the CFU of dried tomato using the Dehytray™. The CFU for yeast increased in dried tomato slices dried using the Dehymeleon™, following a similar trend as that of aerobic bacteria, which was most likely due to the high-water activity of tomato slices at the beginning of drying. The CFU of fresh tomato was $0.16x10^2$ CFU/ml, compared with $3.00x10^3$ CFU/ml for open-air sun drying, and $7.3x10^3$ CFU/ml for Dehymeleon™. These values were significantly higher than for the fresh samples and agree with the study conducted by Tournas (2005), where the CFU of yeast and mold for minimally processed food tended to increase from fresh samples in ranges for yeasts of less than 100 to $4.0x10^8$ CFU, and mold from less than 100 to $4.0x10^4$ CFU.

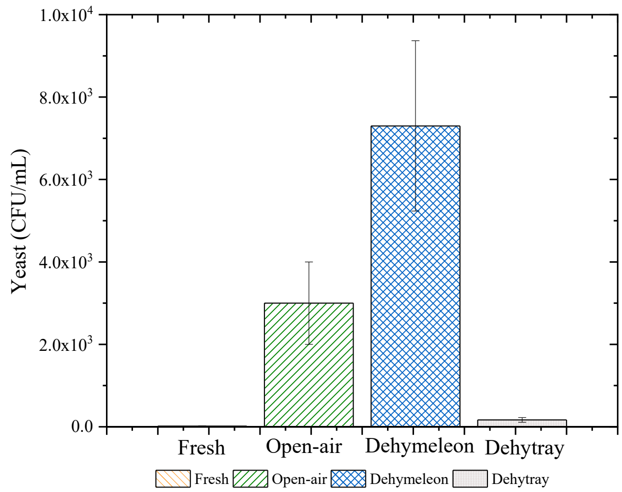


Figure 3.15. A comparison of yeast counts (CFU/mL) for fresh tomatoes, and slices dried using open-air sun drying, Dehymeleon^{TM} and Dehytray^{TM}

Color change

Color in food products is related to high quality when well preserved because it maintains the idea of freshness when it does not differ significantly from that of the fresh product. Changes in color for the tomato slices dried by the three different methods studied in this chapter are shown on **Table 3.16**. For a singular analysis per color, the parameters, L* (lightness), a* (redness) and b* (yellowness) were evaluated. In the case of tomato, the most important single-color value was a* to verify changes in red color for the tomato slices compared with the fresh tomato. Based on this parameter, it was observed that the Dehymeleon^{TM} was the method with less impact on color change in terms of redness, contrary to open-air sun drying and the Dehytray^{TM}, which had a significant difference in color compared with the fresh samples. This results agree with those by numerous authors such as Hussein and Filli (2016), Kaur et al. (2006), Shi et al. (1999) that compare solar drying methods where direct exposure to sunlight denatured lycopene contents, which are related with the red color of the tomatoes. As found by Rajkumar et al. (2007), denaturation of color by direct exposition to sun was an important factor on color change and degradation of some nutrients. The color change can be appreciated in Figure 3.17, where the difference in direct sunlight methods versus as the Dehymeleon™, whose drying chamber provided a shade from direct sunlight exposure can be appreciated.

Table 3.16. Color values of the tomato slices fresh and dried using open-air sun drying, Dehytray™ and Dehymeleon™.

	Color values		
	L*	**a***	**b***
Fresh	60.85 ± 3.56 [a]	22.27 ± 1.83 [a]	25.45 ± 1.41 [a,c]
Open-air	42.75 ± 11.97 [b]	11.50 ± 4.86 [b]	21.05 ± 10.20 [a]
Dehymeleon™	47.50 ± 8.76 [b]	20.31 ± 2.23 [a]	34.57 ± 8.85 [b]
Dehytray™	43.95 ± 11.80 [b]	15.80 ± 2.89 [c]	28.83 ± 10.32 [b,c]

To compare the color degradation with the fresh product, the delta for the color parameters was calculated for each drying method and is shown in **Table 3.17** and Figure 3.16. Delta E, color change was significantly different between open-air sun drying compared with Dehytray™ and Dehymeleon™, while there was no significant difference in Delta E between both solar drying methods. Degradation of a* parameter which could be linked with the higher temperatures presented during the drying process and complemented with the direct exposure to sun (Arslan and Özcan, 2011).

Table 3.17. Color change for tomatoes slices dried by open-air sun drying, Dehymeleon™ and Dehytray™ (Delta E is a value that compares fresh samples with dried samples).

	Open-air sun drying	**Dehymeleon™**	**Dehytray™**
Color change (ΔE)	25.13± 3 [a]	17.22 ± 2.6 [b]	18.62 ± 2.1 [b]

Another important aspect to take in account in this study would be the browning index, due to the pretreatment with citric acid to inhibit enzymatic browning applied before the drying of tomato slices. Browning index was 85.98, 148.16 and 126.04 for open-air sun drying, Dehymeleon™ and Dehytray™, respectively. Although, the Dehymeleon™ had the highest browning index, the overall degradation of color was less due to the reduction in enzymatic reactions. Thus, the high browning index could be explained by the development of Millard reactions during drying due to the high temperatures inside the drying chamber in the cases for Dehymeleon™ and Dehytray™, this last one exceeded 50ºC somedays. It was also observed that for open-air sun drying, which presented lower values of browning index, the phenomenon of bleaching due to the exposure to sunlight occurred (see Figure 3.17 a). Milliard reaction samples can be appreciated in Figure 3.17 b) and c). Finally, some authors had also found successful pre-treatment with citric acid and other organic acids for reduction of enzymatic browning (Otwell and Iyengar, 1992), but still high temperatures will deteriorate and generate non-enzymatic browning as in the study by Billaud et al. (2005). Further studies should be done to be able to understand the linkage between nutritional value and color degradation.

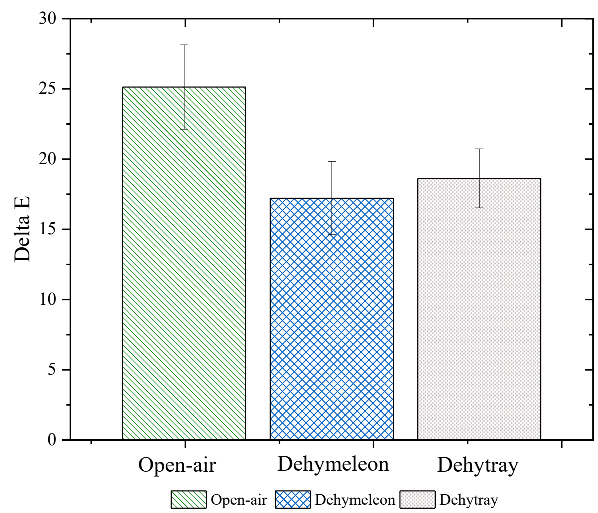


Figure 3.16. Delta E for color change of tomato slices dried using open-air sun drying, Dehytray™ and Dehymeleon™.

a)

b)

c)

Figure 3.17. Drying samples of tomato slices using a) Open-air sun drying, b) Dehymeleon^{TM} and c) Dehytray^{TM}.

3.6 Conclusions

The performance of three different drying methods (open-air sun drying, and two solar dryers – the Dehytray™ and Dehymeleon™) was evaluated, based on their drying rates, effective diffusivity, vitamin C content, CFU of bacteria, coliforms, yeast and molds, and color change. Thin-layer drying experiments were also used to determine the drying rates and diffusivities of tomato slices at certain temperatures (24°C, 35°C and 54°C). The rates of drying of tomato slices using the Dehytray™ and Dehymeleon™ was slightly slower than by open-air sun drying using Dehytrays without the covers on. The influence of the black trays of the Dehytrays™ might have also enhanced open-air sun drying in this study compared to if wooden trays were used as in the industry (Fig. 2.2). The retention of vitamin C in tomato slices dried using the Dehymeleon™ was higher than in tomato slices dried using the Dehytray™ and open-air sun drying. The CFU for aerobic bacteria and yeast were quite high on tomato slices dried using the Dehymeleon™, but acceptable for slices dried using the Dehytray™ or open sun-drying. Less color change occurred in tomato slices dried using the Dehymeleon™, than those dried using the Dehytray and open-air sun drying. While the Dehytray™ dries tomato at a sufficiently fast rate that prevents bacteria and mold growth, the Dehymeleon™ needs improvement, primarily by increasing chamber temperature, distribution, and airflow. Additionally, more airflow in the Dehytray would increase drying rates.

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CHAPTER 4. **DRYING STUDIES ON APPLE SLICES**

4.1 Abstract

Drying kinetics and quality attributes of apple (*Malus domestica,* var. Galasoup o) slices were studied to determine the performance of two different solar drying technologies, Dehymeleon^{TM} and Dehytray^{TM}. Drying experiments were carried out under the weather conditions at Purdue University, West Lafayette, Indiana. Thin layer drying tests were conducted for apple slices of thickness, approximately 7 mm, under three temperatures [24°C (75°F), 35°C (95°F) and 54 °C (130°F)], and airflow velocity of 1 m/s to identify the drying kinetics of the product for diurnal drying cycles typical for solar and/or open-air sun drying. Afterwards, field drying tests were done for apple slices of thickness, approximately 7 mm with two solar drying technologies (Dehymeleon^{TM} and Dehytray^{TM}) and open-air sun drying as the control. The average temperatures achieved for these technologies were 40°C (104°F), 45°C (113°F) and 28°C (82.4°F) for the Dehymeleon^{TM}, Dehytray^{TM} and open-air sun drying, respectively. Quality attributes (color, vitamin C and microbial growth) were measured before and after the field drying tests. Vitamin C (Ascorbic acid) content was affected by the high peaks of temperatures presented in Dehymeleon^{TM} and Dehytray^{TM} drying methods. Denaturing of vitamin C was less observed for Dehymeleon^{TM}, maintaining values of 104 mg/100 g d.m, while apple slices dried using the Dehytray^{TM} and open-air sun drying ranged between 94 - 98 mg/100 g d.m, respectively. There was no significant difference ($\alpha = 0.05$) in the microbial growth for the Dehytray^{TM} and open-air sun drying compared to the fresh product, however, there was significant difference for the Dehymeleon^{TM}. This was observed because the moisture content of apple slices dried in the Dehymeleon^{TM} was above the safe storage equilibrium moisture content (EM) of the product (EM for apples = 11%) for some time that was favorable to mold growth. Finally, color difference (ΔE)

of apple slices dried using the Dehymeleon™ solar-dryer showed the least variation compared with the fresh product followed by the Dehytray™. Apple slices dried using open-air sun drying presented the biggest (ΔE) caused by oxidation and visible deterioration of color quality of the samples.

4.2 Introduction

Apple is one of the fruits that is widely consumed around the world, and its storability and high vitamin content make it a perfect dietary supplement for infants and adults (Zarein et al., 2013). Numerous products are derived from apples including purees, juices, powders, dried apple cubes and slices, among others. From this different types of processed products, dried apple slices or cubes present a big advantage by extending shelf life and reducing operational cost related with storage and transportation (Wang et al., 2017).

Drying of agricultural products have been one of the most used techniques for food preservation around the world. The reduction of water activity in fruits and vegetables provides an important means of food preservation by dehydration. Due to the mechanism of preservation by drying, dried apples can reduce the risk of pathogen contamination such as *Salmonella* and *E. coli* (Derrickson-Tharrington et al., 2005). The inactivation of other kind of microorganism such as yeast and mold also presents an advantage with drying processes (Soliva-Fortuny et al., 2004). Due to the reduction in microbial load, the shelf life is enhanced by the reduction of moisture content. Different drying methods have been implemented for apples, primarily by using industrial dryers due to the harvest season of apples and the speed of massive production. However, the use of industrialized dryers generates a reduction in organoleptic qualities, such as color, aroma, taste and texture. Additionally, due to the high temperatures used in industrial dryers, nutrients denaturation and high energy cost affect the economics of operation of the system. Other kinds of drying methods used are freeze drying and those related with the use of solar energy using solar dryers or common drying such as open-air sun drying.

As mentioned before, open-air sun drying has been use for several years for dehydrating apple slices. However, quality is commonly affected due to the long drying times, which lead to adverse conditions such as microbial growth and enzymatic reactions that negatively affect the final product (Rajkumar et al., 2007). Although, several studies about drying techniques in apples have been done, information about commercial solar dryers (i.e. Dehymeleon™ or Dehytray™) is not available. Information on drying performance of these technologies will help to understand the production of quality dehydrated products using commercial solar available on the market. Therefore, this chapter studies the performance of two recently developed solar drying technologies Dehymeleon™ and Dehytray™, and their effects on quality parameters based on the literature review.

4.3 Materials and methods

4.3.1 Produce material

Apple slices

Fresh apples (*Malus domestica,* var. Gala) from Piazza Produce (Indianapolis, Indiana, USA) were used for the different drying tests described in this document. Apples samples were sliced with a meat slicer (Elite, Platinum, Maxi Matic Inc, China) to a thickness of 7 ± 0.2 mm. Apples slices of different diameters were pretreated with a water solution of citric acid at [5%] by dipping them for 10 minutes to reduce enzymatic browning. Initial moisture content for fresh samples was determined before pretreatments by using the gravimetric air-oven method at 100 ^{o}C for 24 h. (AOAC 2000). Average moisture content was found to be 84.58% (w.b.).

4.3.2 Drying of apples slices and apple halves

Thin layer drying tests

Thin layer drying experiments were conducted at Purdue University in the Spring of 2018 with a thin layer dryer shown in Figure 3.1. Drying was conducted in a cycle with three temperatures ranging between 24°C (75°F), 35°C (95°F) and 54 °C (130°F), which were changed every three hours until apple slices reached constant weight for three replications in order to mimic the cyclicals changes of ambient temperatures. Apples slices of 7 ± 0.2 mm thickness were placed on a mesh tray with an area of 0.093m^2 inside the drying chamber having a perpendicular airflow velocity of 1 m/s. The air used for drying was heated by an electric heater (Chromalox Inc., USA) and blown using a 1/3 hp centrifugal fan (Dayton, Iowa, USA) via an air duct (1) from the top into the drying chamber as shown in Figure 3.1. Temperatures and weight changes were collected every five minutes using a Fluke data logger (model Hydra 2620A, Fluke, Everett, WA, USA). The thin layer apparatus is shown in Figure 3.1.

Drying tests conducted on field

Open field tests were conducted at the ADM Agricultural Innovation Center on Purdue University campus, West Lafayette, Indiana (indicate the geographic (GPS) location using your cell phone an insert here). During the summer of 2018 (from June 23 to July 27, 2018), three different solar drying methods were conducted, Open-air sun drying, Dehymeleon™ and Dehytray™ as described in Chapter 3 of this document. For each drying method, three replications were used. Specific procedures are described in the following section. A schematic of the field-testing process is summarized on Figure 3.4. The solar drying studies were all conducted south of the ADM Agricultural Innovation Center building.

Apple slices dried using the Dehymeleon™

Uncovered Dehytray™ was filled with a thin layer of apples slices, with each tray holding approximately 2 kg of apple slices. Three trays were placed inside the drying chamber, and their weight was measured per tray twice per day with a digital scale platform. Drying was tracked by weight and inspection of spoilage. Three centrifugal fans (Delta Electronics, Taipei, Taiwan, 12vdc, 0.37A, 2700 rpm) and nine axial fans (Orion Fans, Taipei, Taiwan, 6~12vdc,0.600A 3750 rpm) of the Dehymeleon solar dryer were running at different speeds during drying. The top fans were operated at 100% of their full load, while the bottom and front fans were operated at 80% of their full load due to the prevailing high ambient relative humidity during the test. Relative humidity and temperature sensors Extech (model RHT10, Extech instruments, Nashua, NH, USA), were distributed inside the chamber (bottom tray, middle tray and top tray) and programmed to log data every 30 min during the test duration.

Figure 4.1. Trays with apple slices in the drying chamber of the Dehymeleon™.

Apple slices dried using the Dehytray™

Three Dehytray™ were filled with a thin layer of apples slices, with each tray holding approximately 2 kg of apple slices. A temperature and relative humidity sensors Extech (model RHT10, Extech instruments, Nashua, NH, USA) were placed inside one tray of three replications of each solar method and data logger was programmed to log every 30 min during daytime and overnight until the end of the drying tests. Weight was measured for each tray twice per day with a digital scale platform. Drying was tracked by weight and inspected for spoilage.

Figure 4.2. Dehytray^{TM} arrangement when paced under the sun during drying studies.

Apple slices dried using open-air sun drying

Open-air sun drying was used to compare the performance of Dehytray^{TM} and Dehymeleon^{TM} technologies. About 2kg of sliced apples were placed on the Dehytray^{TM}, without the cover as shown in Figure 4.3, and weighed on a digital scale platform twice per day. Trays were monitored till reaching constant weight. Ambient temperatures were tracked with a HOBO data logger (model MX 2300 RH&T, ONSET, Bourne, MA, USA)

Figure 4.3. Open-air sun drying trials with apple slices using uncovered Dehytray™ trays.

4.3.3 Drying kinetics for thin layer drying and open field test of apple slices

Moisture ratio and diffusivity calculations

Variation of moisture content (moisture ratio) for the drying experiments of apple slices was calculated using Equation (3.1) presented in Chapter 3. Equation (3.2) in the same chapter was used to linearize the drying curve by applying natural logarithm, so that drying rate could be calculated. For field tests, an exponential regression in the form of Equation (3.1) was conducted with the software Origin-Pro 2018b (Origin Lab Corporation, Northampton, MA, USA). Using the values obtained by the calculation of moisture ratio from the experimental data, the moisture diffusion (*D*) was calculated using a simplification of Fick's second law for a slab, shown in Equation (3.3). The effective moisture diffusivity values were determined by plotting experimental drying data in terms of *ln (MR)* versus drying time (t).

4.3.4 Quality indicators

Quality assessment was conducted for the following indicators: vitamin C, microbial growth and color change. Test of apple slices were conducted with the same procedures described in Section 3.3.4 in Chapter 3.

4.4 Data Analysis

All observations were reported as means of the corresponding replications. One-way analysis of variance (ANOVA) was conducted using a means difference Turkey test with ($\alpha = 0.05$), using OriginPro 2018b package (Origin-Pro 2018b, Origin Lab Corporation, Northampton, MA, USA) to determine whether the quality indicators for apple slices were significantly different for the various sun drying methods used.

4.5 Results and discussion

This section studies the drying behavior of apple slices under three different methods by: open-air sun drying, Dehymeleon™ and Dehytray™. Also analyses of the thin layer studies conducted to understand the drying kinetics of apple slices by simulating diurnal drying cycle according to Ramirez et al. (2018) was conducted. The relationship between drying temperatures and changes in moisture content were evaluated by quality assessment of vitamin C, microbial growth and color change. The drying behavior of apple slices serves as an assessment of the performance of the drying methods named previously.

4.5.1 Thin layer drying experiments

To understand the drying behavior of apple slices, thin layer tests of a single layer of apple slices with 7 mm of thicknesses, were conducted by simulating diurnal drying cycles, taking into account a previous study presented by Ramirez et al. (2018) where air drying temperatures were simplified for a typical drying day with three values [24°C (75°F), 35°C (95°F) and 54 °C (130°F)], which was changed every three hours until no changes in mass were observed. Product was dried on a surface area of 0.093 m^2 using an initial weight of 569.8± 29g (0.568 kg).

The data obtained during the thin-layer experiments was converted into dimensionless moisture ratio and was plotted versus time as shown in Figure 4.3. This was used to identify the drying mechanism for apples slices, which was characterized mostly by a falling rate. Each falling rate was associated with the change in temperature as can be seen in the graph. Initial moisture content of apple slices was 85.8% w.b., and apple slices were dried till an equilibrium moisture content of 8% w.b. was achieved.

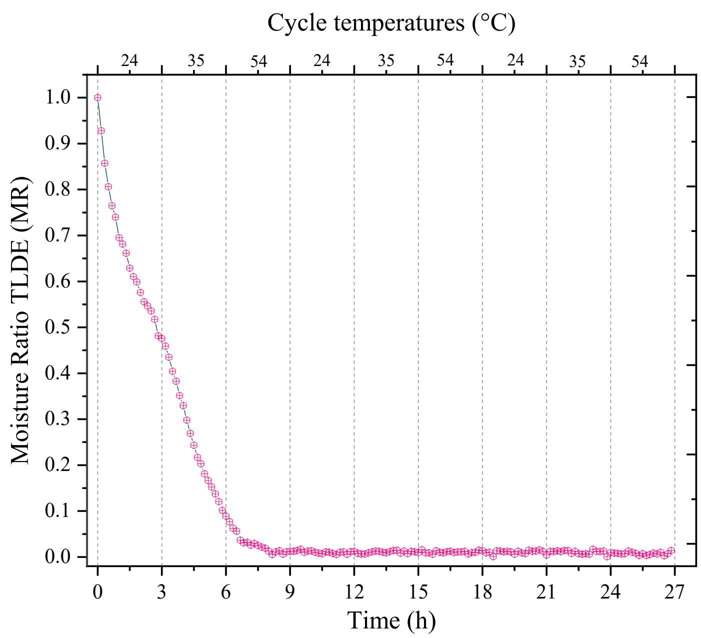

Figure 4.4. Moisture ratio versus time for TLDE test of apple slices.

As expected, the moisture content decreased with the increase in drying time. The graph shows a higher gradient of moisture loss for the first six hours, when free water was expelled from the product increasing its diffusivity. For studies with constant temperature similar to the ones conducted by Zarein et al. (2013) for temperatures of 50ºC and a thickness of 7 mm , the drying time to reach constant weight was similar to the one presented in this study; both tests took six hours to reduce the moisture ratio under values of 0.2. In contrast to the thin-layer test with apple slices done by Sacilik and Konuralp Elicin (2005) under a temperature of 40°C and a thickness of 5 mm, the evaporation of the free water occurred in the first six hours of the tests, while between the six to nine hours the drying rate decreased as more bonded water in the product was expelled. Removal of bonded water could also affect the release of important phenols and other compounds attached to this structure (Vega-Gálvez et al., 2012).

Evaluation of the drying model

Various studies on mathematical modeling of thin layer drying of apple slices have been conducted to predict drying and moisture ratio as a function of time. Onwude et al., (2016) found Modified Midilli and Page models are the most suitable models to predict drying behavior of apple slices. Although, Page has been found to be the most suitable model for apples in this study, other models like Modified Midilli and Henderson have also been adjusted to predict the drying characteristics of apple slices with good results and high coefficients of determination (da Silva et al., 2014; Goyal et al., 2008; Meisami-asl et al., 2010; Z. Wang et al., 2007) (Table 4.1)

Table 4.1. Mathematical models applied to thin-layer drying curve of apple slices.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k=0.322 ± 0.010	0.976	0.194	0.035
Page	$MR = e^{-kt^n}$	k = 0.242 ± 0.018 n= 1.203 ± 0.055	0.983	0.141	0.030
Modified Midilli	$MR = ae^{-kt} + b$	a = 1.022 ± 0.029 b = -0.004 ± 0.007 k = 0.323 ± 0.017	0.976	0.190	0.034
Henderson and Pabis	$MR = ae^{-kt}$	a = 1.021 ± 0.031 k = 0.328 ± 0.014	0.976	0.192	0.034

Drying rate and diffusivity

Drying of apple slices had four falling rates governed by the changes in temperature. Data of drying rate and moisture diffusivity for each falling rate is shown in Table 4.2. Drying rate was higher for the second and third falling rate, while a lower falling rate was present in the fourth rate because the product had reached a constant mass. Falling rate is common in the drying of fruits like apples (Lozano et al., 1983), due to the high presence of free water and the configuration of the samples, in this case slices, which increased the drying surface area and the possibility of releasing water.

Table 4.2. Drying kinetics for apple slices using TLDE.

Main falling rates	Total drying time (h)	Average temperature (^{0}C)	Initial MC%	Final MC%	Drying Rate (kg H_2O/h*m^2)	Moisture Diffusivity D_{eff} (m^2/s)
1st Falling rate	1-3	24	85.6	73.42	0.228 ± 0.009	452.8 x 10 $^{-7}$
2nd Falling rate	3-6	35	73.42	36.54	0.573 ± 0.015	113.8x 10^{-7}
3rd Falling rate	6-9	54	36.54	12.48	0.789 ± 0.082	156.7x 10^{-7}
4th Falling rate	9-26	37.6	12.48	9.06	0.022 ± 0.009	4.37 x 10^{-7}

As is shown on Table 4.2, most of the moisture is released in the first six hours, the second falling rate had the most important reduction, as a result of the increase in temperature, this results can be compared with the ones obtained by Sacilik and Konuralp Elicin (2005), were for temperatures around 40°C, water reduction was about 50% after six hours, similar to the result obtained in this study. As stated before, drying temperature is inversely proportional to drying time, which indicates that the air-drying temperature is the primary factor affecting the drying rate of a product. This was reported by Zarein et al. (2013) for apple drying. Drying time for the thin-layer dryer at constant heat was only nine hours to reach a constant mass. When compared with the solar drying methods, it was faster by 27 hours compared with the open-air sun drying and Dehymeleon™ and 39 hours faster than the Dehytray™. It must be noted that besides the type of solar method used or solar dryer design affecting the drying performance of a crop, the amount of solar irradiance available at a location during drying determines the performance of the solar drying method used. Therefore, the results of the solar drying methods used in this study must be limited to the prevailing conditions in West Lafayette, Indiana, USA or a similar location at the time of this study, and so no generalizations of the results in other areas are made.

4.5.2 Field experiments for open-air sun drying, Dehytray^{TM}, and Dehymeleon^{TM}

Field-drying tests were conducted during summer of 2018 (July 23 to July 27) at the ADM Agricultural innovation center, and drying trays and dryers were placed outside in the daytime for drying under the sun and brought inside the high ceiling workshop/barn area for storage overnight. Data of temperature and relative humidity collected during the drying tests is shown in Figure 4.5. For this study, direct sun exposure hours were around 12 hours per day, with tests starting at 8:00 am and samples taken inside at 9:00 pm.

During the tests period, daytime ambient temperatures were almost constantly oscillating between 26°C to 28°C and increased inside the enclosed dryers around noon time. For this same period, ambient relative humidity was almost constant, reaching about 70% every day. This represented a problem during drying, because even when the temperatures of the solar dryers were raised, the relative humidity was high, reducing the capacity of air to absorb water from the product. As shown on Fig. 4.5, the temperatures inside the Dehytray^{TM} and Dehymeleon^{TM} were higher than ambient air temperature. Difference between the ambient temperature of open-air sun drying with the Dehytray^{TM} and Dehymeleon^{TM} was on average, Δ15.75 °C and Δ12°C, respectively. The relative humidity inside the dryers reached its lowest values when higher temperatures occurred. Dehytray^{TM} and Dehymeleon^{TM} recorded similar temperatures similar to those reported by Konuralp and Sacilik, (2005) for a solar-tunnel dryer, which had a difference of 13.1 °C when compared with ambient temperature values. Although, no rehydration was observed during daytime drying, overnight increase of ambient relative humidity led in some cases to rehydration of the product. Prevention of product rehydration overnight during solar drying should be a topic of future research.

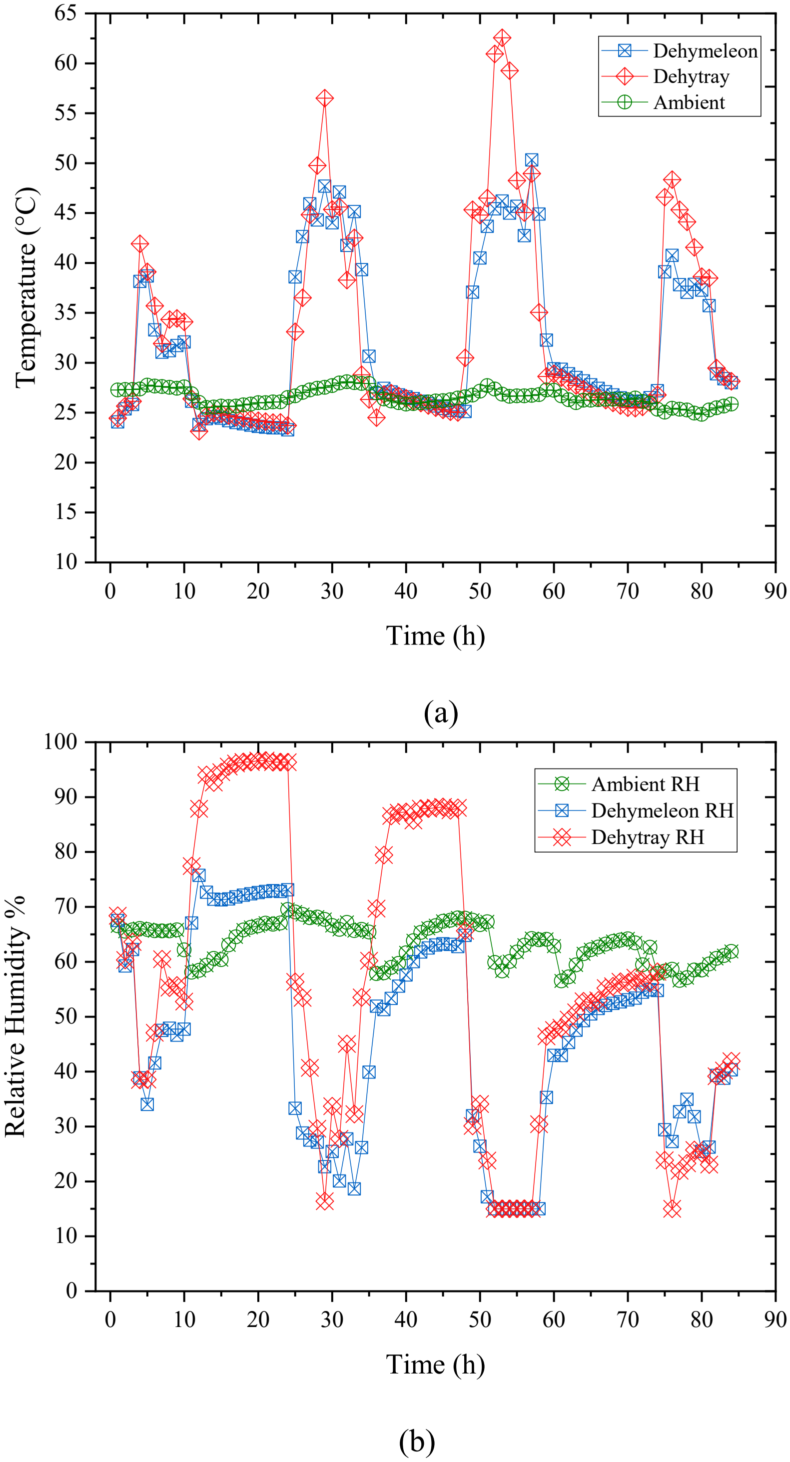

Figure 4.5. Profiles of temperatures a) and relative humidity b) for Open-air (Ambient), Dehytray^{TM} and Dehymeleon^{TM} during the drying of apple slices in West-Lafayette, Indiana, USA.

Drying of apple slices was highly dependent on weather parameters such as ambient air temperature, relative humidity, and airflow during the drying test. Weather conditions for each day were slightly different, following a constant pattern for ambient temperature and relative humidity. The following sections explain in detail the performance of each drying method implemented during the studies.

Open-air sun drying of apple slices

Open-air sun drying was used as the comparison method in the field experiments to determine the performance of the Dehytray^{TM} and Dehymeleon^{TM} solar dryers for drying apple slices. Changes in mass, moisture content, and moisture ratio were measured and calculated for this drying process and are shown in Table 4.3 and are plotted in Figure 3.7. The reduction of moisture content during the first hours of drying contrast with the drying behavior presented by the apple slices during the thin-layer drying test. Moisture ratio curve for open-air sun drying is shown in Figure 3.7(c). Due to the ambient temperature and relative humidity fluctuations, the reduction in moisture content of the product extended for about 12 more hours rather than the duration recorded during the thin-layer drying test. This is primarily due to several factors, namely that the drying air temperatures experienced by the apple slices in both Dehytray^{TM} and Dehymeleon^{TM} solar dryers fluctuated with the ambient temperatures, and a high constant temperature could not be achieved for the 12 h of exposure to sun. Additionally, airflow through the apple slices were quite lower in the solar dryers compared to the thin-layer drying apparatus and in fact there is no fan system in the Dehytray^{TM}, which depends entirely on airflow by passive convection.

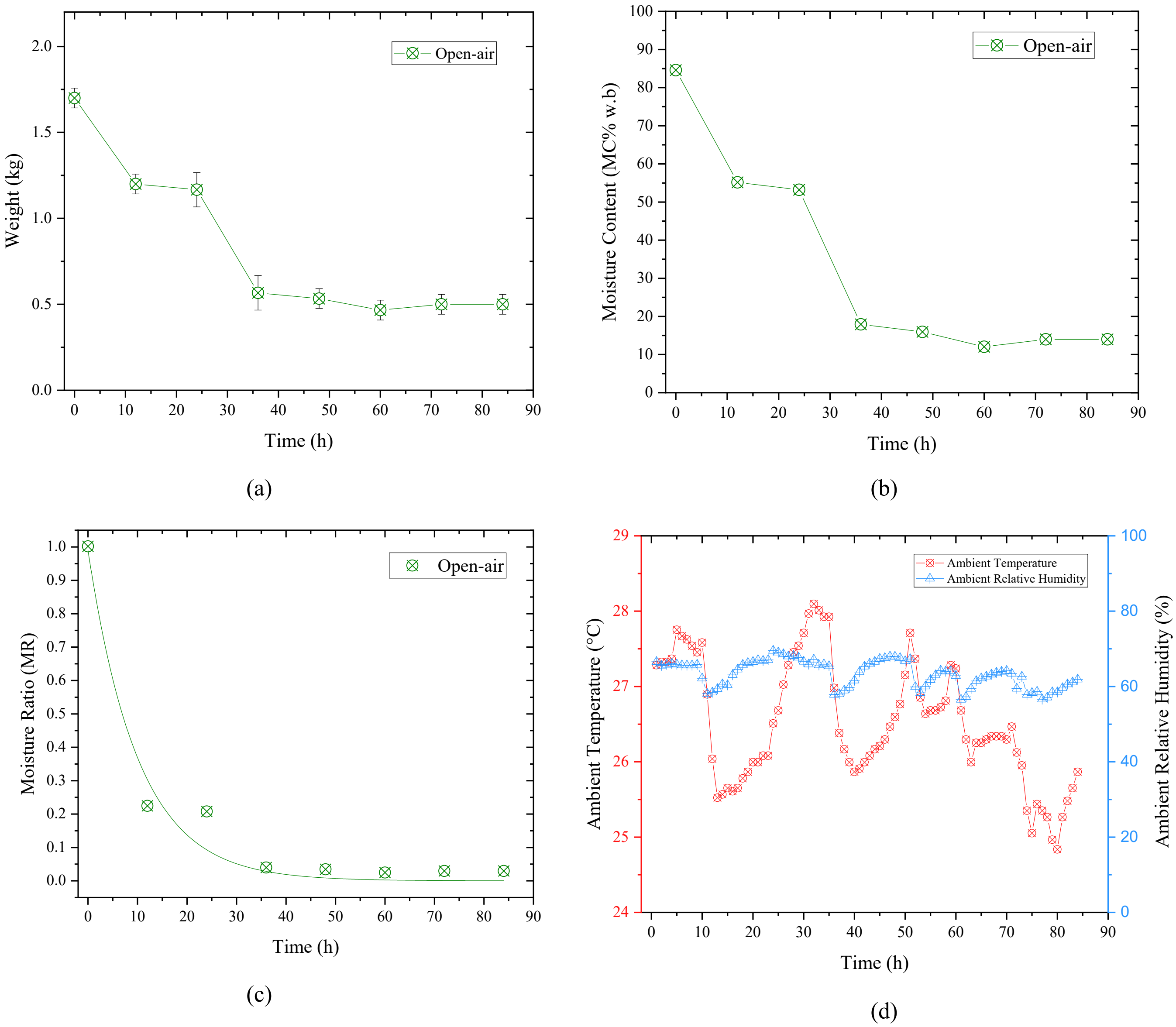

Figure 4.6. Open-air drying curves, temperatures and relative humidity values during the drying of apple slices a) Weight loss, b) Moisture content change, c) Moisture ratio variation versus time and d) Ambient temperature and relative humidity.

Table 4.3. Weight change, moisture content, moisture ratio for apple slices dried by open-air sun drying using the Dehytray™ without the cover on.

Time (h)	Weight (kg)	Moisture content % (w.b)	Moisture ratio (MR)
0	1.70 ± 0.10	84.58	1.002
12	1.20 ± 0.10	55.17	0.225
24	1.16 ± 0.05	53.21	0.208
36	0.56 ± 0.06	17.91	0.040
48	0.53 ± 0.05	15.95	0.035
60	0.46 ± 0.05	12.03	0.025
72	0.50± 0.04	13.99	0.030
84	0.50 ± 0.06	13.99	0.030

Evaluation of the model for moisture ratio in open-air sun drying of apple slices

The moisture ratio models by Newton, Page, Modified Midilli, and Henderson-Pabis were used to predict the moisture content as a function of drying time fitted with a high coefficient of determination (R^2). Values for the regressions are shown in Table 4.4. As for the drying behavior shown during the TLDE, the Page model had the highest R^2 and lowest SSE.

Table 4.4. Mathematical models applied to open-air drying curve

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k =0.099 ± 0.031	0.971	0.023	0.057
Page model	$MR = e^{-kt^n}$	k = 0.369 ± 0.329 n = 0.534 ± 0.280	0.989	0.008	0.038
Modified Midilli	$MR = ae^{-kt} + b$	a = 0.953 ± 0.155 b = 0.117 ± 0.539 k = 0.041 ± 0.066	0.980	0.015	0.055
Henderson and Pabis	$MR = ae^{-kt}$	a = 0.987 ± 0.149 k = 0.098± 0.035	0.971	0.022	0.061

Drying of apple slices using the Dehymeleon™

Drying studies of apple slices using the Dehymeleon™ were conducted in three trays with approximately 2 kg of apple slices per tray spread in a thin layer. Each tray was used as one replication, and therefore three replications of dried apple slices were obtained. Trays were put inside the dryer and were weighed twice per day, in the morning and at the end of the day in the evening during the drying test period. Data of weight variation, moisture change, and moisture ratio are shown in Table 4.5 and plotted in Figure 4.7

Table 4.5. Weight change, moisture content, moisture ratio for apple slices dried using the Dehymeleon™.

Time (h)	Weight (kg)	Moisture content % (w.b)	Moisture ratio (MR)
0	1.76 ± 0.10	84.58	1.002
12	1.39 ± 0.23	63.71	0.321
24	1.19 ± 0.21	52.32	0.200
36	0.66 ± 0.06	21.96	0.051
48	0.59 ± 0.06	18.17	0.041
60	0.49 ± 0.06	12.47	0.026
72	0.49 ± 0.05	12.47	0.026
84	0.49 ± 0.05	12.47	0.026

For the performance of the Dehymeleon™ as a drying method, it was observed that the temperatures did increase inside the drying chamber compared to ambient temperature values shown in Figure 4.7. The average chamber temperature for the Dehymeleon™ was 40°C with a delta from the ambient of Δ 12°C. During the diurnal weather pattern, the relative humidity (RH) inside the chamber of the Dehymeleon™ was lower than the ambient. This can be explained by the heat gain inside the dryer and the airflow provided by the fans, which constantly expelled the moistures released from the apple slices, and thus reduced the relative humidity of the air in the chamber.

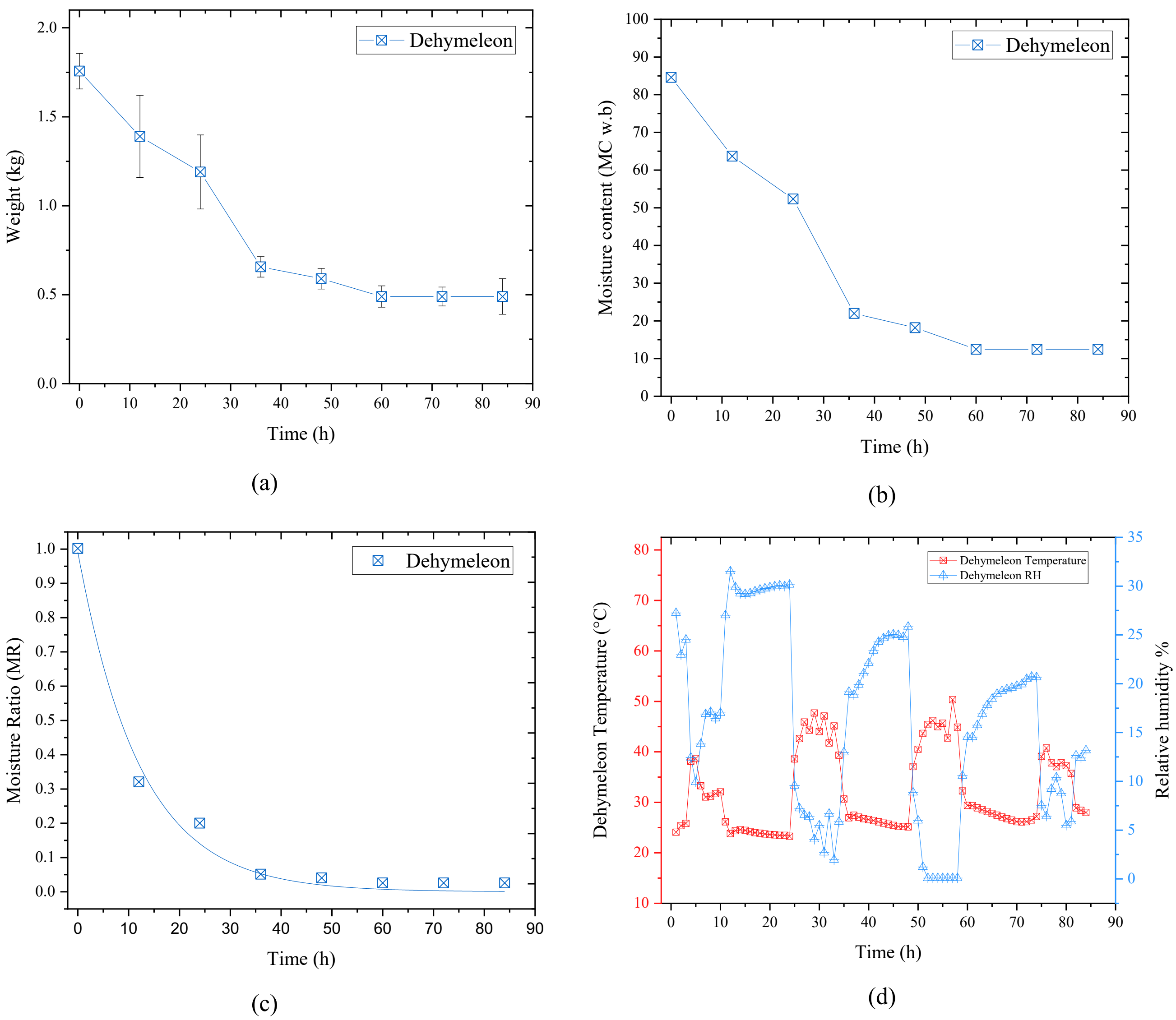

Figure 4.7. Dehymeleon™ drying curves, temperatures and relative humidity values during the drying of apple slices a) Weight loss, b) Moisture content change, c) Moisture ratio variation versus time and d) Ambient temperature and relative humidity.

Reduction of RH in the chamber was influenced by the constant airflow inside the chamber provided by six exhaust fans located at the bottom and 3 exhaust fans in the front of the dryer, which were ran at 15% of their operating full load, removing air from the drying chamber (0.64m^3) with an air speed of 0.87 m/s. The inlet airflow from heating tubes was at a rate of 5.71 m/s using centrifugal blower fans (fan make and specs) running at 100% of its full load capacity. This pattern of airflow was consistent during the length of the tests during day and night, the constant removal of air from the drying chamber explains the low relative humidity present overnight for the Dehymeleon^{TM}, being close to ambient RH and lower than the ones observed for Dehytray^{TM}. Due to this mold growth was not observed during the Dehymeleon^{TM} test.

Therefore, microbial growth did not occur on the apple slices being dried using the Dehymeleon^{TM} during the test because water activity in apple slices were quickly reduced to below levels that support microbial growth and maintaining the relative humidity inside the dryer in the range of 20%-70%. The enclosed chamber also prevented the product from being contaminated by external factors. The drying of apple slices using the Dehymeleon^{TM} dryer was characterized by a falling rate, which is clearly shown on Figure 4.7(c). From the curves, it is also appreciable that the reduction of RH in the dryer chamber helped to prevent rehydration overnight, compared to the open-air sun drying method where rehydration overnight was observed.

Evaluation of the model for moisture ratio

Drying behavior of apple slices using the Dehymeleon^{TM} was modeled using moisture ratio models such as: Newton, Page, Modified Midilli, and Henderson-Pabis, to predict the moisture content as a function of drying time fitted with a high coefficient of determination (R^2). Values for the regressions are shown in Table 4.6. As for the drying behavior shown during the TLD, the Page model had the highest R^2 and lowest SSE.

Table 4.6. Mathematical models applied to Dehymeleon™ drying curve for apple slices.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k = 0.082 ±0.013	0.9893	0.008474	0.03479
Page model	$MR = e^{-kt^n}$	k = 0.1836 ± 0.105 n = 0.7226 ± 0.185	0.9952	0.003265	0.02333
Modified Midilli	$MR = ae^{-kt} + b$	a = 0.965 ± 0.091 b = 0.090 ± 0.022 k = 0.029 ± 0.042	0.9907	0.00528	0.0325
Henderson and Pabis	$MR = ae^{-kt}$	a = 0.989 ± 0.090 k = 0.081 ± 0.016	0.9877	0.00836	0.03733

Drying of apple slices using the Dehytray™

Apple slices drying experiments were also conducted using the Dehytray™ solar dryer. Approximately six kilograms of sample were divided into three Dehytray™ (2 kg per tray replicate) and their respective covers placed on them before they were placed in the sun to dry. Apples were dried from an initial moisture content of 84.6% to a final moisture content of 15.5%, and exposure to the sun for drying was stopped when samples reached a constant mass. It was observed that the Dehytray™ heat gain depended highly on weather conditions, primarily temperature and relative humidity. On the first day of drying when weather conditions were more less favorable for drying, the Dehytray™ reduced the moisture content of apple slices to 14.6%, compared to 29.4% moisture achieved for open-air drying and 20.81% for Dehymeleon™.

Low drying rate for Dehytray™ at the beginning of the test affected the samples overnight, causing rehydration to occur due to the presence of high relative humidity inside the enclosed covered tray. While there is a vent at the center of the tray provided by three slots, as well as two rows of holes along the tray side walls, these openings do not appear to be sufficient enough to expel moisture released from the drying product. Although the cover represents an obstacle to air flow, other benefits such as increased temperature from heat retention within the enclosed tray, pest protection and prevention of dust contamination were identified as potential benefits with the use of the Dehytray™ solar dryer. The transparent cover also allows ultraviolet wave lengths to penetrate the product (92% penetration), trapping heat like a greenhouse, and can provide an advantage to reduce microbial growth on the dried product. However, direct exposure to sunlight affects some nutritional content and denatures product color, as will be analyzed in Section 4.5.3 of this chapter. Weight data for Dehytray^{TM} apple slices are shown in Table 4.7. Moisture change and ratio are plotted in Figure 4.8.

Table 4.7. Weight change, moisture content, moisture ratio and drying rate constant for apple slices dried by Dehytray^{TM}.

Time (h)	**Weight (kg)**	**Moisture content % (w.b)**	**Moisture ratio (MR)**
0	1.83 ± 0.05	84.58	1.000
12	1.57 ± 0.00	70.03	0.427
24	1.35 ± 0.10	58.22	0.254
36	0.86 ± 0.06	31.85	0.085
48	0.70 ± 0.00	22.76	0.054
60	0.63 ± 0.06	19.13	0.043
72	0.60 ± 0.06	17.31	0.038
84	0.56 ± 0.06	15.49	0.033

Temperatures profiles and relative humidity inside the Dehytray^{TM} are shown in Figure 4.8 (d), the difference of temperature compared with the ambient is on average 16°C, just four degrees higher than the Dehymeleon^{TM}. Therefore, differences with Dehymeleon^{TM} were not observed, but it was found that temperatures inside the tray started to rise when weather conditions allowed for a better heat gain. Temperatures inside the Dehytray^{TM} reached the ranges, 25°C to 65°C, when the ambient temperatures were in the range of 27°C to 30°C, which classifies it as a low temperature dryer according to the definition presented by Sharma et al. (2009).

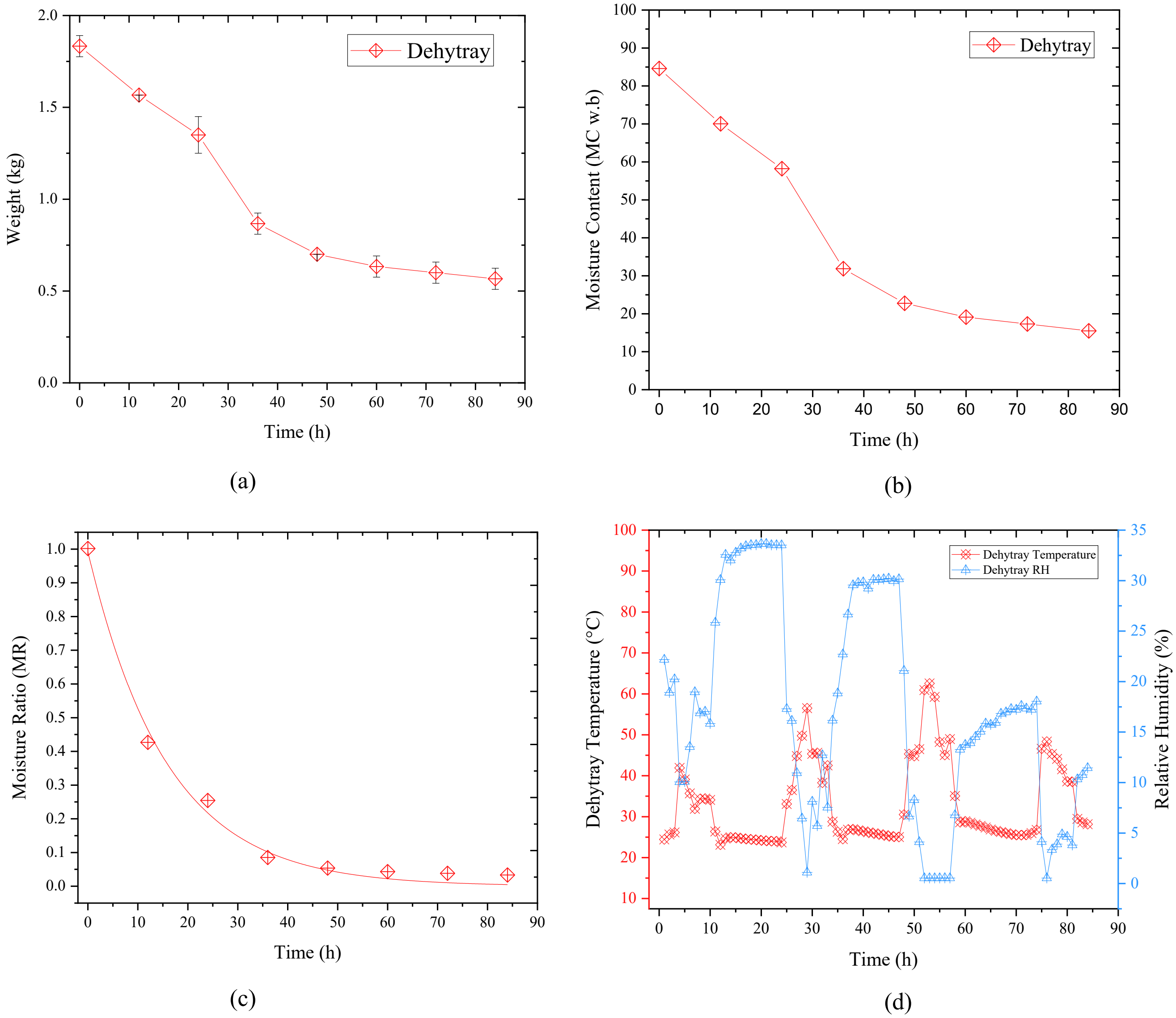

Figure 4.8. Dehytray™ drying curves, temperatures and relative humidity values during the drying of apple slices a) Weight loss, b) Moisture content change, c) Moisture ratio variation versus time and d) Ambient temperature and relative humidity.

Evaluation of the model for moisture ratio

In order to predict moisture content as a function of time, the following models: Newton, Page, Modified Midilli, and Henderson-Pabis models were fitted to the experimental data collected for samples dried with the Dehytray™. Values for the regressions are shown in Table 4.8. As for the drying behavior shown during the TLDE, the modified Midilli and Page models had the highest R^2 and lowest SSE.

Table 4.8. Mathematical models applied to Dehytray™ drying curve for apple slices

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k = 0.064 ± 0.007	0.9934	0.005276	0.02745
Page model	$MR = e^{-kt^n}$	k = 0.102 ± 0.054 n = 0.847 ± 0.165	0.9954	0.003161	0.02295
Modified Midilli	$MR = ae^{-kt} + b$	a = 0.970 ± 0.068 b = 0.028 ± 0.036 k = 0.069 ± 0.012	0.9947	0.002994	0.02447
Henderson and Pabis	$MR = ae^{-kt}$	a = 0.992 ± 0.070 k = 0.063 ± 0.009	0.9924	0.005209	0.02946

Drying rate and diffusivity

Drying of apple slices had a total duration of 84 hours including overnight periods kept in the barn, and 36, 48 and 36 hours of sun-light exposure for Open-air sun drying, Dehytray™ and Dehymeleon™, respectively. Open-air sun drying presented a better performance during the first 12 hours of the test, with a 29.4 percentage point moisture removal, while the Dehymeleon™ achieved 20.8 percentage points, and Dehytray™ achieved 14.6 percentage points moisture removal. The faster initial drying rates of the open-air sun drying method and the Dehytray™ solar dryer can be explained by the direct exposure to sunlight and air flow of these drying systems. Open-air drying and Dehytray™ were affected by the high relative humidity values during the test, which led to rehydration of the samples during the first day of the test. It was observed that the forced air flow by multiple fans inside the drying chamber of the Dehymeleon™ solar dryer helped the removal of saturated air, thereby increasing the drying rate and water diffusion from the wet samples to the environment. Values for drying rate and moisture diffusivity are shown in Table 4.9. The drying rate constant k was determined by plotting the experimental data ln (MR) vs. drying time. A summary of the regressions conducted is presented in Appendix 2.

Moisture diffusivity for the Dehymeleon™ was the highest value among the three methods with a D_{eff} of ($5.14 \times 10^{-7}\ m^2/s$) as a result of the stable temperatures around 45°C and the constant airflow of 1.9 m/s of non-saturated air (calculated using the fans rpm). Studies conducted by Aghbashlo et al. (2010) for industrial drying of apple slices found a moisture diffusivity of ($3.33 \times 10^{-7}\ m^2/s$) for temperatures around 70ºC for an airflow of 1.5 m/s. Values for Dehytray™ where found to be ($4.60 \times 10^{-7}\ m^2/s$), open-air sun dried slices showed a similar performance in terms of water mass removal with a D_{eff} ($4.95 \times 10^{-7}\ m^2/s$).

Summary of drying hours per technology

Table 4.9. Drying time of apple slices for the different methods, initial and final moisture content, and drying rate with moisture diffusivity.

Drying method	Total drying time (h)	Sun-exposed Time (h)	Initial MC%	Final MC%	Drying Rate kg $H_2O/h*m^2$	Moisture diffusivity D_{eff} (m^2/s)
Open-air (slices)	72	36	84.58	14.00	0.041 ± 0.008	4.95×10^{-7}
Dehymeleon™ (slices)	72	36	84.58	12.47	0.044 ± 0.007	5.14×10^{-7}
Dehytray™ (slices)	84	48	84.58	15.48	0.041 ± 0.005	4.60×10^{-7}

4.5.3 Quality indicators for apple slices

Quality of apple slices was measured using three indicators: Vitamin C content, microbial growth and color change. This study focuses on apple slices pretreated with citric acid at 5% to reduce enzymatic browning. It was found that studies for microbial growth when drying with solar techniques was limited in the case of apple slices and other vegetables (Bourdoux et al., 2016a). The following sections present the results for the quality indicators measured for the fresh and dried samples of apples slices used in this study.

Vitamin C content

Vitamin C in apple slices was measured for fresh and dried samples, and the change in vitamin C concentration data is shown in Table 4.10 and Figure 4.9. Despite the fact that limited studies have been done for apples for vitamin C content when dried with solar drying technologies, other works using industrial drying were found to have similar results. For example, Joshi et al. (2011) compared four different drying methods for apple slices: air dried (47°C at 7m/s for 7 hours), oven drying (70°C for 10 hours), vacuum drying (20°C for 24 hours), and freeze drying (50°C for 24 hours) with final contents of vitamin C of 55.53 ± 0.65 (mg/100g d.m), 78.14 ± 10.65 (mg/100g d.m), 110.91 ± 4.41 (mg/100g d.m), 53.13 ± 2.56 (mg/100g d.m), respectively, and for fresh of 112.43 ± 0.18 (mg/100g d.m). These values obtained by Joshi et al. (2011) for the low temperatures used give an idea of the temperatures ranges and how they affect the vitamin C content when drying, being able to be compared with the temperatures reached for the drying methods studied in this thesis.

Table 4.10. Vitamin C content for fresh tomatoes, and apple slices dried by open-air sun drying, Dehymeleon™ and Dehytray™ solar dryers

	Fresh	**Open-air sun drying**	**Dehymeleon™**	**Dehytray™**
Vitamin C (mg/100g d.m)	122.8 ± 10.7 [a]	98.7 ± 13.8 [b]	104.2 ± 13.4 [a,c]	98.2± 14.9 [c]

It was observed that vitamin C changes were closely influenced by the type of drying method, this is also corroborated by Hussein et al., (2016) and Rajkumar et al., (2007) in the case of tomato slices and for the significant differences found between fresh samples and the drying methods such as open-air sun drying and Dehytray™. It has been established that heat changes and open air exposure help to denature ascorbic acid in processed food products (Santos and Silva, 2008b).

For solar drying processes, it was found that the increase in temperatures and direct exposure to sunlight accelerated the oxide-reduction reaction, reducing vitamin C into dehydroascorbic acid. Comparing the drying methods used in this study, two of them directly expose the product to sunlight: (1) open-air sun drying and (2) Dehytray^{TM}. The vitamin C contents for these methods were similar. However a significant difference (α=0.5) of vitamin C is shown when compared with the fresh product with an original content of 122.8 ± 10.7 (mg/100g d.m), while open-air was 98.7 ± 13.8 (mg/100g d.m), and 98.2± 14.9 (mg/100g d.m) for Dehytray^{TM}. The open-air sun drying and Dehytray^{TM} solar dryer reduced vitamin C content by about 13%, while for Dehymeleon^{TM} vitamin C was reduced by only 7.6% compare compared with the fresh product with a final vitamin C content of 104.2 ± 13.4 (mg/100g d.m). From the studies carried by Joshi et al., (2011), methods such as the Dehymeleon^{TM} or Dehytray^{TM} solar dryers can be comparable to freeze drying and air drying due to the temperatures used, but cannot be compared due to other factors such as vacuum and airflow velocities.

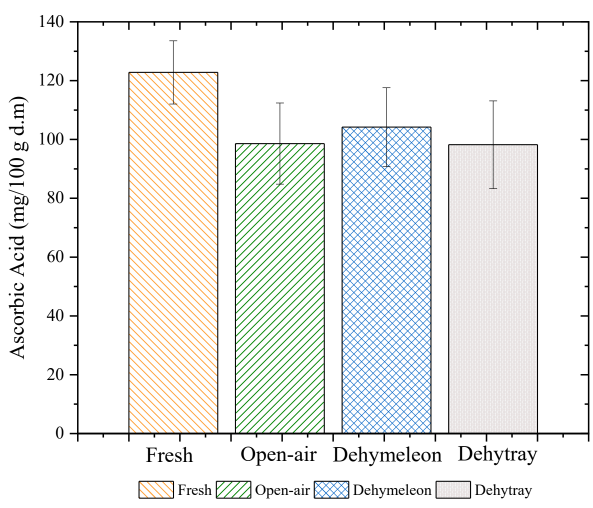

Figure 4.9. Comparison of vitamin C content of dried apple slices for the three drying methods investigated against the value of fresh apples.

Microbial growth

Aerobic Count

Aerobic count values for fresh and dried apple slices are shown in Table 4.11. Colonies formation range between the averages of 1.13×10^4, 1.33×10^4, 1.78×10^5 and 4.67×10^3 CFU/g for the aerobic bacteria present in fresh, open-air drying, Dehymeleon™, and Dehytray™, respectively. Due to the temperatures reached inside the dryers and the average ambient temperature for open-air drying, there were most likely two kinds of bacteria present: Mesophiles which grow between 20°C – 45°C, and thermophiles that grow between 55°C – 85°C (Bourdoux et al., 2016a). Thermophiles might have opportunity to grow when the enclosed drying chambers of the dryers reached temperature peaks around noon but will most likely die when the temperatures decreased. The presence of mesophilic bacteria can be stable during the drying process.

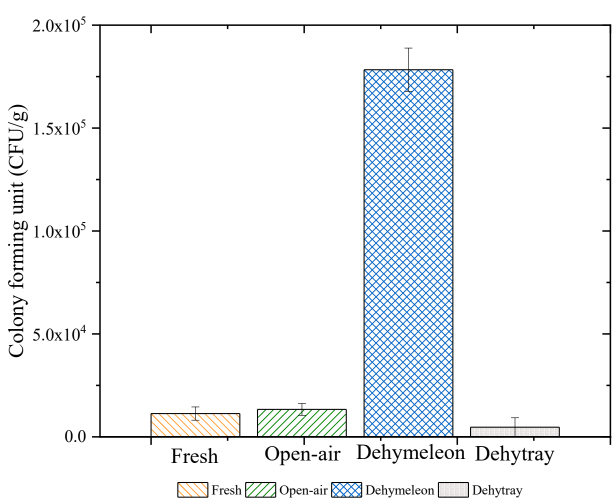

Figure 4.10. Comparison of aerobic bacteria count (CFU/g) on fresh apple and slices dried using open-air sun drying, Dehytray™ and Dehymeleon™.

Due to the limited scope of determining the microbial loads on the samples for this study, specific bacteria pathogens were not identified. However, various studies indicated that *Salmonella, Vibrio cholera,* and *Shigella* are the common bacteria present in fresh apple slices (Nguyen-The and Carlin, 1994; Soliva-Fortuny et al., 2004). Minimal processed foods that have unit operations such as slicing and shredding were found to increase the levels of aerobic bacteria from a range of (10^3-10^4) CFU/g to (10^4-10^5) CFU/g, which can be observed in the results obtained for the Dehymeleon™, and explained by the conditions generated inside the drying chamber. A study described by Nguyen-The and Carlin, (1994) found similar values for the aerobic bacteria at the end of seven days of irradiation treatment for the reduction of microbiota. *Salmonella* was reported to not be affected by low pH values on apple slices in the same study.

Table 4.11. Aerobic bacteria colonies (CFU/g) formation counts for fresh apples, slices dried by open-air, Dehymeleon™ and Dehytray™

	Fresh	**Open-air sun drying**	**Dehymeleon™**	**Dehytray™**
Aerobic count (CFU/g)	$1.13 \times 10^4 \pm 3.21 \times 10^3$ [a]	$1.33 \times 10^4 \pm 2.88 \times 10^4$ [a]	$1.78 \times 10^5 \pm 10.59 \times 10^3$ [b]	$4.67 \times 10^3 \pm 4.61 \times 10^3$ [a]

Coliforms

Coliform colonies values obtained were 0.46×10^3 CFU/g for fresh, 0.90×10^3 CFU/g, 0.23×10^3 CFU/g, and 0.40×10^3 CFU/g, for open-air sun drying, Dehymeleon™ and Dehytray™, respectively. None of them were significantly different from the other due to large standard errors. Values and standard deviation comparison are shown in Figure 4.11 and Table 4.12. Coliforms counts (CFU/g) for fresh apple, and apple slices dried using open-air sun drying, Dehymeleon™ and Dehytray™, respectively.

Table 4.12. Coliforms counts (CFU/g) for fresh apple, and apple slices dried using open-air sun drying, Dehymeleon™ and Dehytray™

	Fresh	Open-air sun drying	Dehymeleon™	Dehytray™
Coliforms (CFU/g)	$0.46x10^3 \pm 0.06\ x10^{3\ a}$	$0.90x10^3 \pm 0.44\ x10^{3\ a}$	$0.23x10^3 \pm 0.06\ x10^{3\ a}$	$0.40x10^3 \pm 0.15\ x10^{3\ a}$

Coliforms studies on apple slices have been carried to recognize the reduction of specific E. coli forms such as *Escherichia coli* O157:H7, in the case of studies by Derrickson-Tharrington et al. (2005), pre-treatments with organic acids were used prior to drying to reduce the microbial load on the fresh samples. Organic acids did not present any advantage in the reduction of the load, but they inactivated the growth of coliforms before drying. In the case of this present study, the capacity to inhibit microbial growth by the citric acid pretreatment was not investigated, rather the effect of elevated temperatures by the solar drying methods was contemplated as the main factor for the reduction of coliforms.

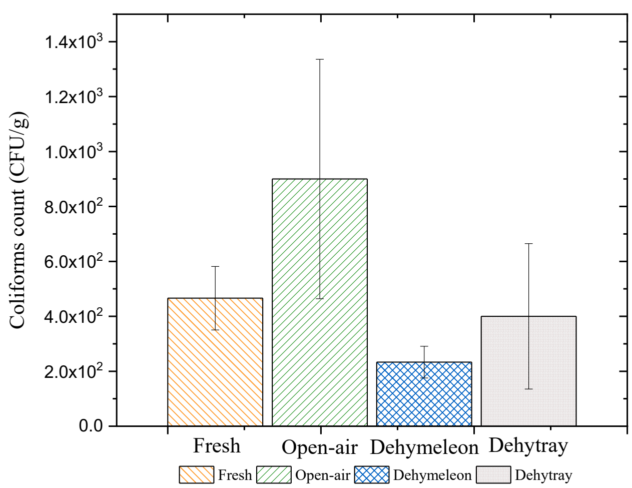

Figure 4.11. A comparison of coliforms counts (CFU/g) for fresh apples, and apple slices dried using open-air sun drying, Dehymeleon™ and Dehytray™

Results in Figure 4.11 show the reduction by the enclosed drying methods and probably due to the higher temperatures inside the drying chambers, with a percentage reduction of approximately 50% for Dehymeleon™ and 13% for Dehytray™ from the fresh samples. Effect of temperature on coliform colonies can be corroborated by Bourdoux et al. (2016) for convective dryers with constant temperatures of 68°C, where dried apple slices had a log reduction of 3.3-3.5 log [CFU/g] or number in the order of 10^3 CFU/g. Mccoy et al., (2015), presents ranges between 10^3-10^6 CFU/g for raisins and other vegetables for normal coliforms colonies, the values obtained for Dehytray™ and Dehymeleon™ lie in this range showing quality indicators of microbial stability for the products dried by this methods.

Yeast and Mold

The growth of yeast and mold colonies affected by the three different drying methods was evaluated for fresh and dried samples of apple slices, and is shown in Table 4.13, and plotted in Figure 4.12 and Figure 4.13. The presence of yeast and mold on the fresh samples is in the order of 5 log [CFU/g] for yeast and 3 log [CFU/g] for molds. Other values for initial loads of yeast and mold on fresh apple slices reported by Soliva-Fortuny et al. (2004), ranged from 1.70 to 2.20 log[CFU/g]. These values are not similar and might be explained by various factors such as the sample origin, and the different methods of sample preparation and pre-treatments used.

Table 4.13. Yeast and mold colonies count (CFU/g) for fresh apples, slices dried by open-air sun-drying, Dehymeleon™ and Dehytray™.

(CFU/g)	Fresh	Open-air sun drying	Dehymeleon™	Dehytray™
Yeast	$3.6 \times 10^4 \pm 2.5 \times 10^4$ ᵃ	$0.080 \times 10^4 \pm 0.020 \times 10^4$ ᵇ	$3.0 \times 10^4 \pm 2.0 \times 10^4$ ᵃ	$0.200 \times 10^4 \pm 0.100 \times 10^4$ ᵇ
Mold	$1.66 \times 10^3 \pm 1.52 \times 10^3$ ᵃ	$1.86 \times 10^3 \pm 2.71 \times 10^3$ ᵃ	$0.11 \times 10^3 \pm 0.06 \times 10^3$ ᵃ	0 ± 0 ᵃ

Yeast and mold growth are high causes of spoilage in minimally processed food. This kind of food can increase yeast and mold colonies from fresh samples in ranges for yeasts of less than

100 to 4.0x10^8 CFU/g, and mold counts ranging from less than 100 to 4.0x10^4 CFU/g as reported by Tournas (2005). In the case of apple slices dried in this study, both, yeast and mold are between the safe ranges but with some differences in the responses to the drying methods.

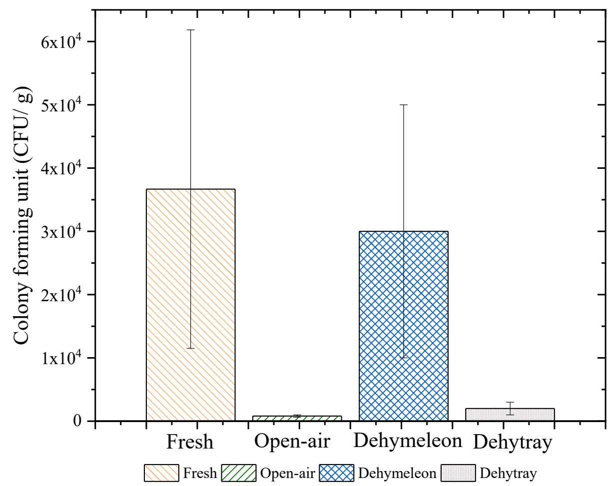

Figure 4.12. Comparison of yeast colonies formation for apple slices by drying method against fresh value

The effect of temperature, direct sunlight and water removal were important when reducing the amount of microbial load of yeast and mold. In the case of yeast, reductions around 94%-97% of the original colonies were possible in Dehytray™ and open-air sun drying. This is explained by the nature of yeast and its photo sensibility when exposed to direct sunlight. In contrast, although the Dehymeleon™ reduced the initial colony load by 16%, it was not as significant as the other two solar methods. This might have been probably due to the shade effect of the Dehymeleon™ drying chamber.

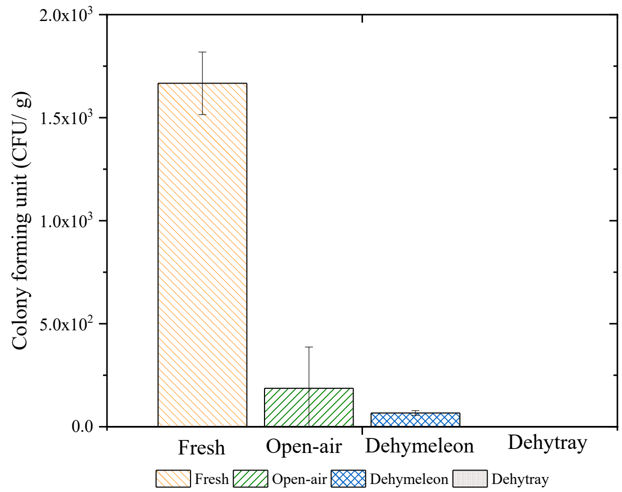

Figure 4.13. Comparison of mold colonies formation for apple slices by drying method against fresh value

The reduction of mold loads presented a different trend from yeast because they vary on the growth medium, where molds are found to be more common in damp and dark humid areas. Similar to yeast, a reduction due to the direct exposure to light was also a key factor. The increase in temperatures as is seen for Dehymeleon^{TM} and Dehytray^{TM} also help to reduce the initial mold load from fresh samples from 3 log [CFU/g] to 2 log [CFU/g] for Dehymeleon^{TM}. This is an important advantage from enclosed drying methods versus the open-air sun drying due to the risk of toxins generation that molds have when present in food matrixes for human or animal consumption.

Color change

Color change for apple slices was evaluated with three parameters, where L* (lightness), a* (redness) and b* (yellowness). In the particular case of apple slices when cut, the most important single-color value was L* to verify changes in browning. For the same purpose a* parameter was also studied as an important value, due to its linkage to the Milliard reaction and caramelization. Changes in color values are listed in Table 4.14 and total color change compare with fresh values are shown in Table 4.15 and plotted in Figure 4.14. A tracking of color change for fresh and dried samples is pictured in Figure 4.15 where the difference in direct sunlight methods versus shade method such as the Dehymeleon™ can be appreciated.

Table 4.14. Color values of apples slices, fresh and dried using open-air sun drying, Dehymeleon™ and Dehytray™.

	Color values		
	L*	**a***	**b***
Fresh	77.49 ± 0.89^{a}	-3.42 ± 0.47^{a}	23.07 ± 1.23^{a}
Open-air	72.87 ± 6.86^{b}	10.23 ± 4.38^{b}	$30.91 \pm 3.67^{b,c}$
Dehymeleon™	73.25 ± 4.76^{b}	4.73 ± 2.15^{c}	31.86 ± 5.64^{c}
Dehytray™	73.55 ± 5.27^{b}	7.86 ± 4.27^{d}	28.36 ± 3.30^{b}

Table 4.15. Color change for apples slices, dried by open-air, DehymeleonTM and DehytrayTM Delta E is a value that compares fresh samples with dried samples using the three solar drying methods.

	Open-air sun drying	**Dehymeleon™**	**Dehytray™**
Color change (ΔE)	18.70 ± 6.5^{a}	12.89 ± 3.8^{b}	15.50 ± 5.5^{a}

To compare the color degradation with the fresh product, delta of color parameters was calculated for each drying method and is shown in **Table 3.17** and Figure 4.14. For total delta E, Dehymeleon™ presented a significant difference in color from the other two drying methods tested in this study. Apple slices dried using the Dehymeleon™ were less exposed to direct sunlight. Instead, Dehytray™ and open air-sun drying, which were more exposed to direct sunlight gave similar results. However, the values for Dehytray™ were better than the open-air sun drying most likely because some shading is provided to the crop by the cover placed over the tray.

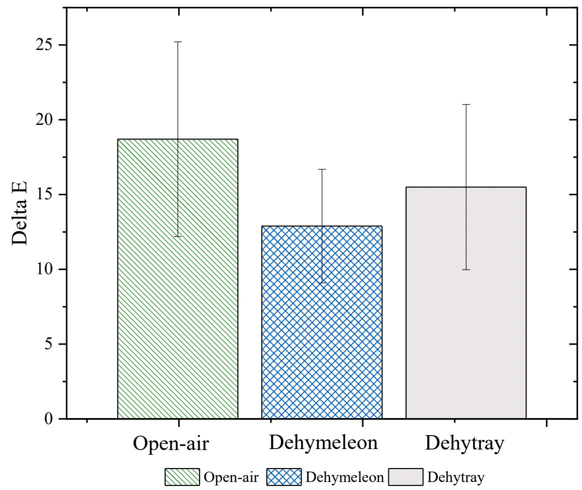

Figure 4.14. Delta E color change for apple slices

Apple slices were pretreated with a solution of 5% citric acid to prevent enzymatic browning. This method has been largely used for apples due to their susceptibility to oxidation when cut into slices (Sagar and Suresh Kumar, 2010). Doymaz (2010) investigated red apple slices for enzymatic inhibitors such as blanching and citric acid and found that citric acid gave better results on prevention of enzymatic browning. In this study, citric acid was found to be effective in stopping oxidation before the drying and revealed how temperatures and direct sun light led into Milliard reactions, in the case of the enclosed dryers and into oxidoreduction processes in the case of open-air sun drying.

a) Fresh b) Fresh c) Fresh

a) Dried b) Dried c) Dried

Figure 4.15. Drying samples of apple slices for a) Open-air sun drying, b) Dehymeleon^{TM} and c) Dehytray^{TM}.

4.6 Conclusions

The performance of three different solar drying methods for drying apple slices was investigated. Moisture removal, temperature change, and water diffusivity were characterized for each method to evaluate their drying performance for drying cut apple slices. Additionally, quality assessment was carried in order to compare the performance of each method. Pre-treated apple slices presented a higher water diffusivity when dried with open-air sun drying method and Dehymeleon™, due to better air flow over the material. Open-air and Dehytray™, were more dependent on ambient temperatures than Dehymeleon™, because the latter one had the advantage of controlling the airflow, which allowed the removal of saturated air. Direct exposure to sunlight influenced the microbial load reduction and inactivation during the drying process. Drying curves were fitted to four different thin-layer drying equations and corroborated that the lab and field test were related in the time for the reduction of critical moisture at the beginning of the test. Changes in vitamin C and color change were extremely linked because both are a result of the oxidoreduction reactions in the product as a response to all the external factors during the drying process. Dehymeleon™ preserved the higher amount of vitamin C, which matched with the low change in color compared with the fresh sample and the other two drying methods. Finally, pre-treatment with citric acid reduced considerably enzymatic browning, allowing the identification of other sources of color change such as direct light exposure and temperature peaks.

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CHAPTER 5. DRYING STUDIES ON MINT LEAVES

5.1 Abstract

Drying kinetics and quality attributes of mint leaves (*Mentha spitaca*) were studied to determine the drying performance of two different solar drying technologies (Dehymeleon™ and Dehytray™) and their effect on dried mint quality. Drying experiments were carried out under weather conditions at Purdue University, West Lafayette, Indiana. Thin layer drying tests were conducted for whole mint leaves at three temperatures [24°C (75°F), 35°C (95°F) and 54 °C (130°F)], and air flow velocity of 1 m/s to determine its drying kinetics for diurnal drying cycles typical for solar and/or open-air sun drying. Afterwards, field drying tests were done for whole mint leaves with two solar drying technologies (Dehymeleon™ and Dehytray™) and open-air sun drying as the control. The average temperatures achieved for these technologies were 40°C (104°F), 45°C (113°F) and 28°C (82.4°F) for the Dehymeleon™, Dehytray™ and open-air sun drying, respectively. Quality attributes (color and microbial growth) were measured before and after the field drying tests. There was no significant difference ($\alpha = 0.05$) in the microbial growth for the Dehytray™ and open-air sun drying compared to the fresh product, however, there was significant difference for the Dehymeleon™. Finally, the color difference (ΔE) for Dehymeleon™ solar-dryer showed the least variation compared with the fresh product followed by the Dehytray™ and open-air sun drying. Open-air sun drying showed the largest color difference (ΔE).

5.2 Introduction

Herbs such as mint (*Mentha spitaca* L.) have been largely used for medical and aromatic purposes through the centuries. Its usage varies from dried leaves, powders to essential oils. Mint oil is the most common essential oil used around the world (Dwivedi et al., 2004). However, mint leaves are also commonly used fresh and dried for flavoring, spicing and for tea infusions, which have digestive, calming, tonic, antiseptic and anti-asthmatic properties. Mint has a high nutraceutical value; indeed, its antioxidant activity and flavonoids components are highly valued in the food industry, which is also due to its after taste that provides a cooling feel. Its oil scents of citronella are also used in aromatic soaps, perfumery, detergents, repellants and pesticides for various insects (Park et al., 2002). The interest in these components make preservation and storage of this seasonal plant crucial for its availability during the whole year. Various techniques or treatments for preservation such as drying, and oil extraction have been applied on this plant (Park et al., 2002). Drying is one of the most accessible techniques and the most suitable due to reduction of the high moisture content of mint, which oscillates around 80% to 90%.

Drying techniques used on mint have been related mostly with the common methods such as open-air sun drying and open-air shade drying due to the sensibility of its compounds to light exposure. For example, in shade drying mint is tied in small bundles and hung up or spread on screens (Doymaz, 2005). Studies on mint drying behavior and other related studies on leafy and aromatic plants such as the ones conducted by Akpinar (2010) are on the rise. Other studies to understand the drying kinetics of mint leaves have been performed by Doymaz, (2005); Ertekin and Heybeli, (2013) and Park et al., (2002). These studies focused on thin layer drying experiments to understand the drying behavior of mint at different temperatures that ranged between 30ºC to 60ºC. The temperature was closely related with the reduction in drying times and also on the drying diffusivity of the product.

Open-air sun drying has been used for several years in drying mint leaves. However, quality is affected due to dust, debris and insect infestation during open-air sun drying. There are no studies about mint drying using commercially available solar dryers (i.e. Dehymeleon^{TM} or Dehytray^{TM}). Information on the drying performance of commercial technologies will be helpful in understanding the quality of dehydrated products by these technologies. This chapter presents studies on the performance of two new solar dehydration technologies, Dehymeleon^{TM} and Dehytray^{TM}, and their effects on some quality parameters of mint.

5.3 Materials and methods

5.3.1 Produce material

Mint leaves

Mint leaves (*Mentha spitaca*) from Piazza Produce (Indianapolis, Indiana) were used for the different drying tests described in this document. Mint leaves were obtained by separating them from the stem by hand. Initial moisture content for fresh samples was determined before field drying studies by using the air-oven moisture loss upon drying method at 100 °C for 24 h. (AOAC 2000). Average moisture content was found to be 87.9% (w.b.). No pre-treatments were applied for mint leaves. All moistures are reported on a wet basis (w.b.).

5.3.2 Drying of mint leaves

Thin layer drying tests

Thin layer drying experiments were conducted at Purdue University in the Spring of 2018 using the thin layer dryer presented in Chapter 3, Figure 3.1. Drying was conducted by setting the temperatures of the thin-layer dryer to run in a cycle to simulate cyclical ambient temperature changes using three temperatures, 24°C (75°F), 35°C (95°F) and 54 °C (130°F). Temperatures were changed every three hours until the dried product reached constant weight. Mint leaves were placed on a tray with an area of 0.093m^2 inside the thin-layer apparatus drying chamber. The perpendicular air flow velocity from top to bottom was 1 m/s. The air used for drying was heated by an electric heater (Chromalox Inc., USA) and blown using a 1/3 hp centrifugal fan (Dayton, Iowa, USA) via an air duct (1) from the top into the drying chamber as shown in Chapter 3, Figure 3.1. Temperatures and weight change were collected every five minutes by a Fluke data logger (model Hydra 2620A, Fluke, Everett, WA, USA).

Sun drying field studies

Sun drying field tests for three different sun drying methods were conducted at the ADM Agricultural Innovation Center, West Lafayette, Indiana during the summer of 2018. Tests conducted for the three different sun drying methods, Open-air sun drying, Dehymeleon^{TM} and Dehytray^{TM} are described in Chapter 3 of this thesis. Specific procedures used for drying mint are described in the following section.

Sun drying using the Dehymeleon^{TM}

Uncovered Dehytray^{TM} was filled with a thin layer of mint leaves; each tray held approximately 0.8 kg of mint leaves. Three trays were placed inside the drying chamber of the Dehymeleon, and their weight was measured twice per day (in the morning prior to placement in the sun and in the evening at dusk) using a digital scale platform. Drying progress was tracked by weight, while dried mint leaves were monitored for spoilage by visual inspection. The three set of fans of the Dehymeleon were set to run at different speeds during drying. The top fans were ran at 100% of its full speed, while bottom and front fans were set at 80% of full speed due to the high ambient relative humidity that was present during the test period (at beginning test date to ending test date). Relative humidity and temperature sensors Extech (model RHT10, Extech instruments, Nashua, NH, USA) were distributed inside the chamber and set to log data every 30 min throughout the test duration.

Figure 5.1. Arrangement of trays in the Dehymeleon^{TM} during drying of mint leaves.

Dehytray^{TM}

Three Dehytrays were filled with a thin layer of mint leaves, each tray held approximately 0.8 kg of mint leaves. Temperature and relative humidity sensors, Extech (model RHT10, Extech instruments, Nashua, NH, USA) were placed inside one replicate tray of each drying method and data logged every 30 min during daytime sun drying events and overnight when trays were stored in the high bay workshop at ADM Innovation Center. Weight was measured for each tray twice per day using a digital scale platform. As with the drying studies using the Dehymeleon, drying progress was tracked by weight, while dried mint leaves were monitored for spoilage by visual inspection.

Figure 5.2. Arrangement of Dehytray^{TM} placed under the sun during drying of mint leaves.

Open-air sun drying

Open-air sun drying was used to compare the performance of the Dehytray^{TM} and Dehymeleon^{TM} technologies with the most commonly used method, open-air sun drying. About 0.8 kg of mint leaves were placed on the Dehytray^{TM} without the cover as shown in Figure 5.3, and weighed on a digital scale platform twice per day. Weights were measured at the beginning of the day prior to the trays being placed in the sun, and at the end of the day at dusk, when the trays were brought into the ADM building. The trays were monitored until they reached a constant weight after which drying was stopped. Ambient temperatures and RH were tracked using a HOBO data logger (model MX 2300 RH&T, ONSET, Bourne, MA, USA).

Figure 5.3. Arrangement of uncovered (open-air sun drying) and Dehytrays during field tests drying mint.

5.3.3 Drying kinetics for: thin layer drying and open field test of mint leaves

Moisture ratio and diffusivity calculations

Variation of moisture content (moisture ratio) for the drying experiments of mint leaves was calculated using the equation (3.1) presented in Chapter 3. Equation (3.2) in the same chapter was used to linearize the drying curve by applying natural logarithm, so that the drying rate could be calculated. For field tests, an exponential regression of the form of Equation (3.1) was estimated using the software, Origin-Pro 2018b (Origin Lab Corporation, Northampton, MA, USA). Using the values obtained by the calculation of moisture ratio from the experimental data, moisture diffusion (D) was calculated using a simplification of Fick's second law for a slab, Equation (3.3). The effective moisture diffusivity values were determined by plotting experimental drying data in terms of $ln\ (MR)$ versus drying time (t).

5.3.4 Quality indicators

Quality assessment was conducted for the following indicators: microbial growth for aerobic bacteria and color change. Test on mint leaves were conducted with the same procedures described in the section 3.3.4 of Chapter 3 in this thesis.

5.4 Data Analysis

All observations were reported as means of the corresponding replications. One-way analysis of variance (ANOVA) was conducted using a means difference Turkey test with ($\alpha = 0.05$), using OriginPro 2018b package (Origin-Pro 2018b, Origin Lab Corporation, Northampton, MA, USA) to determine whether the quality indicators were significantly different for the various sun drying methods used.

5.5 Results and discussion

This section presents results on the drying behavior of mint leaves under three different methods: open-air sun drying, and the use of two solar dryers, Dehymeleon^{TM} and Dehytray^{TM}. An analysis of the drying behavior of mint leaves by thin layer experiment using cyclical temperature changes to simulate diurnal ambient temperature changes was also conducted to understand the drying kinetics of mint leaves. The relationship of drying temperatures and changes in moisture content were evaluated by quality assessment of microbial growth and color change. The drying behavior of mint leaves serves as an assessment of the performance of three drying methods used.

5.5.1 Thin layer drying experiments

Changes of moisture ratio for whole dried mint leaves were conducted by simulating diurnal drying cycles as for the two previous studies, temperatures in the drying chamber were changed to 24°C (75°F), 35°C (95°F) and 54 °C (130°F) at 3-hours interval in close approximation to a typical drying day using the Dehymeleon until the product reached constant weight. Product was dried on a surface area of 0.093 m^2 and had an initial wet weight of 569.8± 29g (0.568 kg).

The data obtained during the thin-layer drying experiments was converted into dimensionless moisture ratio and was plotted versus time as shown in Figure 5.4. This was used to identify the drying kinetics for mint leaves, which was characterized mostly by a falling rate followed by a constant rate when constant weight was reached. Each falling rate was associated with the change in temperature as can be seen on Fig. 5.4. Initial moisture content for mint leaves was 85.8% and was dried to an equilibrium moisture content of 8%.

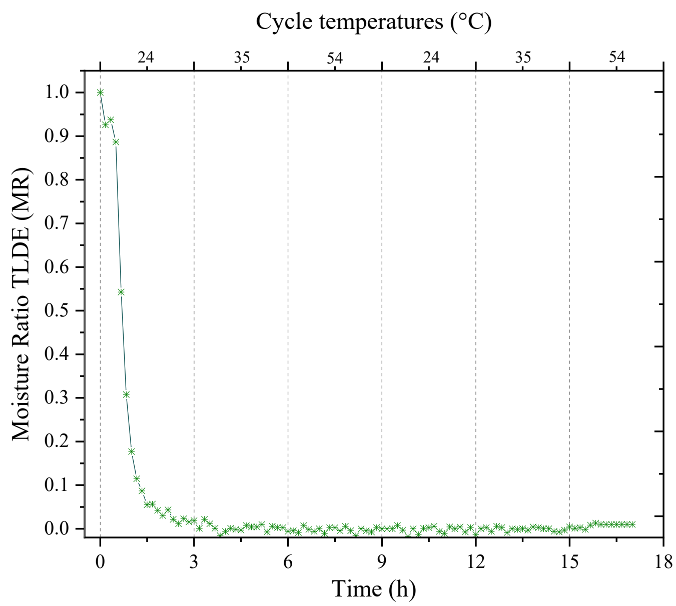


Figure 5.4. Moisture ratio versus time for TLDE test of mint leaves.

Moisture content decreased as a function of time and temperature. The graph shows a higher gradient of moisture loss in the first three hours, which was due to the loss of loosely bound free water present in the leaves.

Evaluation of the model

Studies on mathematical modeling of thin-layer of mint leaves have been conducted to predict drying and moisture ratio as a function of time. After conducting regression analysis of the change in moisture versus drying time. Page was found as the most suitable model to predict drying behavior of mint leaves. This was corroborated by the values shown in Table 5.1. This result was also compared with other thin-layer experiments conducted by Doymaz (2005) and Ertekin and Heybeli (2013) for mint where Page model was also the model used to predict the moisture ratio of Mint leaves drying.

Table 5.1. Mathematical models applied to Thin-layer drying curve of mint leaves.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k=1.222 ± 0.117	0.9214	0.2914	0.0535
Page	$MR = e^{-kt^n}$	k = 1.715 ± 0.139 n= *2.855* ± 0.245	0.989	0.041	0.020
Modified Midilli	$MR = ae^{-kt} + b$	a = 1.186 ± 0.029 b = -0.004 ± 0.010 k = *1.388* ± 0.143	0.938	0.227	0.040
Henderson and Pabis	$MR = ae^{-kt}$	a = 1.183 ± 0.074 k = 1.402 ± 0.137	0.938	0.228	0.047

Drying Rate and Diffusivity

As is shown on Table 5.2, the first three drying hours represent a reduction of 74.9 percentage points of moisture from the mint leaves, the first falling rate. The second falling rate had 5.39 percentage points of moisture. This is as a result of the constant airflow inside the thin-layer drying chamber. Although, the temperature was not high, the availability of large amounts of free loosely bound water that was easily removed played an important role the rapid drying of mint, especially during the first 3 hours. This analysis reflects an important situation in drying processes where non-heated air is able to remove water in higher rates when airflow is high and conditions such as low RH in air are favorable. In sun drying where weather conditions are not always favorable by increasing the drying air temperature, drying could be manage by increasing the airflow rate over the product.

Table 5.2. Drying kinetics for mint leaves using TLDE.

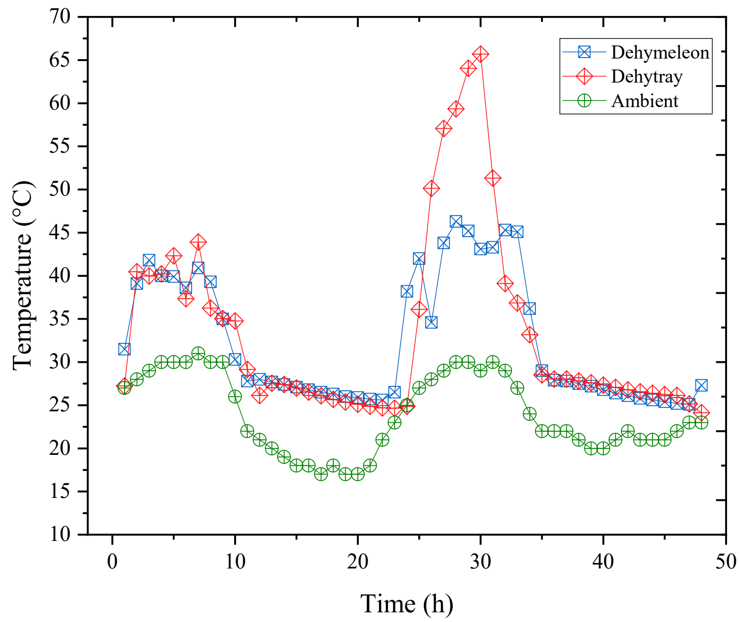
Main falling rates	**Total drying time (h)**	**Average temperature (^{0}C)**	**Initial MC%**	**Final MC%**	**Drying Rate (kg H_2O/h*m^2)**	**Moisture Diffusivity D_{eff} (m^2/s)**
1st Falling rate	1-3	24	87.9	13	1.601 ± 0.104	2.59 x 10 $^{-8}$
2nd Falling rate	3-17	40.4	13	7.61	0.0407 ± 0.024	0.66 x 10^{-9}

5.5.2 Field Experiments for Open-Air Sun Drying, Dehytray™, and Dehymeleon™

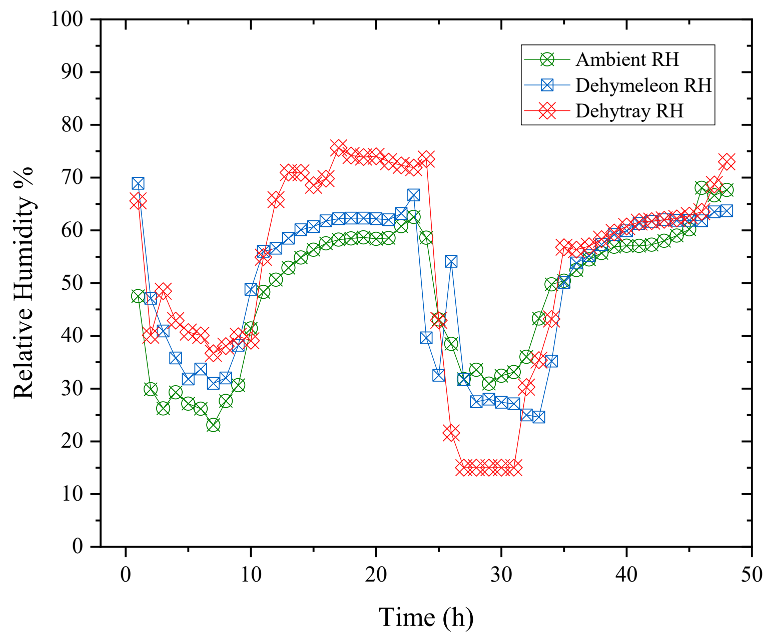
Field-drying tests were conducted during the summer of 2018 (August 13^{th} to August 15^{th}) at the ADM Agricultural innovation center, where drying trays and dryers were placed outside on the North-side of the building and brought inside the high bay workshop area from dusk till morning. Temperature and relative humidity data were collected during the drying period (Fig. 5.5a). For this study, mint leaves were directly exposed to the sun for about 12 hours per day, with sun drying starting at 8:00 to 9:00 pm, after which the trays for open-air sun drying, Dehytray™, and Dehymeleon™ were moved inside the building, and brought out about 8:00am the following day until product had reached its target moisture level.

During mint drying studies, the ambient temperatures were close to 30°C during daytime sun exposure and close to 15°C at night when stored indoors. The temperatures inside the dryers, Dehytray™ and Dehymeleon™ increased from early morning and peaked primarily around solar noon, reaching temperatures around 40°C. On the second day, for Dehytray™ reached temperatures close to 65°C. During the drying period, ambient relative humidity had a similar behavior as the relative humidity inside the dryers (Fig. 5.5b). However, due to the constant releasing of water from the product, the relative humidity inside the dryers tended to be a little higher. This did not present a problem during diurnal drying but did cause higher relative humidity values inside the Dehytray™ and Dehymeleon™ dryers during the night.

The difference between the ambient temperature seen by the mint leaves in open-air sun drying and the Dehytray™ and Dehymeleon™ were on average Δ10.75ºC and Δ12ºC, respectively. The relative humidity inside the dryers, Dehytray™ and Dehymeleon™ reached their lowest values when temperatures were at the peak (Fig. 5.5b). The temperatures inside Dehytray™ and Dehymeleon™ can be compare with those reported by Akpinar (2010b) for an indirect forced convection solar dryer, which had a difference of 20ºC when compared with ambient temperature values. No rehydration to the product (mint leaves) was observed during the test.



a)



b)

Figure 5.5. Profile temperatures a) and relative humidity b) for Open-air (Ambient), Dehytray^{TM} and Dehymeleon^{TM} during the drying of mint leaves.

Open-air Sun Drying- Mint Leaves

Open-air sun drying was used as the control method to test the performance of the Dehytray^{TM} and Dehymeleon^{TM} in drying mint leaves. Changes in mass, moisture content, and moisture ratio were measured and calculated for the drying process and are shown in Table 5.3 and are plotted in Figure 5.6 for the open sun-drying of mint leaves. The reduction in water content during the first hours of drying contrast with the drying behavior presented by the mint leaves for the thin-layer drying test. Moisture ratio curve for open-air sun drying is shown in Figure 5.6c.

Table 5.3. Weight change, moisture content, moisture ratio for mint leaves dried by open-air sun drying using the Dehytray^{TM} without the cover on.

Time (h)	Weight (kg)	Moisture content % (w.b)	Moisture ratio (MR)
0	0.775 ± 0.01	82.77	1
12	0.342 ± 0.06	26.85	0.076
24	0.308 ± 0.05	22.55	0.061
36	0.208 ±0.06	9.65	0.023
48	0.200 ±0.06	9.50	0.022

<u>*Evaluation of the model for moisture ratio*</u>

Newton, Page, Modified Midilli, and Henderson-Pabis models were used as moisture ratio models to predict the moisture content as a function of drying time, which had a high coefficient of determination (R^2). Values for the regressions are shown in Table 5.4. The Page model had the highest R^2 and lowest SSE for the TLDE.

Table 5.4. Mathematical models applied to open-air drying curve

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k = 0.204 ± 0.082	0.995	0.004	0.031
Page model	$MR = e^{-kt^n}$	k = 1.247 ± 0.829 n = 0.283 ± 0.222	0.999	0.0003	0.010
Modified Midilli	$MR = ae^{-kt} + b$	a = 0.966 ± 0.106 b = 0.033 ± 0.054 k = 0.255 ± 0.197	0.997	0.001	0.021
Henderson and Pabis	$MR = ae^{-kt}$	a = 0.987 ± 0.149 k = 0.098± 0.035	0.971	0.022	0.061

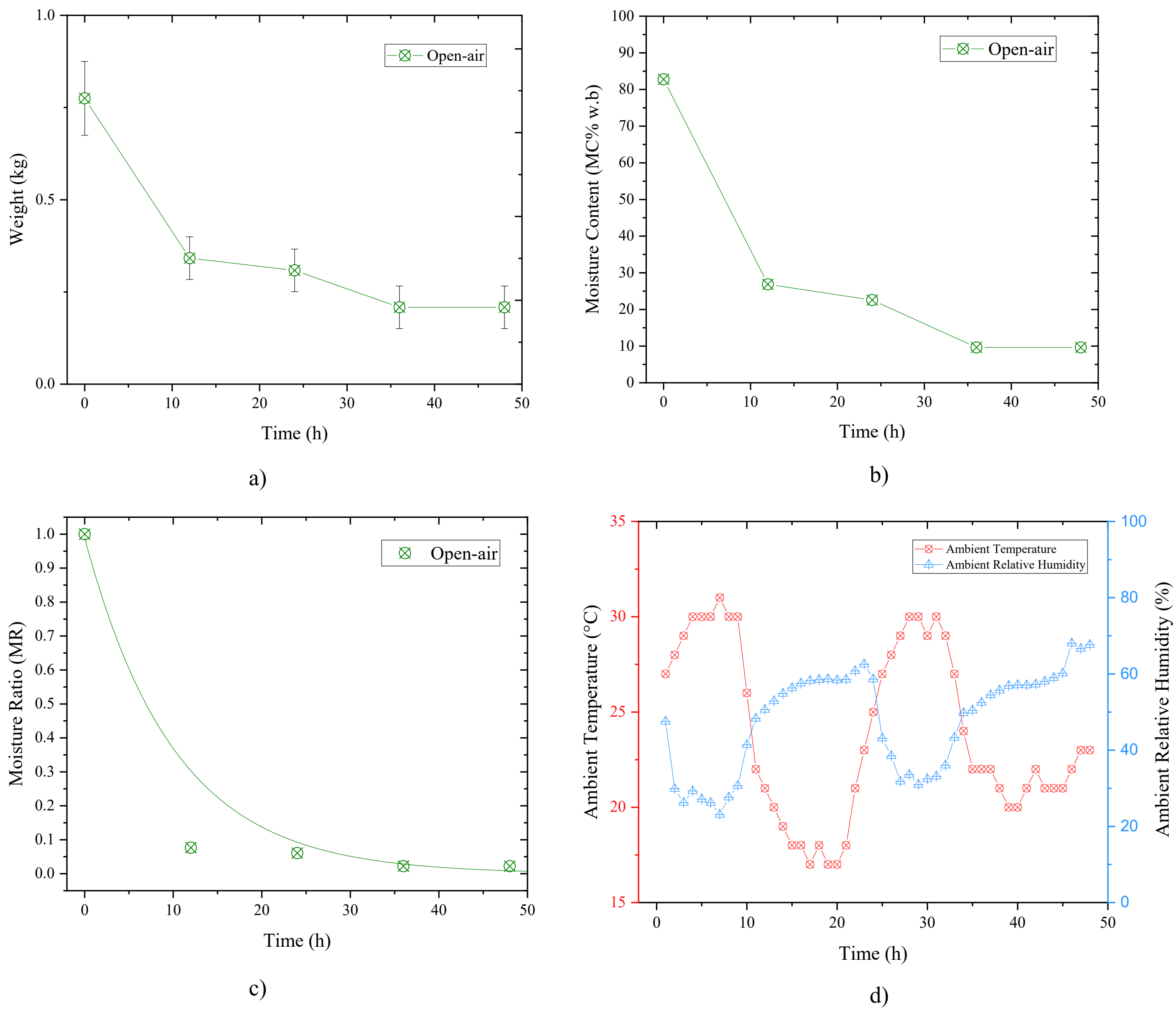


Figure 5.6. Open-air drying curves, temperatures and relative humidity values during the drying of mint leaves a) Weight loss, b) Moisture content change, c) Moisture ratio change versus time and d) Ambient temperature and relative humidity.

Dehymeleon™- Mint Leaves

Dehymeleon™ tests were conducted using three trays in the drying chamber with approximately two kilograms of mint leaves per replication per tray. Trays were put randomly inside the dryer and were weighed twice per day during the drying period (in the morning and at night). Data of weight change, moisture change, and moisture ratio are shown on Table 5.5 and plotted in Figure 5.7.

Table 5.5. Weight change, moisture content, moisture ratio for mint leaves dried using the Dehymeleon™.

Time (h)	**Weight (kg)**	**Moisture content % (w.b)**	**Moisture ratio (MR)**
0	0.708±0.057	82.77	1
12	0.408±0.057	40.42	0.141
24	0.258±0.028	19.24	0.0498
36	0.175±0.028	7.47	0.017
48	0.175±0.028	7.40	0.016

It was observed that the temperatures inside the drying chamber of the Dehymeleon™ increased compare with ambient temperatures shown in Figure 5.7. The average diurnal temperature in the drying chamber of the Dehymeleon™ was 40 ºC, which was approximately 10ºC above the ambient temperature. The relative humidity (RH) in the drying chamber of the Dehymeleon™ was quite similar to the ambient RH, which may have because of the fans exhausting the moisture released from the product during the drying process.

The Dehymeleon™ drying process was characterized by a falling rate as shown in Figure 5.7c. The Dehymeleon™ reduced microbial growth during the test by reducing water activity and maintaining a relative humidity inside the dryer ranging from 20-70%. The fans constantly exhausting the moisture released from the product during the drying process controlled the RH in the chamber from becoming high, and most likely prevented rehydration of the product at night.

Additionally, the enclosed chamber environment provided a hygienic environment for drying and protected the product from contamination by dust and other environmental elements.

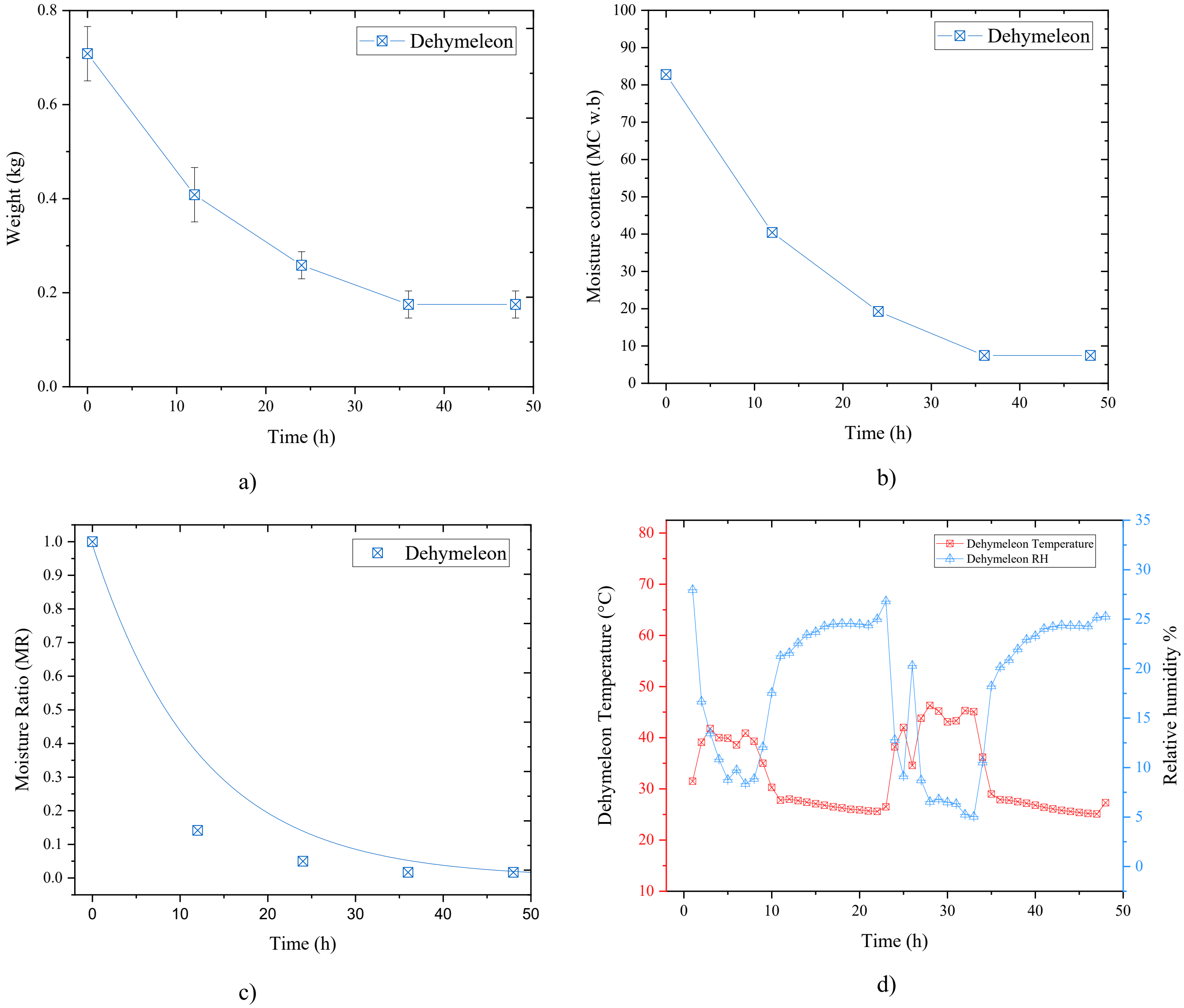


Figure 5.7. Dehymeleon^{TM} drying curves, temperatures and relative humidity values during the drying of mint leaves a) Weight loss, b) Moisture content change, c) Moisture ratio change versus time and d) Ambient temperature and relative humidity.

Evaluation of the model for moisture ratio

Drying behavior of mint leaves by the Dehymeleon^{TM} was modeled using Newton, Page, Modified Midilli, and Henderson-Pabis moisture ratio models to predict the moisture content as a function of drying time. The coefficient of determination (R^2) was quite high for these models. Values for the regressions are shown in Table 5.6. As for the drying behavior shown, the Page model had the highest R^2 and lowest SSE for the TLDE.

Table 5.6. Mathematical models applied to the Dehymeleon™ drying curve for mint leaves.

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	k = 0.158 ± 0.026	0.998	0.001	0.0177
Page model	$MR = e^{-kt^n}$	k = 0.425± 0.134 n = 0.615 ± 0.114	0.999	0.00006	0.0046
Modified Midilli	$MR = ae^{-kt} + b$	a = 0.978 ± 0.044 b = 0.021 ± 0.030 k = 0.173 ± 0.086	0.993	0.0002	0.0109
Henderson and Pabis	$MR = ae^{-kt}$	a = 0.993 ± 0. 058 k = 0.158 ± 0.034	0.997	0.0012	0.0205

Dehytray™ - mint leaves

For the field drying experiments with mint leaves conducted using the Dehytray™ drying method, approximately three kilograms of whole mint leaves were divided in three Dehytray™ with their respective covers placed on them during the drying process. Mint leaves were dried from an initial moisture content of 82.8% to a final moisture content of 8%, when samples reached a constant mass. It was observed that Dehytray™ heat gain depended highly on weather conditions such as temperature and relative humidity. For the first day of drying, the Dehytray™ reduced moisture content by 9.4 percentage points, compared to 55.9 percentage points for open-air sun drying and 42.4 percentage points for the Dehymeleon™. The slow drying rate of the Dehytray™ is clearly due to the lack of airflow. Although Dehytray™ had a low drying rate at the beginning of the test, samples were not visibly affected and microbial tests still performed better than in the case of open-air sun drying. The transparent cover also allowed ultraviolet wavelengths to penetrate the product, and can be an advantage to reduce microbial growth also present in direct sun exposure. However, direct exposure to sunlight affects the content of some nutritional value and denatures color, as will be analyzed in section 5.5.3 of this chapter. Weight data for Dehytray^{TM} mint leaves is shown in Table 5.7. Moisture change and ratio are plotted in Figure 5.8.

Table 5.7. Weight change, moisture content, moisture ratio and drying rate constant for mint leaves dried by Dehytray^{TM}.

Time (h)	**Weight (kg)**	**Moisture content % (w.b)**	**Moisture ratio (MR)**
0	0.713±0.057	82.77	1
12	0.647±0.057	73.42	0.57632
24	0.247±0.057	17.35	0.04377
36	0.180±0.057	8.00	0.01813
48	0.180±0.057	8.00	0.01813

Temperature and relative humidity profiles inside the Dehytray^{TM} are shown in Figure 5.8d. The temperature inside the Dehytray^{TM} was on average 12ºC higher than the ambient, and just two degrees higher than the Dehymeleon^{TM} in the first day of drying. On the second day, the temperatures inside the Dehytray^{TM} was almost 35ºC above the ambient, which might explain the reduction in bacteria, despite the low rate of drying presented at the beginning of the test. Therefore, differences with Dehymeleon^{TM} were not observed, but it was found that temperatures inside the Dehytray^{TM} started to rise when weather conditions allowed a better heat gain.

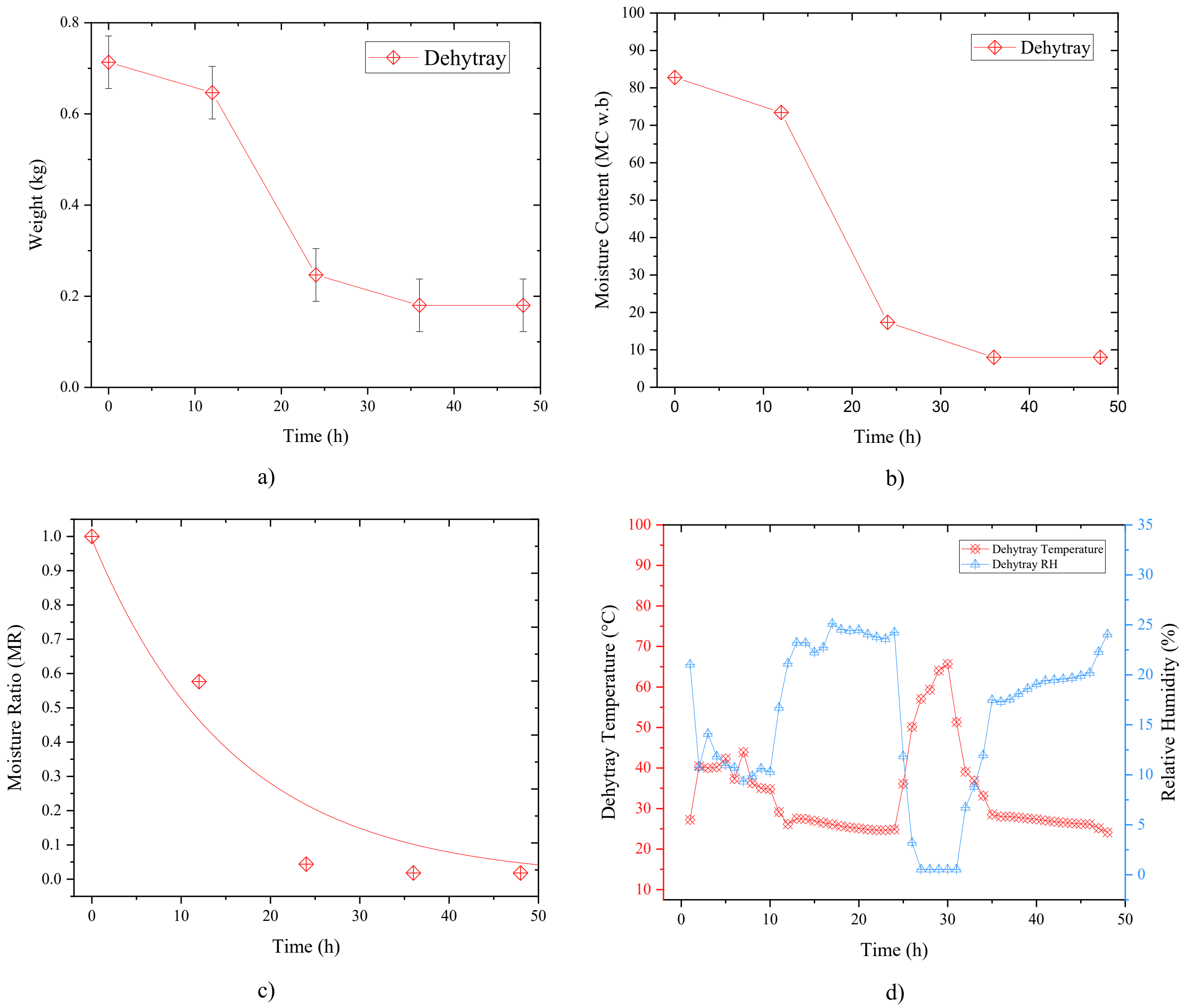


Figure 5.8. Dehytray^{TM} drying curves, temperatures and relative humidity values during the drying of mint leaves a) Weight loss, b) Moisture content change, c) Moisture ratio change versus time and d) Ambient temperature and relative humidity.

Evaluation of the model for moisture ratio

In order to predict the moisture content as a function of time, the Newton, Page, Modified Midilli, and Henderson-Pabis models were fitted to the experimental data collected for samples dried with Dehytray^{TM}. Values for the regressions are shown in Table 5.8. As for the drying behavior expressed in the TLDE, the Modified Midilli and Page models had the highest R^2 and lowest SSE.

Table 5.8. Mathematical models applied to the Dehytray™ drying curve for mint leaves

Model	Equation	*Parameter*	R^2	*SSE*	*RMSE*
Newton	$MR = e^{-kt}$	$k = 0.071 \pm 0.039$	0.942	0.0453	0.1064
Page model	$MR = e^{-kt^n}$	$k = 0.001 \pm 0.001$ $n = 2.502 \pm 0.535$	0.999	0.0006	0.0147
Modified Midilli	$MR = ae^{-kt} + b$	$a = 1.140 \pm 0.949$ $b = -0.114 \pm 0.882$ $k = 0.057 \pm 0.124$	0.955	0.0350	0.1324
Henderson and Pabis	$MR = ae^{-kt}$	$a = 1.033 \pm 0.380$ $k = 0.073 \pm 0.056$	0.944	0.04413	0.1213

Drying rate and diffusivity

Drying of mint leaves took a total of 48 hours including overnight storage in the barn. The methods, Open-air, Dehytray™ and Dehymeleon™ were exposed to the sun for about 24 hours. Open-air sun drying had a better drying rate performance during the first 12 hours of drying, reducing the water content of the sample by 55 percentage points, while the Dehymeleon™ reduced the moisture by 42.4 percentage points, and the Dehytray™ by only 9 percentage points. The faster initial drying rates for the Open-air sun drying and Dehymeleon methods was most likely due to the better air flow in these two drying methods. The Dehytray has no fan and depends on natural convection to remove moisture from its enclosed chamber. Values for drying rate and moisture diffusivity are shown in Table 5.9. The drying rate constant k was determined by plotting the experimental data ln (MR) vs. drying time. A summary of the regressions conducted is presented in Appendix 3.

Moisture diffusivity for Dehymeleon™ was the highest value among the three methods with a D_{eff} of (5.14×10^{-9} m^2/s) as a result of the stable temperatures around 40ºC and the constant airflow of 1.9 m/s of non-saturated air flushing out saturated air from the chamber during drying of mint leaves. Studies conducted by Park et al. (2002) for oven drying of mint leaves found a moisture diffusivity of 1.125×10^{-12} m^2/s for constant temperatures around 40ºC for an airflow of

1.0 m/s. Values for Dehytray™ where found to be 4.60 x 10^{-9} m^2/s, open-air sun dried leaves showed a similar level in terms of water mass removal with a D_{eff} of 4.95 x 10^{-9} m^2/s.

<u>Summary of drying hours per drying method used (Open-air sun drying, Dehytray</u> ™ <u>and Dehymeleon</u> ™

Table 5.9. Drying time of mint leaves for the different methods, initial and final moisture content, and drying rate with moisture diffusivity.

Drying method	Total drying time (h)	Sun-exposed Time (h)	Initial MC%	Final MC%	Drying Rate kg $H_2O/h*m^2$	Moisture diffusivity D_{eff} (m^2/s)
Open-air	48	24	82.77	9.5	0.041 ± 0.008	4.95 x 10^{-9}
Dehymeleon™	48	24	82.77	7.4	0.044 ± 0.007	5.14 x 10^{-9}
Dehytray™	48	24	82.77	8.0	0.041 ± 0.005	4.60 x 10^{-9}

5.5.3 Quality indicators for mint leaves

Quality of mint leaves was measured with two indicators: aerobic bacteria growth and color change. Due to the scope of this study, specific bacteria pathogens were not identified. However, the log reductions in aerobic counts achieved for the drying methods were compared to log reductions achieved by the use of a chemical sanitizers. The following sections present the results for the quality indicators measured for the fresh and dried samples of mint leaves used in this study.

Microbial growth

Aerobic Count

Aerobic count values for fresh and dried mint leaves are shown in Table 5.10. Colonies formation range between the averages of 253.3x10^4, 84.0x10^4, 1.25x10^4 and 99.6x10^4 CFU/g for the aerobic bacteria present in fresh, open-air drying, and drying using the Dehymeleon™, and Dehytray™ solar dryers, respectively.

Table 5.10. Aerobic bacteria colonies (CFU/g) formation counts for whole mint leaves dried by open-air sun drying, Dehymeleon™ and Dehytray™

	Fresh	**Open-air sun drying**	**Dehymeleon™**	**Dehytray™**
Aerobic count (CFU/g)	$253.3 \times 10^4 \pm 128.5 \times 10^3$ a	$84.0 \times 10^4 \pm 33.0 \times 10^4$ b	$1.25 \times 10^4 \pm 10.6 \times 10^4$ a	$99.6 \times 10^4 \pm 52.3 \times 10^4$ a

Due to the temperatures reached inside the dryers and the average ambient temperature for open-air sun drying, there could be two kinds of bacteria present: Mesophiles which grow between 20ºC - 45ºC and thermophiles, which grow between 55ºC - 85ºC (Bourdoux et al., 2016a). Thermophiles might grow when the enclosed dryers reached peak temperature around solar noon, but will die when temperatures decrease. The presence of mesophilic bacteria was reduced from the original counts; this due to the reduction in water activity during the drying process.

For the case of mint leaves and other aromatics, *Salmonella,* is one of the most common bacteria present in dried or fresh mint leaves or dried chamomile during storage as was described by Keller et al. (2015). The *Salmonella* reported in this study survived after processing with temperatures around 55ºC and remained alive after six months of storage at ambient conditions. The study also concluded that even though this aromatic plant has some components that are believed to inhibit the growth of pathogens, the amount present is insufficient to prevent the spread and the growth of pathogens such as *Salmonella.* However, the methods used in this thesis particularly in the case of mint present reductions of 0.47 log, 0.40 log and 2.3 long for Open-air sun drying, Dehytray™ and Dehymeleon™ respectively. The log reductions obtained can be compared with some of the values achieved by chemical sanitizers commonly use during post-harvest washing operations. For example, in the case of leaves like spinach studied by Neal et al. (2012), sanitizers such as L-lactic acid, ozonated water and normal water wash were used to reduce Salmonella and E. Coli from fresh spinach leaves. The results from the study carried by Neal et al.

(2012) show that normal water wash presents 0.7 log reduction, followed by the ozonated water with 1.0-log reduction, both of them were significantly different when compared with L-lactic acid, which had a log reduction 2.3, being the best disinfectant method among the test. The value obtained for L-lactic acid is similar to the one obtained in this thesis for the mint leaves dried by Dehymeleon™. The reduction obtained in both cases presents a good advantage, but it is still lower than the 5.0-log reduction obtained with other thermal treatments.

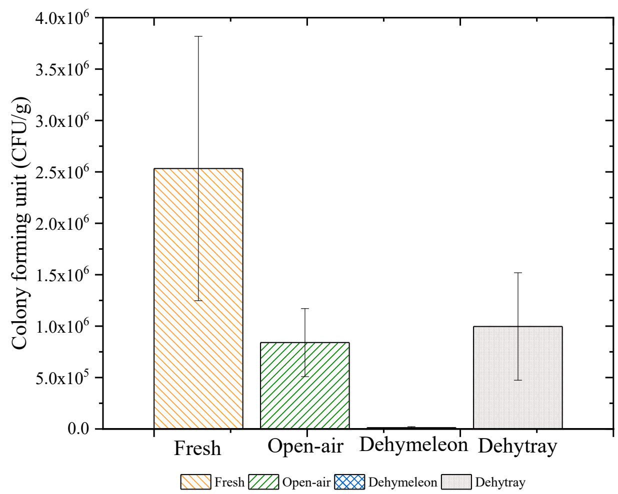


Figure 5.9. Comparison of aerobic bacteria count (CFU/g) on fresh mint leaves and whole dried leaves using open-air sun drying, Dehytray™ and Dehymeleon™.

Color change

Color change for mint leaves was evaluated using three parameters, notably L* (lightness), a* (redness) and b* (yellowness). In the particular case of mint leaves, L* helps to verify changes in browning. Changes in color values are listed in Table 5.11 and total color change compare with fresh values are shown in Table 5.12 and plotted in Figure 5.11.

Table 5.11. Color values of mint leaves fresh and dried using the three sun drying methods.

	Color values		
	L*	**a***	**b***
Fresh	42.67 ± 6.62 [a]	-13.32 ± 4.20 [a]	21.72 ± 4.77 [a]
Open-air	33.91 ± 4.46 [b]	-1.53 ± 1.36 [b,c]	13.38± 2.48 [b,c]
Dehymeleon™	40.51 ± 3.95 [a]	-4.33 ± 2.06 [c]	17.75 ± 1.89 [c]
Dehytray™	36.71 ± 5.17 [b]	-1.49 ± 1.28 [b]	14.26 ± 1.65 [b]

Values from Table 5.1 indicate the change in L*, a* and b* compared with fresh mint leaves. For L* values, the Dehymeleon™ was the method that had a non-significant impact on this value compared with the fresh mint leaves but showed a different trend for a* and b*, where it was significantly different compared with fresh mint leaves. Changes in a* values could be reflected in the browning of mint leaves after drying due to the development of more bluish colors. Similar values for fresh mint leaves and dried leaves were obtained by Ertekin and Heybeli (2013) when drying with an infrared dryer at temperatures of 30ºC.

Table 5.12. Color change for mint leaves dried using open-air sun drying, Dehymeleon™ and Dehytray™

Delta E is a value that compares fresh samples with dried samples by difference.

	Open-air sun drying	**Dehymeleon™**	**Dehytray™**
Color change (ΔE)	18.38± 7.05 [a]	13.44 ± 3.72 [b]	17.74 ± 5.67 [a]

For having a more accurate comparison a delta or difference between color parameters was calculated for each drying method and is shown in Table 5.12 and graphed in Figure 5.10. For the total delta E, the Dehymeleon™ was significantly different from the other two drying methods, Open-air sun drying and the Dehytray™ solar dryer tested in this study. This was most likely due to the shade and thus less exposure to sunlight provided by the enclosed drying chamber of the Dehymeleon™. The Dehytray™ and open-air sun drying methods had similar results due to their exposure to direct sunlight. However, values for Dehytray™ present a better performance taking into account the higher temperatures presented during the drying process.

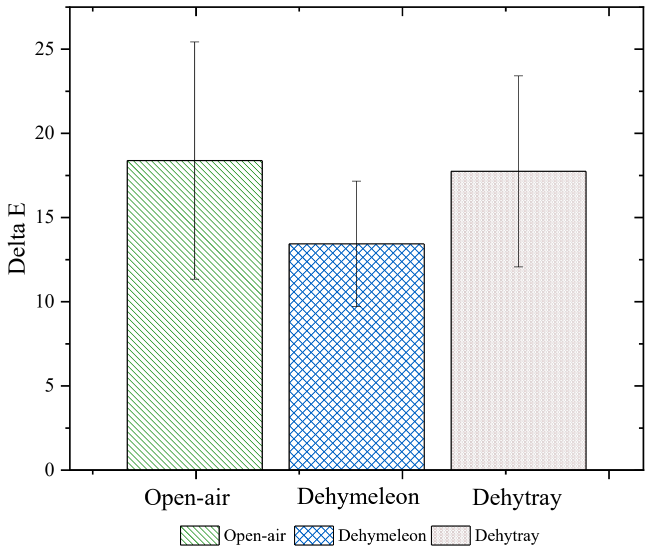


Figure 5.10. Delta E color change for mint leaves

a)

b)

c)

d)

Figure 5.11. Color of dried samples of mint leaves for a) Fresh mint leaves, b) dried using Open-air sun drying c) dried using Dehymeleon™ and d) dried using Dehytray™.

5.6 Conclusions

The performance of three different solar drying methods for drying mint leaves, Open-air sun drying, Dehymeleon™ and Dehytray™ was investigated. The curves for moisture ratio did not show a constant rate-drying but showed the common trend of a falling rate for fruits and vegetables. This is most likely due to the large percentage of free water present in fresh whole mint leaves. Additionally, the effective diffusivity increased with the air temperature. The heat gain or increment in temperature inside the dryers was directly dependent on the prevailing weather conditions at the field location (West Lafayette, Indiana). This was observed during the second day of drying when the temperature inside the Dehytray™ increased by about 20ºC above the ambient temperature. Goodness of fit of the experimental data with four thin-layer drying models, Newton, Page, Modified Midilli, and Henderson-Pabis models was determined by comparing the coefficient of determination, SSE and root mean square errors. From the analysis the most suitable model was found to be the Page model.

Quality assessment was conducted on mint leaves in order to compare the performance of each method with respect to microbial load reduction and color change. The Dehymeleon™ was found to have less impact on dried mint color compared to fresh whole mint, while both the Open-air sun drying and Dehytray™ had more impact on color due to more exposure to sunlight with these methods. As the drying methods were highly dependent on ambient temperatures, the ability of the solar dryers to increase their drying chamber temperatures above the ambient becomes crucial. For all the drying methods, the aerobic bacterial count on dried mint leaves was less that measured for fresh mint leaves. The log reductions in of aerobic count achieved for Open-air sun drying, Dehymeleon™ and Dehytray™ were 0.47, 2.3 and 0.40, respectively.

5.7 References

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CHAPTER 6. . CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The performance of three different drying methods (open-air sun drying, and two solar dryers – the Dehytray™ and Dehymeleon™) was evaluated under West Lafayette, Indiana weather conditions using three different agricultural products (tomatoes slices, apples slices and mint leaves). Performance of the drying methods was measured based on drying rates, effective diffusivity, vitamin C content, CFU/g of bacteria, coliforms, yeast and molds, and color change. Drying kinetics of the products were described by thin-layer drying experiments that determined the drying rates and diffusivities of (tomatoes slices, apples slices and mint leaves) at certain temperatures (24°C, 35°C and 54°C) determined based on temperatures achieved inside the Dehymeleon™ after an empty (no-load) drying run. The rates of drying for the solar dryers, Dehytray™ and Dehymeleon™ compared to the open-air sun drying method using Dehytray™ without the covers varied from slightly slower in the case of tomato slices and mint leaves, and higher as in the case of apple slices. The drying rate was dependent on favorable weather conditions in West Lafayette, Indiana, where the field tests were conducted, which varied for each test. The retention of vitamin C in dried tomato and apple slices using the Dehymeleon™ was higher than for the dried products using the Dehytray™ and open-air sun drying, as result of different variables that contributed directly with the oxido-reduction reactions caused by direct exposure to sunlight and drying diffusivity. The CFU for aerobic bacteria and yeast were quite high in tomato and apple slices dried using the Dehymeleon™, but acceptable for slices dried using the Dehytray™ or open-air sun drying. The Dehytray and Dehymeleon achieved 0.4 log to 2.3 log reductions, respectively, in bacteria and coliform counts for dried apples and mint. Less color change occurred in tomato and apple slices dried using the Dehymeleon™, than those dried using the Dehytray™ and open-air sun drying. While the Dehytray™ dries tomato at a sufficiently fast rate that prevents bacteria and mold growth, the Dehymeleon™ needs improvement in its use in drying tomato, primarily by increasing chamber temperature, temperature distribution, and airflow. Additionally, more airflow in the Dehytray by the use of a fan to exhaust moisture released from the crop during drying would increase drying rates.

6.2 Future work

Future studies should focus on understanding what technological improvements are needed to optimize solar drying of fresh produce (specialty crops):

- How water activity is linked to the onset of microbial propagation, and its relationship with the desorption isotherms during the drying process would be insightful to optimizing drying operations that would prevent microbial growth on products being dried.

- Understanding the impact of pre-treatments on microbial growth and the relationship between color degradation on a nutritional denaturation would be insightful, especially for use as a rapid quality indicator.

- Studying the impact of fresh product preparation (cutting, slicing, grating, chopping in chunks, etc.) and fresh produce material properties on the rate of drying would help in optimizing drying processes and operations.

- In this study, the materials being dried were left over night in a barn, but not closely monitored. Extending the thermal analysis on the dryer to understand how the overnight variations in temperature and relative humidity affects the drying process especially overnight rehydration and its mitigation would be a contribution to the body of knowledge.

- Exploring the use of antioxidant activity as a quality indicator of deterioration during the drying process would also expand our understanding of the performance of sun drying processes.

APPENDIX A. TOMATOES STUDIES

Result Tables and Graphs of Statistical Analyses using OriginPro 2018b package (Origin-Pro 2018b, Origin Lab Corporation, Northampton, MA, USA)

Thin Layer Drying Experiments

1 *Nonlinear Curve Fit (YldFert1) (7/17/2019 12:39:17)*

Notes

Input Data

Parameters

		Value	Standard Error	t-Value	Prob>|t|	Dependency
Tomatoes MR	a	-0.03889	0.01164	-3.34115	0.00108	0.76169
	b	1.17237	0.02464	47.58195	1.18189E-86	0.49574
	k	0.20654	0.0097	21.2999	3.70526E-45	0.79493

Reduced Chi-sqr = 0.00445927713102
COD(R^2) = 0.99995981207253
Iterations Performed = 9
Total Iterations in Session = 9
Fit converged. Chi-Sqr tolerance value of 1E-9 was reached.
Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	Tomatoes MR
Number of Points	139
Degrees of Freedom	136
Reduced Chi-Sqr	0.00446
Residual Sum of Squares	0.60646
R-Square (COD)	0.99996
Adj. R-Square	0.99996
Fit Status	Succeeded(100)

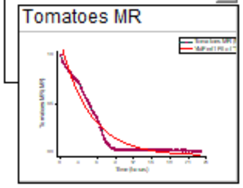
Fit Status Code :
100 : Fit converged. Chi-Sqr tolerance value of 1E-9 was reached.

Summary

	a		b		k		Statistics	
	Value	Standard Error	Value	Standard Error	Value	Standard Error	Reduced Chi-Sqr	Adj. R-Square
Tomatoes MR	-0.03889	0.01164	1.17237	0.02464	0.20654	0.0097	0.00446	0.99996

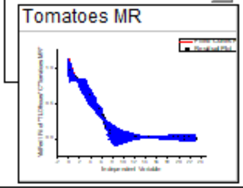
Fitted Curves Plot

Tomatoes MR



Residual Plot

Tomatoes MR



ONE WAY ANOVAS

a) Microbial Test: Aerobic Count

1 ANOVAOneWay (6/24/2019 19:43:43)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehytray	3	0	666.66667	288.67513	166.66667
Dehymeleon	3	0	15400	8155.9794	4708.8569
Open	3	0	1833.33333	1040.833	600.92521
Fresh	3	0	1166.66667	288.67513	166.66667

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	4.54327E8	1.51442E8	8.9386	0.0062
Error	8	1.3554E8	1.69425E7		
Total	11	5.89867E8			

Null Hypothesis: The means of all levels are equal.

Alternative Hypothesis: The means of one or more levels are different.

At the 0.05 level, the population means are significantly different.

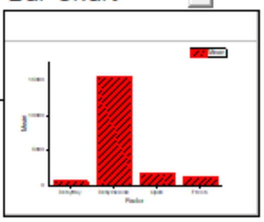
Fit Statistics

	R-Square	Coeff Var	Root MSE	Data Mean
	0.77022	0.86352	4116.12682	4766.66667

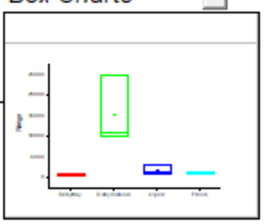
Means Comparisons

Powers

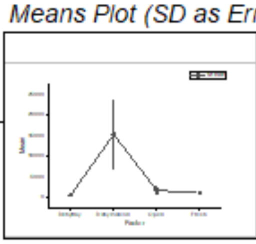
Bar Chart



Box Charts



Means Plot (SD as Error)



b) Microbial Test: Coliform Counts

ANOVAOneWay (6/24/2019 20:07:38)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehytray	3	0	83.33333	15.27525	8.81917
Dehymeleon	3	0	43.33333	15.27525	8.81917
Open	3	0	96.66667	56.86241	32.82953
Fresh	3	0	166.66667	105.98742	61.19187

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	23758.33333	7919.44444	2.12128	0.17576
Error	8	29866.66667	3733.33333		
Total	11	53625			

Null Hypothesis: The means of all levels are equal.
Alternative Hypothesis: The means of one or more levels are different.
At the 0.05 level, the population means are not significantly different.

Fit Statistics

	R-Square	Coeff Var	Root MSE	Data Mean
	0.44305	0.62668	61.10101	97.5

Means Comparisons

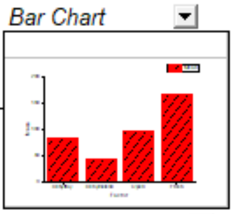
Tukey Test

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Dehymeleon Dehytray	-40	49.88877	1.13389	0.85185	0.05	0	-199.76137	119.76137
Open Dehytray	13.33333	49.88877	0.37796	0.99279	0.05	0	-146.42803	173.0947
Open Dehymeleon	53.33333	49.88877	1.51186	0.7165	0.05	0	-106.42803	213.0947
Fresh Dehytray	83.33333	49.88877	2.36228	0.39657	0.05	0	-76.42803	243.0947
Fresh Dehymeleon	123.33333	49.88877	3.49617	0.13972	0.05	0	-36.42803	283.0947
Fresh Open	70	49.88877	1.98431	0.53121	0.05	0	-89.76137	229.76137

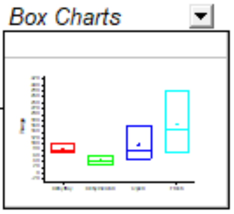
Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.
Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

Powers

Bar Chart



Box Charts



c) Microbial Test: Yeast and Mold

ANOVAOneWay (6/24/2019 20:24:09)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehytray	3	0	166.66667	57.73503	33.33333
Dehymeleon	3	0	7300	2066.39783	1193.03534
Open	3	0	3000	1000	577.35027
Fresh	3	0	16.66667	5.7735	3.33333

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	1.04529E8	3.4843E7	26.42941	1.67143E-4
Error	8	1.05467E7	1318341.66667		
Total	11	1.15076E8			

Null Hypothesis: The means of all levels are equal.
Alternative Hypothesis: The means of one or more levels are different.
At the 0.05 level, the population means are significantly different.

Fit Statistics

	R-Square	Coeff Var	Root MSE	Data Mean
	0.90835	0.4381	1148.19061	2620.83333

Means Comparisons

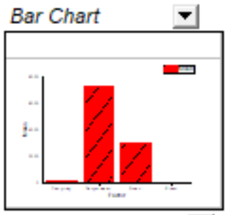
Tukey Test

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Dehymeleon Dehytray	7133.33333	937.4937	10.76067	2.87358E-4	0.05	1	4131.14891	10135.51776
Open Dehytray	2833.33333	937.4937	4.2741	0.06446	0.05	0	-168.85109	5835.51776
Open Dehymeleon	-4300	937.4937	6.48657	0.00774	0.05	1	-7302.18443	-1297.81557
Fresh Dehytray	-150	937.4937	0.22628	0.99842	0.05	0	-3152.18443	2852.18443
Fresh Dehymeleon	-7283.33333	937.4937	10.98694	2.48543E-4	0.05	1	-10285.51776	-4281.14891
Fresh Open	-2983.33333	937.4937	4.50037	0.05144	0.05	0	-5985.51776	18.85109

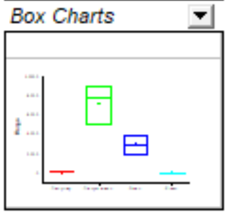
Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.
Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

Powers

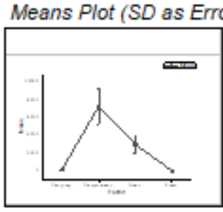
Bar Chart



Box Charts



Means Plot (SD as Error)



Color Test

ANOVAOneWay (7/15/2019 16:30:29)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Fresh	27	0	25.45241	1.43763	0.27667
Open-air	27	0	21.04796	10.39819	2.00113
Dehymeleon	27	0	34.56648	9.01944	1.73579
Dehytray	27	0	28.82722	10.51538	2.02369

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	2632.91287	877.63762	11.62	1.25001E-6
Error	104	7854.93224	75.52819		
Total	107	10487.84511			

Null Hypothesis: The means of all levels are equal.

Alternative Hypothesis: The means of one or more levels are different.

At the 0.05 level, the population means are significantly different.

Fit Statistics

R-Square	Coeff Var	Root MSE	Data Mean
0.25104	0.31633	8.6907	27.47352

Means Comparisons

Tukey Test

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Open-air Fresh	-4.40444	2.36531	2.63341	0.25078	0.05	0	-10.58041	1.77152
Dehymeleon Fresh	9.11407	2.36531	5.44929	0.00114	0.05	1	2.93811	15.29003
Dehymeleon Open-air	13.51852	2.36531	8.0827	6.11598E-7	0.05	1	7.34256	19.69448
Dehytray Fresh	3.37481	2.36531	2.0178	0.48564	0.05	0	-2.80115	9.55078
Dehytray Open-air	7.77926	2.36531	4.65121	0.0074	0.05	1	1.6033	13.95522
Dehytray Dehymeleon	-5.73926	2.36531	3.43149	0.07838	0.05	0	-11.91522	0.4367

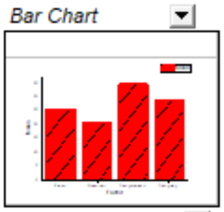
Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.

Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

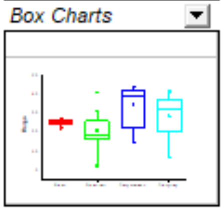
Homogeneity of Variance Test

Powers

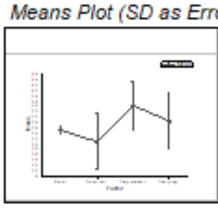
Bar Chart



Box Charts



Means Plot (SD as Error)



APPENDIX B. APPLES STUDIES

Thin Layer Drying Experiments

Nonlinear Curve Fit (Page (User)) (7/18/2019 11:30:43)

Notes

Input Data

Parameters

		Value	Standard Error	t-Value	Prob>|t|	Dependency
Apples	A	1	--	--	--	--
	n	1	--	--	--	--

Reduced Chi-sqr = 0.136907226944
Iterations Performed = 0
Total Iterations in Session = 0
Fit did not converge - reason unknown.
Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	Apples
Number of Points	139
Degrees of Freedom	137
Reduced Chi-Sqr	0.13691
Residual Sum of Squares	18.75629
R-Square (COD)	-0.47351
Adj. R-Square	-0.48426
Fit Status	Failed(-207)

Fit Status Code :
-207 : Fit did not converge - reason unknown.

Summary

	A		n		Statistics	
	Value	Standard Error	Value	Standard Error	Reduced Chi-Sqr	Adj. R-Square
Apples	1	--	1	--	0.13691	-0.48426

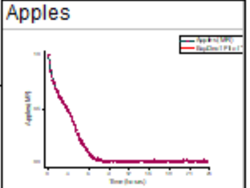
ANOVA

		DF	Sum of Squares	Mean Square	F Value	Prob>F
Apples	Regression	2	0	0	0	1
	Residual	137	18.75629	0.13691		
	Uncorrected Total	139	18.75629			
	Corrected Total	138	12.72902			

At the 0.05 level, the fitting function is NOT significantly better than the function y=0.

Fitted Curves Plot

Apples



Residual Plots

ONE WAY ANOVAS

a) Vitamin C Tests

ANOVAOneWay (8/8/2019 00:01:14)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Fresh	6	0	12.2807	1.07434	0.4386
Open-air	6	0	9.86842	1.38001	0.56339
Dehymeleon	6	0	10.41667	1.34424	0.54878
Dehytray	6	0	9.82143	1.49404	0.60994

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	23.99826	7.99942	4.50814	0.01428
Error	20	35.48875	1.77444		
Total	23	59.487			

Null Hypothesis: The means of all levels are equal.

Alternative Hypothesis: The means of one or more levels are different.

At the 0.05 level, the population means are significantly different.

Fit Statistics

R-Square	Coeff Var	Root MSE	Data Mean
0.40342	0.12571	1.33208	10.5968

Means Comparisons

Tukey Test

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Open-air Fresh	-2.41228	0.76908	4.43581	0.02463	0.05	1	-4.56485	-0.25971
Dehymeleon Fresh	-1.86404	0.76908	3.42767	0.10463	0.05	0	-4.01661	0.28854
Dehymeleon Open-air	0.54825	0.76908	1.00814	0.89082	0.05	0	-1.60433	2.70082
Dehytray Fresh	-2.45927	0.76908	4.52222	0.02159	0.05	1	-4.61185	-0.3067
Dehytray Open-air	-0.04699	0.76908	0.08641	0.99992	0.05	0	-2.19957	2.10558
Dehytray Dehymeleon	-0.59524	0.76908	1.09455	0.86525	0.05	0	-2.74781	1.55734

Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.

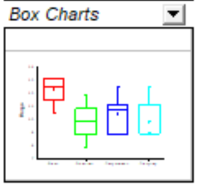
Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

Homogeneity of Variance Test

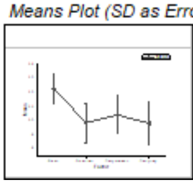
Powers

Bar Chart

Box Charts



Means Plot (SD as Error)



b) Microbial Test: Aerobic Count

1 ANOVAOneWay (8/14/2019 15:33:52)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehytray	3	0	466.66667	461.88022	266.66667
Dehymeleon	3	0	17833.33333	10539.60784	6085.04542
Open	3	0	1333.33333	288.67513	166.66667
Fresh	3	0	1133.33333	321.45503	185.59215

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	6.40482E8	2.13494E8	7.66013	0.00974
Error	8	2.22967E8	2.78708E7		
Total	11	8.63449E8			

Null Hypothesis: The means of all levels are equal.
Alternative Hypothesis: The means of one or more levels are different.
At the 0.05 level, the population means are significantly different.

Fit Statistics

R-Square	Coeff Var	Root MSE	Data Mean
0.74177	1.01688	5279.28341	5191.66667

Means Comparisons

Tukey Test

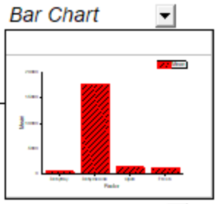
	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Dehymeleon Dehytray	17366.66667	4310.51685	5.69773	0.01602	0.05	1	3562.87628	31170.45705
Open Dehytray	866.66667	4310.51685	0.28434	0.99688	0.05	0	-12937.12372	14670.45705
Open Dehymeleon	-16500	4310.51685	5.41339	0.02101	0.05	1	-30303.79038	-2696.20962
Fresh Dehytray	666.66667	4310.51685	0.21872	0.99857	0.05	0	-13137.12372	14470.45705
Fresh Dehymeleon	-16700	4310.51685	5.47901	0.01973	0.05	1	-30503.79038	-2896.20962
Fresh Open	-200	4310.51685	0.06562	0.99996	0.05	0	-14003.79038	13603.79038

Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.
Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

Homogeneity of Variance Test

Powers

Bar Chart



c) Microbial Test: Coliform Counts

1 *ANOVAOneWay (6/24/2019 12:17:02)*

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehytray	3	0	40	26.45751	15.27525
Dehymeleon	3	0	23.33333	5.7735	3.33333
Open	3	0	90	43.58899	25.16611
Fresh	3	0	46.66667	11.54701	6.66667

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	7266.66667	2422.22222	3.50201	0.06941
Error	8	5533.33333	691.66667		
Total	11	12800			

Null Hypothesis: The means of all levels are equal.
Alternative Hypothesis: The means of one or more levels are different.
At the 0.05 level, the population means are not significantly different.

Fit Statistics

	R-Square	Coeff Var	Root MSE	Data Mean
	0.56771	0.52599	26.29956	50

Means Comparisons

Tukey Test

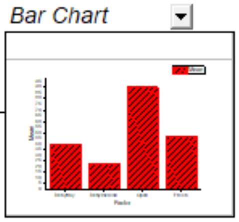
	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Dehymeleon Dehytray	-16.66667	21.4735	1.09764	0.86313	0.05	0	-85.43236	52.09902
Open Dehytray	50	21.4735	3.29293	0.17035	0.05	0	-18.76569	118.76569
Open Dehymeleon	66.66667	21.4735	4.39057	0.05738	0.05	0	-2.09902	135.43236
Fresh Dehytray	6.66667	21.4735	0.43906	0.98884	0.05	0	-62.09902	75.43236
Fresh Dehymeleon	23.33333	21.4735	1.5367	0.70684	0.05	0	-45.43236	92.09902
Fresh Open	-43.33333	21.4735	2.85387	0.25797	0.05	0	-112.09902	25.43236

Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.
Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

Homogeneity of Variance Test

Powers

Bar Chart



d) Microbial Test: Yeast and Mold

ANOVAOneWay (8/15/2019 11:37:32)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehytray	3	0	200	100	57.73503
Dehymeleon	3	0	3000	2000	1154.70054
Open	3	0	80	20	11.54701
Fresh	3	0	3666.66667	2516.61148	1452.96631

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	3.12804E7	1.04268E7	4.03212	0.05096
Error	8	2.06875E7	2585933.33333		
Total	11	5.19679E7			

Null Hypothesis: The means of all levels are equal.
Alternative Hypothesis: The means of one or more levels are different.
At the 0.05 level, the population means are not significantly different.

Fit Statistics

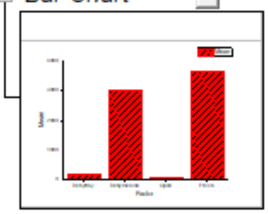
	R-Square	Coeff Var	Root MSE	Data Mean
	0.60192	0.92596	1608.08375	1736.66667

Means Comparisons

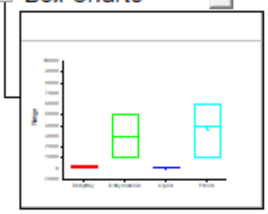
Homogeneity of Variance Test

Powers

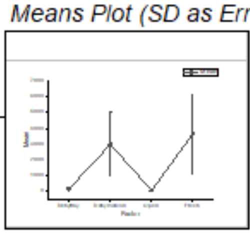
Bar Chart



Box Charts



Means Plot (SD as Error)



Color Test

ANOVAOneWay (8/6/2019 12:55:52)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehymelon	27	0	12.89119	3.79976	0.73126
Dehytray	27	0	15.50208	5.52184	1.06268
Open-sun	27	0	18.70439	6.51022	1.25289

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	2	457.78348	228.89174	7.86463	7.73673E-4
Error	78	2270.10762	29.10394		
Total	80	2727.8911			

Null Hypothesis: The means of all levels are equal.

Alternative Hypothesis: The means of one or more levels are different.

At the 0.05 level, the population means are significantly different.

Fit Statistics

	R-Square	Coeff Var	Root MSE	Data Mean
	0.16782	0.34364	5.39481	15.69922

Means Comparisons

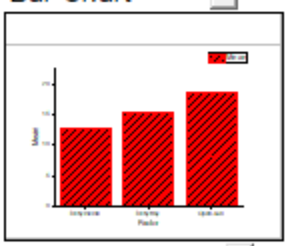
Tukey Test

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Dehytray Dehymelon	2.61089	1.46828	2.51475	0.18361	0.05	0	-0.89721	6.119
Open-sun Dehymelo	5.8132	1.46828	5.59914	4.79712E-4	0.05	1	2.3051	9.32131
Open-sun Dehytray	3.20231	1.46828	3.08439	0.0808	0.05	0	-0.3058	6.71041

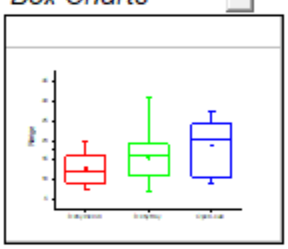
Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.

Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

Bar Chart



Box Charts



APPENDIX C. MINT STUDIES

Thin Layer Drying Experiments

1 Nonlinear Curve Fit (Page (User)) (7/18/2019 11:30:43)

Notes

Description	Nonlinear Curve Fit
User Name	rami120
Operation Time	7/18/2019 11:30:43
Iteration Algorithm	Levenberg Marquardt
Model	Page (User)
Number of Parameters	2
Number of Derived Parameters	0
Number of Datasets	1
Equation	exp(-k*(x^n))
Report Status	New Analysis Report
Special Input Handling	
Data Filter	No

Input Data

		Dep/Indep	Data	Range	Weight Type
Mint	x	Indep	[TLD]"TLD hours"!B"Time"	[1*:162*]	No Weighting
	y	Dep	[TLD]"TLD hours"!C"Mint"	[1*:162*]	No Weighting

Parameters

		Value	Standard Error	t-Value	Prob>|t|	Dependency
Mint	A	1	--	--	--	--
	n	1	--	--	--	--

Reduced Chi-sqr = 0.136907226944
Iterations Performed = 0
Total Iterations in Session = 0
Fit did not converge - reason unknown.
Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	Mint
Number of Points	139
Degrees of Freedom	137
Reduced Chi-Sqr	0.13691
Residual Sum of Squares	18.75629
R-Square (COD)	-0.47351
Adj. R-Square	-0.48426
Fit Status	Failed(-207)

Fit Status Code :
-207 : Fit did not converge - reason unknown.

Summary

	A		n		Statistics	
	Value	Standard Error	Value	Standard Error	Reduced Chi-Sqr	Adj. R-Square
Mint	1	--	1	--	0.13691	-0.48426

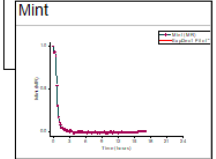
ANOVA

		DF	Sum of Squares	Mean Square	F Value	Prob>F
Mint	Regression	2	0	0	0	1
	Residual	137	18.75629	0.13691		
	Uncorrected Total	139	18.75629			
	Corrected Total	138	12.72902			

At the 0.05 level, the fitting function is NOT significantly better than the function y=0.

Fitted Curves Plot

Mint



1 Linear Fit (10/7/2019 23:18:28)

Notes

Input Data

Masked Data - Values Excluded from Computations

Bad Data (missing values) -- Values that are invalid and thus not used in computations

Parameters

		Value	Standard Error	t-Value	Prob>|t|
1st Falling Rate ln(MR)	Intercept	0.0767	0.18205	0.42132	0.6788
	Slope	-1.6013	0.10368	-15.44492	1.94536E-11

Slope is significantly different from zero (See ANOVA Table).
Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	1st Falling Rate ln(MR)
Number of Points	19
Degrees of Freedom	17
Residual Sum of Squares	2.8933
Pearson's r	-0.96617
R-Square (COD)	0.93348
Adj. R-Square	0.92956

Summary

	Intercept		Slope		Statistics
	Value	Standard Error	Value	Standard Error	Adj. R-Square
1st Falling Rate ln(MR)	0.0767	0.18205	-1.6013	0.10368	0.92956

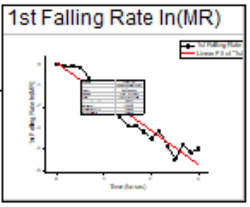
ANOVA

		DF	Sum of Squares	Mean Square	F Value	Prob>F
1st Falling Rate ln(MR)	Model	1	40.59905	40.59905	238.54553	1.94536E-11
	Error	17	2.8933	0.17019		
	Total	18	43.49235			

At the 0.05 level, the slope is significantly different from zero.

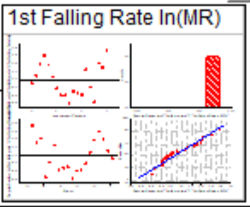
Fitted Curves Plot

1st Falling Rate ln(MR)



Residual Plots

1st Falling Rate ln(MR)



ONE WAY ANOVAS

a) Microbial Test: Aerobic count

ANOVAOneWay (10/7/2019 14:23:08)

Notes

Input Data

Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Dehytray	3	0	996666.66667	523099.73555	302011.77313
Dehymeleon	3	0	12546.66667	10610.20892	6125.80698
Open	3	0	840000	330605.5051	190875.17736
Fresh	3	0	2533333.33333	1285820.10147	742368.58171

One Way ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	9.9456E12	3.3152E12	6.51195	0.01535
Error	8	4.07276E12	5.09095E11		
Total	11	1.40184E13			

Null Hypothesis: The means of all levels are equal.
Alternative Hypothesis: The means of one or more levels are different.
At the 0.05 level, the population means are significantly different.

Fit Statistics

R-Square	Coeff Var	Root MSE	Data Mean
0.70947	0.65123	713508.80219	1095636.66667

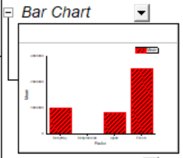
Means Comparisons

Tukey Test

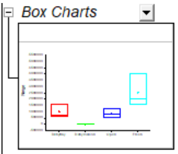
	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Dehymeleon Dehytray	-984120	582577.49745	2.38896	0.38792	0.05	0	-2849737.95888	881497.95888
Open Dehytray	-156666.66667	582577.49745	0.38031	0.99266	0.05	0	-2022284.62555	1708951.29221
Open Dehymeleon	827453.33333	582577.49745	2.00865	0.52196	0.05	0	-1038164.62555	2693071.29221
Fresh Dehytray	1536666.66667	582577.49745	3.73028	0.11088	0.05	0	-328951.29221	3402284.62555
Fresh Dehymeleon	2520786.66667	582577.49745	6.11924	0.01081	0.05	1	655168.70779	4386404.62555
Fresh Open	1693333.33333	582577.49745	4.11059	0.07589	0.05	0	-172284.62555	3558951.29221

Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.
Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

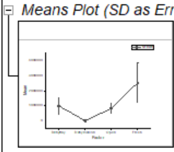
Bar Chart



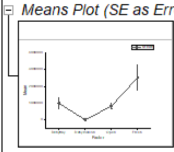
Box Charts



Means Plot (SD as Error)

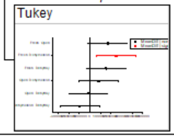


Means Plot (SE as Error)



Means Comparison Plot

Tukey



Color Test

1 ANOVAOneWay (8/8/2019 00:01:14)

- Notes
- Input Data
- Descriptive Statistics

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Fresh	6	0	12.2807	1.07434	0.4386
Open-air	6	0	9.86842	1.38001	0.56339
Dehymeleon	6	0	10.41667	1.34424	0.54878
Dehytray	6	0	9.82143	1.49404	0.60994

- One Way ANOVA
  - Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	23.99826	7.99942	4.50814	0.01428
Error	20	35.48875	1.77444		
Total	23	59.487			

Null Hypothesis: The means of all levels are equal.
Alternative Hypothesis: The means of one or more levels are different.
At the 0.05 level, the population means are significantly different.

- Fit Statistics

R-Square	Coeff Var	Root MSE	Data Mean
0.40342	0.12571	1.33208	10.5968

- Means Comparisons
  - Tukey Test

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Open-air Fresh	-2.41228	0.76908	4.43581	0.02463	0.05	1	-4.56485	-0.25971
Dehymeleon Fresh	-1.86404	0.76908	3.42767	0.10463	0.05	0	-4.01661	0.28854
Dehymeleon Open-air	0.54825	0.76908	1.00814	0.89082	0.05	0	-1.60433	2.70082
Dehytray Fresh	-2.45927	0.76908	4.52222	0.02159	0.05	1	-4.61185	-0.3067
Dehytray Open-air	-0.04699	0.76908	0.08641	0.99992	0.05	0	-2.19957	2.10558
Dehytray Dehymeleon	-0.59524	0.76908	1.09455	0.86525	0.05	0	-2.74781	1.55734

Sig equals 1 indicates that the difference of the means is significant at the 0.05 level.
Sig equals 0 indicates that the difference of the means is not significant at the 0.05 level.

- Homogeneity of Variance Test
- Powers
- Bar Chart